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Technical note

Reducing the sensation of electrical stimulation with dry electrodes by using an array of constant current sources

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ABSTRACT

Hydrogel electrodes are commonly used for functional and other electrical stimulation applications since the hydrogel layer has been shown to considerably reduce the perception of stimulation compared to dry electrodes. However, these hydrogel electrodes must be changed regularly as they dry out or become contaminated with skin cells and sweat products, thus losing their adhesiveness and resistive properties. Dry electrodes are longer lasting but are more uncomfortable due to unequal current distribution (current hogging). We hypothesise that if current through a dry electrode is equally shared amongst an array of small sub-electrodes, current hogging and thus the sensitivity perceived due to stimulation will be reduced. We constructed an 8 × 8 array of millimetre sized dry electrodes that could either be activated as individual current sources, or together as one large source. A study was performed with 13 participants to investigate the differences in sensation between the two modes of operation. The results showed that 12 out of 13 participants found the new (distributed-constant-current) approach allowed higher stimulation for the same sensation. The differences in sensation between single and multiple sources became larger with higher intensity levels.

1. Introduction

The application of electrical current to stimulate nerves for functional and therapeutic purposes is well established [1,2]. Electrodes play a major role in the success of stimulation since the efficacy of intervention, avoidance of tissue injury and the associated discomfort are all determined by the stimulation waveform and type of electrode used [2]. Surface electrodes are the most commonly used electrode types in typical functional electrical stimulation (FES) application for correction of foot drop caused by damage to the brain or spinal cord. Guiraud et al. reported that implanted FES devices for gait restoration have been restricted to experimental concepts, and have very little follow-up data [3]. The size, shape, material and placement of surface electrodes determines how effectively the underlying muscles and nerves are stimulated with the least amount of discomfort [4]. Good surface electrodes should be comfortable during use, easy to apply, stay in place for at least a day, re-usable, cost effective and reliable [5].

In the past, carbon–rubber electrodes were commonly used. However, these require the application of electrode gel which can be messy and inconvenient. Therefore, low-cost self-adhesive hydrogel electrodes are currently use as standard. As the resistivity of the hydrogel layer increases, the stimulation-induced discomfort decreases [6]. Though high resistivity hydrogel electrodes possess most of the desired properties required for good electrodes, they have poor reusability. Using old, dried out and dirty electrodes increases the chances of causing skin irritation, reduces self-adhesiveness and increase electrode-tissue impedance. Regular replacement of these electrodes increases the costs of therapy, especially when more sophisticated and costly electrodes are required [8].

Taking these issues into consideration, dry electrodes appear attractive for long-term applications. However, dry electrodes may cause pain or discomfort when high intensity electrical stimulation is applied. At low current intensities, stimulation evokes a sensory reaction without muscle contraction; as the current intensity is increased in order to evoke a muscle contraction, this sensory response increases and can cause pain and skin irritation [9]. Hair follicles, sweat pores and other structures beneath the skin form paths of low resistance for the current passing through the electrodes and thereby cause uneven current densities ("current hogging"). It is thought that the local high current densities due

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to current hogging lead to the greater pain associated with surface stimulation [6]. We hypothesise that if current can be more evenly distributed across the stimulated area (thus avoiding current hogging) then stimulation will be more comfortable. One way to achieve this even distribution is to use a high impedance hydrogel electrode [6]; however, Cooper et al. conducted a study on the properties of high resistivity hydrogel samples and concluded that they became contaminated with skin products and lost their desired properties if they were used for several days [7], causing significant problems in long term applications. An alternative approach to achieve equal distribution of the current within the electrode is to use multiple constant current sources, each connected to one of an array of small, adjacent mini electrodes.

2. Material and methods

2.1. Participants

Ethical approval for the study was obtained from the Sheffield Hallam University Research Ethics Committee and participants were recruited from students and staff within the University. After obtaining informed consent, thirteen adults, (11 male and 2 female) were recruited to the study. Participants were excluded if they had any prior adverse responses to any form of electrical stimulation or had any skin conditions such as eczema.

2.2. Equipment and materials

A 64 channel, constant current stimulator, Shefstim, was used to provide stimulation [10]. The parameters of stimulation i.e., pulse width, amplitude and frequency were controlled by custom software and PC. A commercially available hydrogel electrode (StimTrode 5 × 5 cm, Axelgaard Manufacturing Ltd., USA) was used as the anode. The cathode was a dry electrode array of 64 electrodes (in an 8 × 8 matrix), constructed from stainless steel paper pins. The heads of the pins were approximately 1 mm in diameter and were used as the electrodes. The pins were placed through a piece of stripboard with spacing of 2.54 mm and a 5 mm thick foam backing. The pins were then soldered onto another piece of stripboard via which the electrodes were connected to the outputs of the stimulator. The whole electrode formed a square of 30 mm x 30 mm (Fig. 1).

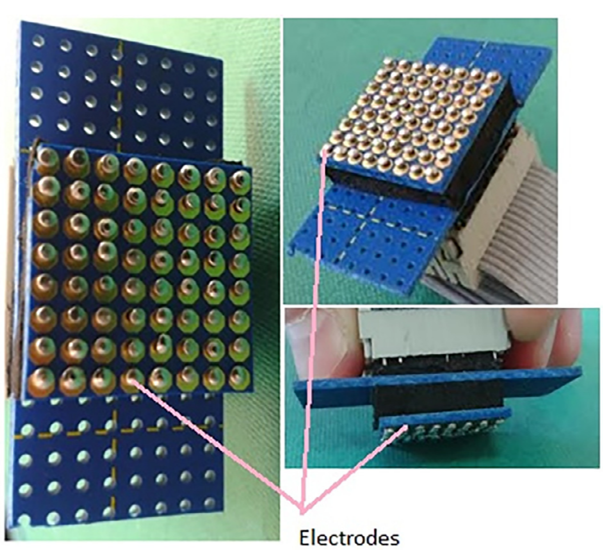

Fig. 1. The 8 × 8 electrode array constructed using stainless steel pins.

A breakout box was constructed so that each of the 64 channels could either act as individual electrodes (multiple sources) or all could be shorted to act as a single electrode (single source). This allowed the same electrode array to be placed on the same location and used to compare conventional (single source) and the novel (multiple sources) stimulation techniques, without having to remove the electrode. The participant was blinded as to the nature of stimulation, and the two stimulation types were delivered alternately.

2.3. Experiment design

The participants were asked to sit on a chair and rest their left arm on a table in front of them. The electrode array was placed approximately 5 cm below the elbow on the extensor aspect of the left forearm and was secured with two Velcro straps. The anode was placed on the wrist of the same arm. The experimental protocol consisted of two parts:

2.3.1. Identification of comfort threshold (CT)

This was defined as the threshold at which the participant felt that the sensation was at a maximum level that would be just tolerable for long periods of stimulation. This threshold stimulation current was identified for both single and multiple sources in random order by slowly increasing the intensity of stimulation and repeated twice more for each stimulation type. The maximum current of the three measurements was taken as the comfort threshold.

2.3.2. Difference in sensation

For each participant, stimulation was applied at 25%, 50%, 75% and 100% of the largest comfort threshold current identified above, starting at the lowest intensity. Stimulation was randomly switched between single source (type A) and multiple sources (type B), whilst keeping intensity constant. The participant was asked to mark the difference in perceived sensation on the visual analogue scale provided (Fig. 2). Switching between A and B was repeated until the participant was confident about his decision.

2.4. Outcome measures

2.4.1. Identification of comfort threshold (CT)

After the stimulation intensity was set to the appropriate level for the measurement being made, current stimulation intensity was recorded (measured by ShefStim). At the same time the delivered charge was measured as the voltage (V_C) across a1 μF capacitor (C) connected in series with the participant in the anode path using a battery operated oscilloscope (Tektronix THS 720). The delivered charge was calculated as $Q\ [\mu C] = C\ [\mu F] * V_C\ [V]$ and applied current for in one pulse as $I\ [mA] = \frac{Q\ [\mu C]}{t\ 200\ [\mu s]} * 10^3$.

2.4.2. Difference in sensation

The perceived sensation was measured using the Visual Analogue Scale (VAS). The VAS values are expressed as percentage measured on 10 cm line between ‘no difference’ and ‘much more uncomfortable’ for either A (single source) or B (multiple sources).

2.5. Analysis

2.5.1. Identification of comfort threshold (CT)

The Wilcoxon matched-pair signed rank test was used for the current threshold measurements. All values are expressed as mean values with confidence intervals unless indicated differently on the graphs.

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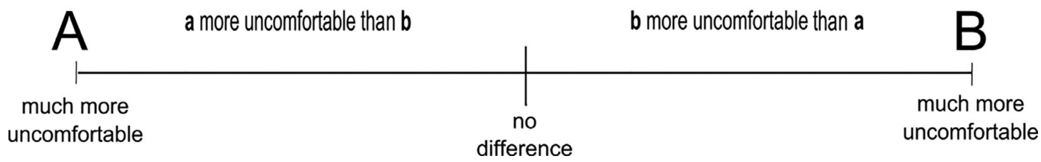

Fig. 2. Visual Analogue scale used in the experiment.

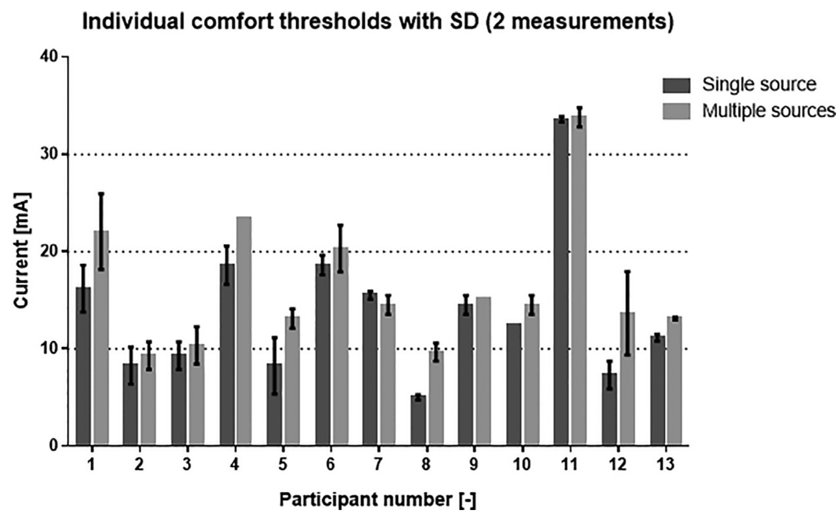

Fig. 3. Individual comfort thresholds for each subject for single and multiple sources.

2.5.2. Difference in sensation

The Wilcoxon signed rank test was also used to compare the differences in sensation to a hypothetical value of 0% i.e., no difference in sensation.

3. Results

The results of the comfort threshold measurements showed that 12 out of 13 participants had a higher comfort threshold for multiple current sources. The median comfort threshold for multiple sources was 14.5 mA (10.4–22.1, 97.75% CI of median) in comparison to 12.4 mA (8.3 to 18.6, 97.75% CI of median) for a single source. The Wilcoxon non-parametric test gave a highly significant p value of 0.0017 with median difference of 2.0 mA (0.7–4.9 mA, 97.75% CI of median).

The magnitude of the differences between the comfort thresholds varied across the participants (mean 19%) but was as high as 93% more current delivered for one participant (Pt #8). Only one participant (Pt #7) had a higher comfort threshold for the single source (6% lower for the multiple source). Fig. 3 shows a graphical representation of the results obtained in this test.

Two out of the 52 VAS measurements were not collected due to an operator error. These measurements were at 25% CT for Pt #2 and Pt #8. The values reported below are differences in VAS values expressed in percent. Positive values indicate the extent that multiple source stimulation is more comfortable than single source, whereas negative values indicate the single source is more comfortable. The 25% of comfort threshold (CT) measurements showed median difference of + 5% (0% to + 39%, 98.83% CI) and a Wilcoxon signed rank test compared the values to a hypothetical value of 0 with $p = .089$, the 50% of CT measurement showed a median difference of 16% (4% to 28%, 97.75% CI, $p = .0164$), the 75% CT measurement showed a median of 20% (3–69%, 97.75% CI, $p = .0083$) and maximum intensity showed a median of 32% difference (0–61%, 97.75% CI, $p = .0020$).

The differences in sensations between single and multiple sources became larger with higher intensities levels (50%, 75% and max.) in participants Pt#1, Pt#3, Pt#9 and Pt#13. However, in some participants the differences were consistent typically in Pt#2, Pt#4, Pt#5, Pt#6 as shown on Fig. 4. Participant #7 perceived the single source as more comfortable than multiple sources at lower currents, but reported the opposite at maximum CT, similarly Pt #8, at 25% CT.

4. Discussion

We hypothesised that if current is more evenly distributed across the stimulated area then the stimulation will be more comfortable. The results of the study show that participants were able to tolerate higher stimulation intensities with multiple sources of stimulation. We expected multiple sources to be increasingly more comfortable than single source stimulation as stimulation levels increased. Indeed this was the case globally and some participants clearly showed this phenomenon individually. However, some participants did not perceive much difference between the two stimulation types and two found multiple sources to be only more comfortable only at the highest levels. An explanation for this could be due to differing perceptions of sensation for submaximum stimuli. It could also be that the pitch of the electrodes was not small enough to optimise the control of current hogging. Another factor that could be influential is that there was no skin preparation, such as hydration of the skin, prior to the application of the dry electrode to the participants' forearms, and that varying degrees of skin hydration explain the wide variation in comfort thresholds. It is also possible that those participants with thicker hair, more sweat glands and naturally drier skin could have found multiple sources to be more comfortable, although this was not measured (Fig. 5).

Although the multiple-source constant current stimulation is more comfortable than a single constant-current source, there was no attempt in this study to stimulate at functional levels, so we do not know if it is comfortable enough at the currents required for functional use. The minimum tolerable current intensity (Pt #2) was 9 mA, through an approximate 6.25 cm^2 contact area.

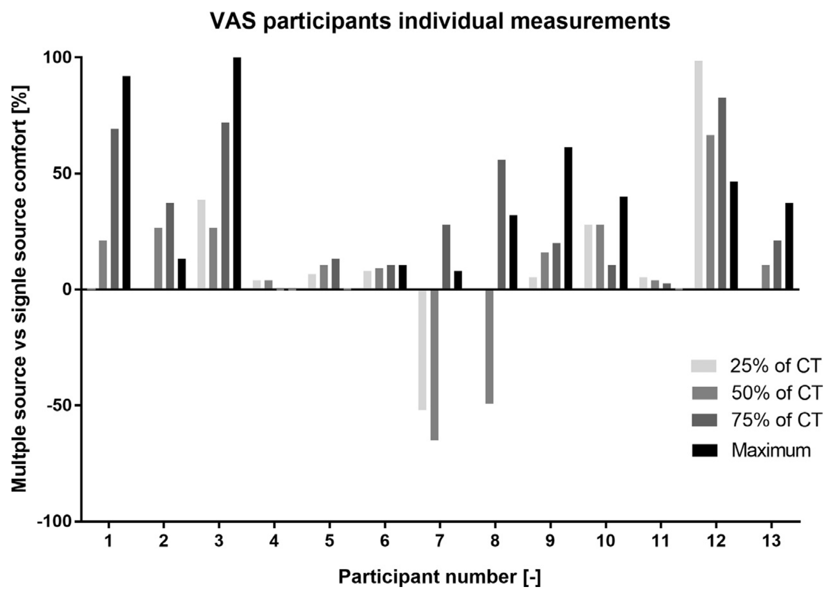

Fig. 4. The relative comfort of multiple sources compared to single sources at four stimulation levels for each participant. Positive values indicate that multiple sources were more comfortable than the single source. measurements at 25% CT for Pt #2 and Pt #8 were not collected.

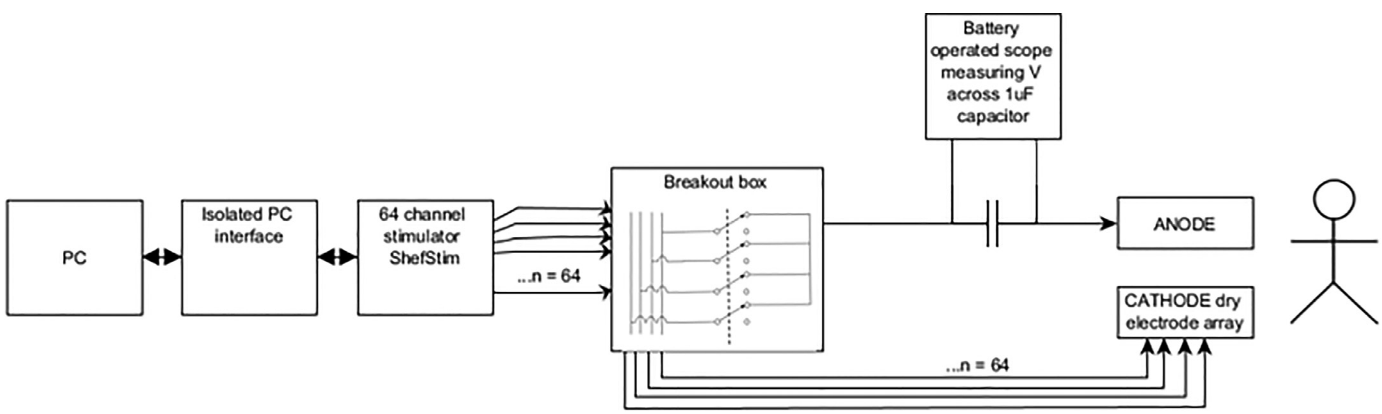

Fig. 5. System setup used in the experiment.

As electrodes in common clinical use are often 25 cm^2, a larger electrode area may allow a minimum of 36 mA tolerable current, which is sufficient for most foot-drop applications.

Although the *Shefstim* stimulator is very compact for its capabilities (it measures 142 mm x 50 mm x 14 mm and weighs 125 g including batteries), the necessity of having 64 individual constant-current sources makes it larger and more expensive than a well-designed single-channel stimulator. An alternative, lower-cost approach would be to use resistors to impose near constant-current for each channel. For a maximum current inequality of 10%, each resistance would have to be of the order of nine times greater than the maximum skin resistance presented by a single channel, so this would require an approximately 10 times higher stimulation drive voltage to compensate for the drop across the resistors, leading to a higher power consumption. Increasing the tolerance for current inequality would lower this wasted energy.

The experimental electrode array used in this study is too bulky and inconvenient to use clinically. A smaller, flexible design integrated into an elasticated garment to hold-it in place on the skin would be required for this to be a clinically usable approach.

Further work should compare comfort levels between stimulation through multiple sources and a single source using a hydrogel electrode. This will give us a clear picture of whether the hydrogel electrode could be replaced with an array of dry electrodes. Additional work should also investigate the tolerable level of current mismatch between channels.

Although stimulation with multiple sources was shown to be more comfortable, it is clear that there is a large difference in response between participants. Further work should seek to identify the reasons for these differences, e.g., it is possible that participants with thicker hair and drier skin found multiple current sources more comfortable than participants with less hair and more hydrated skin. Understanding these parameters may help to improve the technique further.

5. Conclusions

The purpose of this study was to see whether the sensation associated with the use of dry electrodes could be reduced. Stimulation through multiple sources showed improved comfort levels compared to single source stimulation in most subjects, suggesting that it may avoid current hogging.

Conflict of interest

None.

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Ethical approval

Ethical Approval obtained from Sheffield Hallam University by Dr Ben Heller in October 2013.

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