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1 **Title: Reducing the sensation of electrical stimulation with dry electrodes by**
2 **using an array of constant current sources**

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25 **Abstract**

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

42 **Keywords:** Dry electrodes; electrical stimulation; array stimulation

43 **1. Introduction**

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

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

67 Taking these issues into consideration, dry electrodes appear attractive for long-term
68 applications. However, dry electrodes may cause pain or discomfort when high
69 intensity electrical stimulation is applied. At low current intensities, stimulation evokes
70 a sensory reaction without muscle contraction; as the current intensity is increased in
71 order to evoke a muscle contraction, this sensory response increases and can cause
72 pain and skin irritation [9]. Hair follicles, sweat pores and other structures beneath the
73 skin form paths of low resistance for the current passing through the electrodes and
74 thereby cause uneven current densities (“current hogging”). It is thought that the local
75 high current densities due to current hogging lead to the greater pain associated with
76 surface stimulation [6]. We hypothesise that if current can be more evenly distributed
77 across the stimulated area (thus avoiding current hogging) then stimulation will be
78 more comfortable. One way to achieve this even distribution is to use a high
79 impedance hydrogel electrode [6]; However, Cooper et al. conducted a study on the
80 properties of high resistivity hydrogel samples and concluded that they became
81 contaminated with skin products and lost their desired properties if they were used for
82 several days [7], causing significant problems in long term applications. An alternative
83 approach to achieve equal distribution of the current within the electrode is to use
84 multiple constant current sources, each connected to one of an array of small, adjacent
85 mini electrodes.

86 **2. Material and methods**

87 Participants

88 Ethical approval for the study was obtained from the Sheffield Hallam University
89 Research Ethics Committee and participants were recruited from students and staff
90 within the University. After obtaining informed consent, thirteen adults, (11 male and

91 2 female) were recruited to the study. Participants were excluded if they had any prior
92 adverse responses to any form of electrical stimulation or had any skin conditions such
93 as eczema.

94 Equipment and Materials

95 A 64 channel, constant current stimulator, Shefstim, was used to provide stimulation
96 [10]. The parameters of stimulation i.e., pulse width, amplitude and frequency were
97 controlled by custom software and PC. A commercially available hydrogel electrode
98 (StimTrove 5x5cm, Axelgaard Manufacturing Ltd., USA) was used as the anode. The
99 cathode was a dry electrode array of 64 electrodes (in an 8 x 8 matrix), constructed
100 from stainless steel paper pins. The heads of the pins were approximately 1mm in
101 diameter and were used as the electrodes. The pins were placed through a piece of
102 stripboard with spacing of 2.54 mm and a 5 mm thick foam backing. The pins were
103 then soldered onto another piece of stripboard via which the electrodes were
104 connected to the outputs of the stimulator. The whole electrode formed a square of
105 30 mm x 30 mm.

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

113 Experiment design

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

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

125 *b) Difference in sensation:* For each participant, stimulation was applied at 25%, 50%,
126 75% and 100% of the largest comfort threshold current identified above, starting at the
127 lowest intensity. Stimulation was randomly switched between single source (type A)
128 and multiple sources (type B), whilst keeping intensity constant. The participant was
129 asked to mark the difference in perceived sensation on the visual analogue scale
130 provided (Figure 2). Switching between A and B was repeated until the participant was
131 confident about his decision.

132 Outcome measures

133 *a) Identification of comfort threshold (CT):* After the stimulation intensity was set to the
134 appropriate level for the measurement being made, current stimulation intensity was
135 recorded (measured by ShefStim). At the same time the delivered charge was
136 measured as the voltage (V_C) across a $1\ \mu\text{F}$ capacitor (C) connected in series with the

137 participant in the anode path using a battery operated oscilloscope (Tektronix THS
138 720). The delivered charge was calculated as $Q [\mu\text{C}] = C [\mu\text{F}] * V_C [\text{V}]$ and applied

139 current for in one pulse as $I [\text{mA}] = \frac{Q [\mu\text{C}]}{t_{200} [\mu\text{s}]} * 10^3$

140 *b) Difference in sensation:* The perceived sensation was measured using the Visual
141 Analogue Scale (VAS). The VAS values are expressed as percentage measured on
142 10 cm line between 'no difference' and 'much more uncomfortable' for either A (single
143 source) or B (multiple sources).

144 Analysis

145 *a) Identification of comfort threshold (CT):* The Wilcoxon matched-pair signed rank test
146 was used for the current threshold measurements. All values are expressed as mean
147 values with confidence intervals unless indicated differently on the graphs.

148 *b) Difference in sensation:* The Wilcoxon signed rank test was also used to compare
149 the differences in sensation to a hypothetical value of 0% i.e. no difference in
150 sensation.

151 **3. Results**

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

158 The magnitude of the differences between the comfort thresholds varied across the
159 participants (mean 19%) but was as high as 93% more current delivered for one

160 participant (Pt #8). Only one participant (Pt #7) had a higher comfort threshold for the
161 single source (6% lower for the multiple source). Figure 3 shows a graphical
162 representation of the results obtained in this test.

163 Two out of the 52 VAS measurements were not collected due to an operator error.
164 These measurements were at 25% CT for Pt #2 and Pt #8. The values reported below
165 are differences in VAS values expressed in percent. Positive values indicate the extent
166 that multiple source stimulation is more comfortable than single source, whereas
167 negative values indicate the single source is more comfortable. The 25% of comfort
168 threshold (CT) measurements showed median difference of +5% (0% to +39%,
169 98.83% CI) and a Wilcoxon signed rank test compared the values to a hypothetical
170 value of 0 with $p = 0.089$, the 50% of CT measurement showed a median difference
171 of 16% (4% to 28%, 97.75% CI, $p = 0.0164$), the 75% CT measurement showed a
172 median of 20% (3% to 69%, 97.75% CI, $p = 0.0083$) and maximum intensity showed
173 a median of 32% difference (0% to 61%, 97.75% CI, $p = 0.0020$).

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

180 **4. Discussion**

181 We hypothesised that if current is more evenly distributed across the stimulated area
182 then the stimulation will be more comfortable. The results of the study show that
183 participants were able to tolerate higher stimulation intensities with multiple sources of

184 stimulation. We expected multiple sources to be increasingly more comfortable than
185 single source stimulation as stimulation levels increased. Indeed this was the case
186 globally and some participants clearly showed this phenomena individually. However,
187 some participants did not perceive much difference between the two stimulation types
188 and two found multiple sources to be only more comfortable only at the highest levels.
189 An explanation for this could be due to differing perceptions of sensation for sub-
190 maximum stimuli. It could also be that the pitch of the electrodes was not small enough
191 to optimise the control of current hogging. Another factor that could be influential is
192 that there was no skin preparation, such as hydration of the skin, prior to the
193 application of the dry electrode to the participants' forearms, and that varying degrees
194 of skin hydration explain the wide variation in comfort thresholds. It is also possible
195 that those participants with thicker hair, more sweat glands and naturally drier skin
196 could have found multiple sources to be more comfortable, although this was not
197 measured.

198

199 Although the multiple-source constant current stimulation is more comfortable than a
200 single constant-current source, there was no attempt in this study to stimulate at
201 functional levels, so we do not know if it is comfortable enough at the currents required
202 for functional use. The minimum tolerable current intensity (Pt #2) was 9 mA, through
203 an approximate 6.25 cm² contact area. As electrodes in common clinical use are often
204 25 cm², a larger electrode area may allow a minimum of 36 mA tolerable current, which
205 is sufficient for most foot-drop applications.

206 Although the *Shefstim* stimulator is very compact for its capabilities (it measures
207 142mm x 50mm x 14mm and weighs 125 g including batteries), the necessity of having
208 64 individual constant-current sources makes it larger and more expensive than a well-

209 designed single-channel stimulator. An alternative, lower-cost approach would be to
210 use resistors to impose near constant-current for each channel. For a maximum
211 current inequality of 10%, each resistance would have to be of the order of nine times
212 greater than the maximum skin resistance presented by a single channel, so this would
213 require an approximately 10 times higher stimulation drive voltage to compensate for
214 the drop across the resistors, leading to a higher power consumption. Increasing the
215 tolerance for current inequality would lower this wasted energy.

216

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

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

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

231 **5. Conclusions**

232

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

237 **Conflict of interest:** None

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239 Sheffield, UK

240 **Ethical approval:** Ethical Approval obtained from Sheffield Hallam University by Dr
241 Ben Heller in October 2013

242

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