Psychometric Evaluation of Multi-Point Bone-Conducted Tactile Stimulation on the Three Bony Landmarks of the Elbow

Raphael M. Mayer [1,*], Alireza Mohammadi [1], Ying Tan [1] Gursel Alici [3,4], Peter Choong [2,4] and Denny Oetomo [1,4]

***Abstract*— Sensory feedback is highly desirable in upper limb prostheses as well as in human robot interaction and other human machine interfaces. Bone conduction as sensory feedback interface is a recently studied approach showing promising properties. A combination of different feedback information is often necessary for prosthetic grasping, thus multiple feedback channels are required for effective sensory feedback. The use of multiple bone conduction stimulation sites simultaneously has not yet been studied. For example, three bony landmarks are present at the elbow, however it is not known how much human subjects are able to discern from the simultaneous vibrotactile stimulation of these bony landmarks. In this paper, the psychometric evaluation of multiple stimulation sites on the physiologically given bony landmarks on the elbow is investigated. The proposed approach is evaluated on a human-subject experiments with six able-bodied subjects and one subject with transradial amputation. Vibrotactile transducers are placed on the bony landmarks of the elbow to determine the identification rate of each stimulation point separately as well as the identification rate of the number of active stimulation points for different frequencies. The outcomes show high identification rates for a frequency range from 100 to 750 Hz whilst performance deteriorates to at chance level at higher frequencies. A decreasing performance in identifying the number of active stimulation sites for an increasing number of simultaneous active transducers was observed. The obtained good performance in location identification suggests that information can be encoded via the location of the stimulation.**

I. INTRODUCTION

With the long term goal of providing prosthesis users with sensory feedback in mind ([1], [2]), several sensory feedback interfaces have been studied and developed in the past decade ([3], [4], [5]). Recent studies have utilised vibrotactile feedback on the bone, called bone conduction ([6], [7], [8]), as sensory feedback interface. In [6], a larger bandwidth using vibrotactile feedback on the bone compared to the skin was demonstrated for bone-anchored prosthesis due to the multi-sensory perception involving auditory and tactile pathways. Having a larger bandwidth allows to feedback sensory information obtained from a prosthetic hand equipped with a large number of sensors ([9], [10]), necessary for effective prosthetic grasping ([11], [12], [13]). Comparable performance in a non-invasive manner has been achieved via bone conduction by placing vibrotactile transducers onto the bony landmarks of the elbow in [7]. In contrast to vibrotactile feedback on skin, no static force dependency was observed in [8]. Vibrotactile static force dependency refers to how well human can feel a vibrotactile sensation on the skin which is a function of how firm the transducer is pressed against the skin. Being independent from the static force makes an integration of such transducers into a prosthetic socket feasible, as the volume fluctuations present in residual limbs ([14], [15]) no longer affects the perception of the delivered stimulation.

For effective prosthetic grasping, a combination of different types of feedback information are required simultaneously ([11], [12], [13]), justifying the need for multiple feedback channels to the user. In bone conduction however, the number of feedback channels is restricted by the physiologically available locations of bony landmarks, thereby limiting the overall bandwidth for feedback to the human user. For example, three bony landmarks are accessible on the elbow. The literature on bone conduction so far has focused on optimizing the interface in the temporal domain by investigating into the maximum possible range in amplitude and frequency domain (Clemente2017, Mayer2019). Optimizing the spatial domain, by investigating the effect of placing transducers over multiple sites, has not yet been exploited in bone conduction. This will provide further potential to increase the number of feedback channels and therefore the overall bandwidth of such an interface.

Investigations in some other sensory feedback interfaces have determined the spatial resolution by the two point discrimination (2PD) introduced in [16]. 2PD describes the minimum distance between two stimulation points necessary for the two stimuli to be perceived as separate sensations [16]. A minimum distance of 40mm for mechanotactile [16] and vibrotactile feedback [17] (on the forearm) and 9mm for electrotactile feedback [18] has been reported. Different methods have been used ranging from simple Yes/No procedures ([18], [16], [19]) to more advanced two-interval forced choice (2IFC) [20] in order to determine the minimum 2PD. In the case of using bone conduction as sensory feedback, the 2PD is inherently determined by the physiology which are bony landmarks of the elbow. Hence

[1] Human Robotics Laboratory, Department of Mechanical Engineering, The University of Melbourne, Australia
[2] Department of Surgery, St Vincent's Hospital, The University of Melbourne, Australia
[3] School of Mechanical, Materials, Mechatronic and Biomedical Engineering, University of Wollongong, Australia
[4] ARC Centre of Excellence for Electromaterials Science
*r.mayer@student.unimelb.edu.au

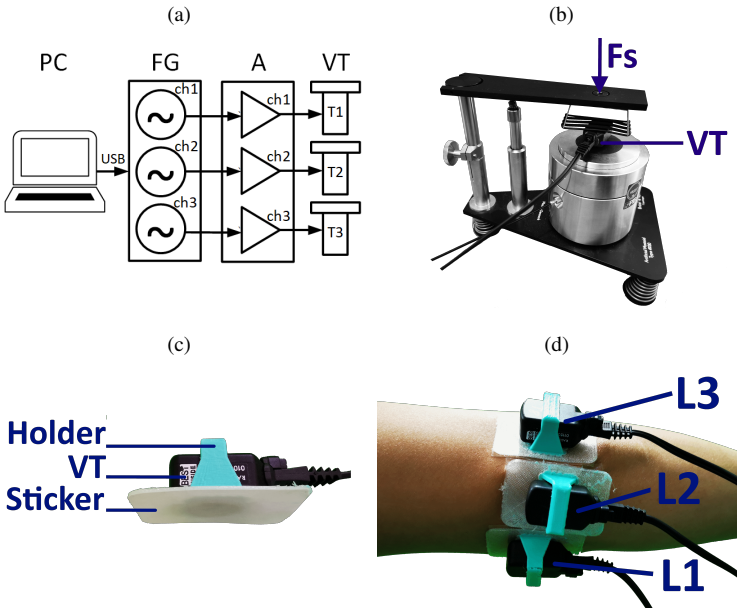

Fig. 1: Experimental setup of (a) block scheme for controlling the stimulation parameters of the three vibrotactile transducers (VT) via a personal computer (PC) connected via USB to a frequency generator (FG) and an amplifier (A): (VT) B81 transducers from RadioEar Corporation; (A) 15W Public Address amplifier Type A4017 (Redback Inc., Australia) having a suitable $4-16\Omega$ output to drive the 8Ω B81 transducers and a harmonic distortion of $<3\%$ at 1kHz; (FG) National Instruments NI USB-6343 and (PC) Windows Surface Book 2 (Intel Core i7-8, 16GB RAM, Windows 10$^{\text{TM}}$); (b) the VT are mounted onto the Artificial Mastoid Type 4930 (Brüel & Kjære, Denmark) with a a static force $F_s = 5.4N$ for calibration; (c) the transducers are fixed using a 3D printed holder (PLA/TPU) and medical grade double sided sticker Type 1510 (3M$^{\text{TM}}$) to the (d) bony landmarks (figure shows right arm) of the dominant hand: (L1) epicondylis medialis, (L2) ulnar olecranon and (L3) epicondylus lateralis.

a different approach is required, which does not seek to know the minimum distance, but how much differentiation is possible between closely located bony landmarks around the elbow.

In this paper, human-subject experiments determine two metrices in order to investigate the capability of identifying between the given bony landmarks on the elbow.

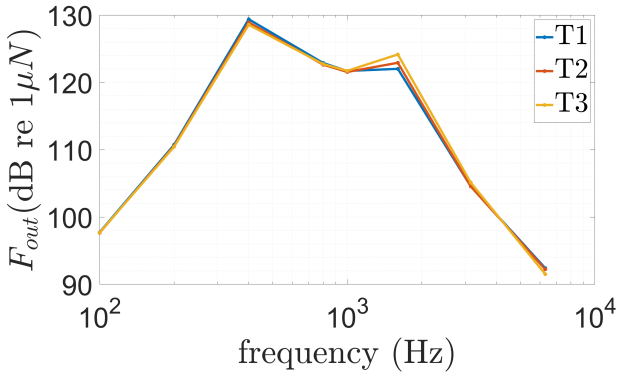

Fig. 2: Calibration of the three used transducers T1, T2 and T3 for $f \in [100, 200, 400, 750, 1500, 3000, 6000]$ Hz and $a = 0.5$ V

The transducers are placed on the bony landmarks, namely the ulnar olecranon, the lateral and medial epicondyl. First metrics describes the capability to identify the location of the stimulation applied one at a time to the bony landmarks, while the second metrics characterises the capability of identifying how many stimulation points are active simultaneously. The investigation is conducted for a frequency range similar as used in [7] at a fixed amplitude well above the sensation threshold.

II. METHODS

The experiment was conducted with six able-bodied subjects (5 male, 1 female; age 27.7 $\pm$ 4.8 years) and one subject with transradial amputation (male; age 22 years). All subjects read the plain language statement and signed the consent form approved by the Ethics Committee of the University of Melbourne (Ethics Id 1852875.1).

A. Setup

The setup is shown in Fig. 1a showing the VT being driven by the (FG) and (A) and controlled by the (PC) where a custom MATLAB® GUI was used to guide the user through the experiment as well as to control the stimulation parameters. The whole setup was calibrated to produce equal outputs of 121.7dB re 1μN on each (VT) at a frequency of 1kHz . The calibration setup is shown in Fig. 1b and the

TABLE I: The observed SPLIR and NPIR for all frequencies for the stimulation locations L1, L2 and L3 and the number of N =1, 2 or 3 simultaneous stimulation sites. Results are shown as mean and standard deviation for the able-bodied subjects and separately for the subject with transradial amputation. For the SPLIR the overall mean and standard deviation over the locations for each frequency is given.

		frequency (Hz)						
		100	*200*	*400*	*750*	*1500*	*3000*	*6000*
SPLIR (%)								
able-bodied	L1	96.67 ± 8.16	100.00 ± 0.00	100.00 ± 0.00	100.00 ± 0.00	70.00 ± 41.47	36.67 ± 23.38	46.67 ± 32.66
	L2	96.67 ± 8.16	86.67 ± 20.66	86.67 ± 24.22	90.00 ± 16.73	76.67 ± 23.38	40.00 ± 37.95	66.67 ± 27.33
	L3	90.00 ± 10.95	96.67 ± 8.16	100.00 ± 0.00	100.00 ± 0.00	73.33 ± 43.20	36.67 ± 29.44	30.00 ± 32.86
	$\overline{x} \pm \delta$	94.44 ± 3.85	94.44 ± 6.94	95.56 ± 7.70	96.67 ± 5.77	73.33 ± 3.33	37.78 ± 1.92	47.78 ± 18.36
amputee	L1	100.00	100.00	100.00	100.00	100.00	40.00	40.00
	L2	100.00	100.00	100.00	100.00	20.00	0.00	40.00
	L3	100.00	100.00	100.00	100.00	100.00	60.00	80.00
	$\overline{x} \pm \delta$	100.00 ± 0.00	100.00 ± 0.00	100.00 ± 0.00	100.00 ± 0.00	73.33 ± 46.19	33.33 ± 30.55	53.33 ± 23.09
NPIR (%)								
able-bodied	$N = 1$	67.78 ± 24.37	62.22 ± 25.88	77.78 ± 16.15	83.33 ± 11.74	73.33 ± 23.48	67.78 ± 33.31	66.67 ± 33.73
	$N = 2$	44.44 ± 27.86	55.56 ± 26.22	65.56 ± 14.86	51.11 ± 10.89	41.11 ± 18.58	33.33 ± 34.77	31.11 ± 36.19
	$N = 3$	13.33 ± 16.33	73.33 ± 32.66	36.67 ± 29.44	36.67 ± 36.70	3.33 ± 8.16	0.00 ± 0.00	3.33 ± 8.16
amputee	$N = 1$	73.33	80.00	80.00	93.33	86.67	66.67	73.33
	$N = 2$	33.33	40.00	53.33	53.33	33.33	46.67	46.67
	$N = 3$	0.00	20.00	20.00	80.00	0.00	0.00	0.00

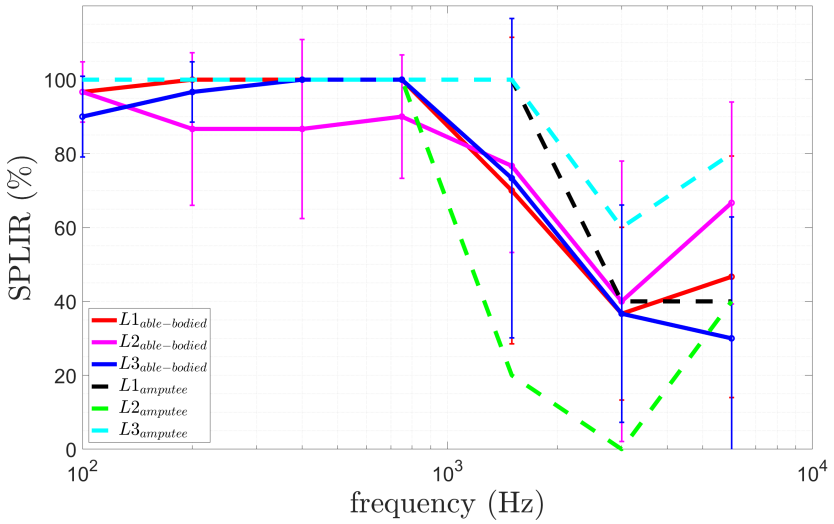

Fig. 3: shows the mean and standard deviation of the SPLIR for each location 1, 2 and 3 for the 6 able-bodied subjects. The results of the subject with transradial amputation are plotted seperatly with dashed lines.

obtained calibration results in Fig. 2. The (VT) are mounted onto the bony landmarks of the dominant hand of the healthy subjects and the residual limb of the subject with transradial amputation. Fig. 1d shows the placement of the (VT) using medical grade double sided tape and a 3D printed holder as shown in Fig. 1c.

B. Protocol

The experiment is divided into two parts:

1) Single-Point Location Identification: The subject is asked to report on the location of the stimulation. Therefore, the subjects are presented with the stimulation $x(t) = a\sin(2\pi ft)$ on the three different locations without the prior knowledge of where the stimulation is presented. The order of stimulation location and the chosen parameters is randomized where $f \in [100, 200, 400, 750, 1500, 3000, 6000]$ Hz, $a = 0.5$ V and each repeated 5 times in total. Stimulation time is 1sec. At the start of the experiment the subjects are allowed to familiarise themselves with the stimulations and explore the association of the three stimulation sites by voluntary inducing stimulations on each location.

2) N-Point Identification: The subject is asked whether one, two or three stimulation sites are active simultaneously. Therefore, the subjects are presented with stimulations applied on one, two and three sites for each frequency $f \in$

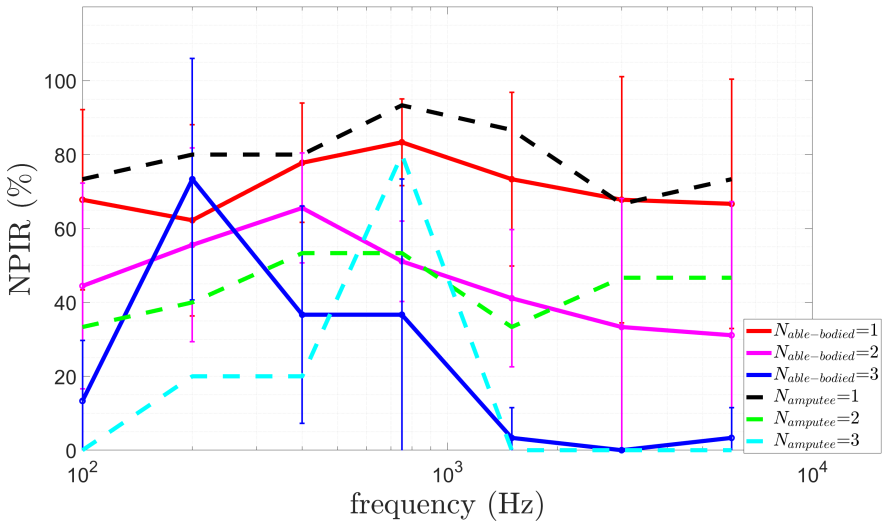

Fig. 4: N-Point Identification Rate (NPIR) for N =1, 2 or 3 simultaneous stimulation sites for the six able-bodied subjects. The results of the subject with transradial amputation is plotted separately with dashed lines.

[100, 200, 400, 750, 1500, 3000, 6000] Hz and $a = 0.5$ V each repeated 5 times for each combination, see Table II. The stimulations are presented in a randomized order, meaning randomly one, two or three sites are stimulated, and the subjects are asked to report whether one, two or three stimulation sites are perceived.

TABLE II: Combination of locations L1, L2 and L3 for one $N = 1$, two $N = 2$ or three $N = 3$ active stimulation sites for the N-Point Identification.

	N=1			**N=2**			**N=3**
L1	x			x		x	x
L2		x		x	x		x
L3			x		x	x	x

C. Performance Measure

Two performance measures have been used for the two different experiments:

1) Single-Point Location Identification Rate (SPLIR): is the success rate with which the subject correctly identifies the correct stimulation location.

2) N-Point Identification Rate (NPIR): is the success rate with which the subject correctly identifies if one, two or three stimulation points are active.

A non-parametric statistic analysis, specifically a Friedman test was applied [21]. This was followed up by a post-hoc analysis via Wilcoxon signed rank test [22]. An analysis of variance (ANOVA) was not suitable due to non-normal distributed data (Shapiro-Wilk test). The obtained p values are given in the tables for the Friedman test as well as the applied post-hoc test.

III. Results and Discussion

In the following sections, firstly, the performance of identifying the location of the stimulation via bone conduction on the bony landmarks of the elbow is shown. Secondly, the performance of distinguishing the number of stimulation sites, namely one, two or three sites simultaneously, is reported. The plots indicate the results of the able-bodied subject group and the results obtained with the subject with transradial amputation separately. The statistical evaluation is based on the able-bodied subject group.

A. Single-Point Location Identification

Fig. 3 and Table I show the results obtained for the Single-Point Location Detection (SPLIR) test. The mean SPLIR for all locations is $94.44 \pm 3.85\%$ at 100Hz to $96.67 \pm 5.77\%$ at 750Hz, whilst dropping for higher frequencies to $73.33 \pm 3.33\%$ at 1500Hz to $47.78 \pm 18.36\%$ at 6000Hz. The results obtained with the subject with transradial amputation outperforming the healthy subjects for frequencies below 750Hz and obtaining similar results above for L1 and L3 localisation. LPIR of L2 is lower and in accordance with the subject with transradial amputation's report after the experiment of feeling less sensible on L2 which is the ulnar olecranon.

Friedman test results for all subjects (Table III) show that there is no statistical significant difference between the obtained data from location L1, L2 and L3, suggesting the data is compatible with all groups having the same distribution. Hence no post-hoc test was performed. High identification rates are observed for frequencies up to 750Hz dropping to at chance level above that frequency. As shown in [7] for non-invasive bone conduction and in [6], tactile perception is dominant for lower frequencies and auditory for higher frequencies. In [7], dominant auditory perception

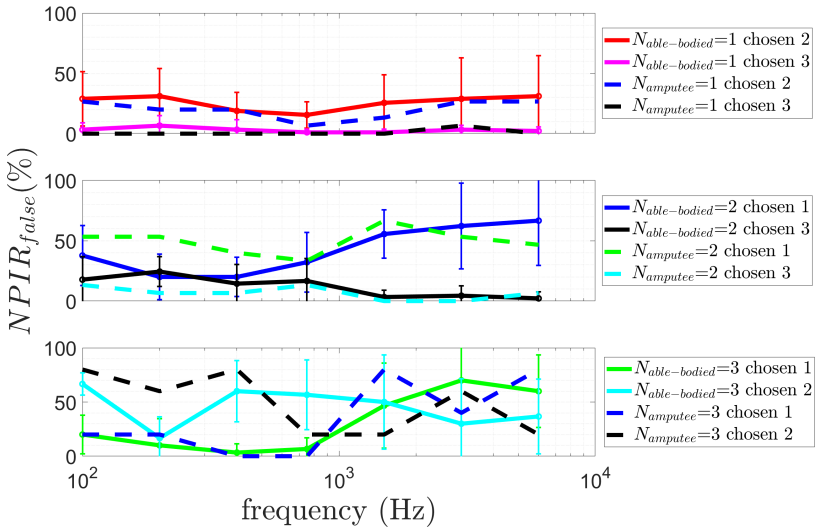

Fig. 5: False identification rate of $NPIR_{false}$ for one, two and three simultaneous stimulation sites. The results of the subject with transradial amputation is plotted separately with dashed lines.

TABLE III: Single-Point Location Identification Rate: The p values of the Friedman test for able-bodied subjects for all frequencies comparing the stimulation locations L1, L2 and L3. Significance level is $p < 0.05$.

frequency (Hz)						
100	*200*	*400*	*750*	*1500*	*3000*	*6000*
0.264	0.368	0.135	0.135	0.779	0.953	0.165

TABLE IV: N-Point Identification Rate: The p values of the Friedman test for all frequencies comparing the groups $N = 1$, $N = 2$ and $N = 3$ for able-bodied subjects. Significance level is $p < 0.05$.

frequency (Hz)						
100	*200*	*400*	*750*	*1500*	*3000*	*6000*
0.030	0.664	0.032	0.042	0.002	0.008	0.008

for vibrotactile bone conduction on the skin is observed above 750Hz. The observed decrease of SPLIR above 750Hz and the previous findings suggest that location identification is superior for tactile perception and converges towards at chance probability (33.3%) for auditory perception. The better performance of the subject with transradial amputation compared to the group of able-bodied subjects coincides with the smaller perception threshold reported in [7].

B. N-Point Identification

Fig. 4 and Table I show the obtained results for the multiple stimulation sites identification test. Friedman test results, as shown in Table IV, indicates a statistical significant performance for [100 400 750 1500 3000 6000]Hz for the identification of the number of stimulation sites. No statistical difference is observed at 200Hz suggesting the data is compatible with all groups having the same distribution.

A post-hoc test was performed and the results are shown in Table V:

N=1 vs. 2: A statistical significant lower performance of detecting two stimulation sites versus one is obtained for $f \in [750, 1500, 3000]$ Hz while none was obtained for $f \in [100, 400, 6000]$ Hz suggesting the data is compatible with all groups having the same distribution.

TABLE V: N-Point Identification Rate: The p values of the post-hoc Wilcoxon signed rank test for all frequencies, for able-bodied subjects, except 200Hz, as it shows no statistical significant difference in the Friedman test in Table III. Significance level is $p < 0.05$.

	frequency (Hz)						
	100	*200*	*400*	*750*	*1500*	*3000*	*6000*
$N = 1$ vs. 2	0.140	-	0.416	0.026	0.017	0.026	0.246
$N = 1$ vs. 3	0.042	-	0.027	0.058	0.018	0.027	0.027
$N = 2$ vs. 3	0.058	-	0.092	0.246	0.017	0.027	0.041

N=1 vs. 3: A statistical significant lower performance of detecting three stimulation sites versus one is obtained for all frequencies except for 750Hz.

N=2 vs. 3: A statistical significant lower performance of detecting three stimulation sites versus two is obtained for all frequencies $f > 750$ Hz, none could be found for $f \leq 750$ Hz suggesting the data is compatible with all groups having the same distribution.

The highest identification rate is found for a single stimulation site, with a decreasing performance for two sites and three sites. Similar performance is achieved by the subject with transradial amputation though for three stimulation sites the best performance is achieved at 750Hz

whilst for able-bodied subjects at 200Hz.

To further investigate the cause of the low NPIR for $N = 2$ and $N = 3$, the false identification rate NPIR_{false} for each number of stimulation site and the false choices are plotted in Fig. 5. The low performance of detecting three stimulation sites, see Fig. 4, is due to false identification of one or two sites. For higher frequencies, the subjects chose one stimulation site when three are active. This is in accordance with the increasing perception threshold reported in [7] and therefore lower sensibility. Qualitatively the subjects reported to identify the number of stimulation sits rather by associating it with the intensity perceived e.g.: three sites feel more intense then two, rather than perceiving the location of each site and reasoning the number of stimulation sites. Therefore, perceiving high frequencies with less intensity leads to the assumption of one or two active stimulation sites. A similar trend can be observed for two active stimulation sites, where the false identification rate for choosing only one increases with frequency while choosing three converges towards zero.

IV. CONCLUSIONS

This study investigates the use of multiple bone conduction stimulation sites simultaneously in a in human-subject experiment using vibrotactile transducers on the bony landmarks of the elbow.

The observed single-point location identification rate of each stimulation location shows high identification rates for a frequency range from 100 to 750Hz whilst performance drops to at chance level for higher frequencies for all three locations. Low performance is observed for identifying the number of active stimulation sites, giving the highest identification rate for single stimulation site of $71.27 \pm 7.30\%$ dropping to $46.03 \pm 12.30\%$ for two sites and $23.81 \pm 26.76\%$ for three sites.

A good performance in location identification allows to encode sensory information via the location of the stimulation. The influence of different stimulation frequencies onto the ability to identify multiple stimulation sites has yet to be investigated as this study uses identical frequencies for each location.

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