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The Variability of Psychophysical Parameters following Surface and Subdermal Stimulation: A Multiday Study in Amputees

Jian Dong, Bo Geng, Imran Khan Niazi, Imran Amjad, Strahinja Dosen, IEEE Member, Winnie Jensen and Ernest Nlandu Kamavuako, IEEE Member

Abstract—Electrotactile stimulation has been suggested as a modality for providing sensory feedback in upper limb prostheses. This study investigates the multiday variability of subdermal and surface stimulation. Electrical stimulation was delivered using either surface or fine wire electrodes placed right under the skin in eight amputees for seven consecutive days. The variability of psychophysical measurements, including detection threshold (DT), pain threshold (PT), dynamic range (DR), just noticeable difference (JND), Weber fraction (WF) and quality of evoked sensations, was evaluated using the coefficient of variation (CoV). In addition, the systematic change in the mean of the parameters across days was assessed in both stimulation modalities. In the case of DT, PT, DR, and perceived intensity at 100 Hz, the CoV of surface stimulation was significantly smaller than that of subdermal stimulation. Only PT showed a significant systematic change in the mean value across days for both modalities. The outcome of this study has implications for the choice of modality in delivering sensory feedback, though the significance of the quantified variability needs to be evaluated using usability tests with user feedback.

Index Terms—Prostheses, surface electrotactile stimulation, subdermal electrical stimulation, sensory feedback, sensation variability.

I. INTRODUCTION

Around 1.6 million people were living with limb amputation in the year 2005, and it has been estimated that 3.6 million people will be living with amputation in the United States of America by the year 2050 [1]. Currently, some of the functionality of a lost arm can be replaced by a prosthesis. A prosthesis is defined as an artificial device that replaces a biological limb both functionally and morphologically. The human hand has a highly complex structure that comprises many degrees of freedom; the hand has remarkable capabilities in performing dexterous and delicate movements. This is possible due to the sophisticated closed-loop control integrating

efferent motor output and afferent sensory feedback. Consequently, mimicking the structure and function of the human hand using an artificial system is a very challenging task.

Even though advanced prosthetic hands that can partly replicate the motor dexterity of a natural human hand are available (e.g. DEKA Hand and iLimb), a continuing challenge is to restore the sensory function of the hand. For upper limb prosthetic users, the absence of sensory feedback impedes the efficient use of their prostheses, which can lead to user frustration and abandonment of the device [2]. The sensory awareness, which is available with body-powered prostheses due to a direct connection between the gripper and the user's shoulder, does not exist in myo-electrically controlled systems [3]. In this case, the users must rely primarily on the direct observation of the device (visual feedback) [4] and secondarily, on subtle clues such as the sounds of the motor and transmission (intrinsic feedback) [5]. Therefore, restoring somatosensory feedback to the prosthesis user can decrease visual attention and improve control by providing explicit information about the state of the device.

The somatosensory feedback can be provided using different stimulation methods to elicit tactile sensations [6]. Current non-invasive solutions are mostly based on delivering electrocutaneous stimulation [7], or vibration [8] to the skin on the residual limb. The residual limb can also be stimulated mechanically (e.g. pushing the limb by using a force applicator, squeezing the limb by a cuff, or by stretching the skin) [9]. The feedback can be restored through invasive methods as well, i.e. by electrically stimulating peripheral nerves [10]. In this case, the aim of the stimulation is to activate the same neural structures that have been used before the amputation, leading to somatotopic feedback. The same result may be achieved using non-invasive methods by delivering the stimulus to the

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phantom map if it exists on the residual limb [11].

In general, the feedback information is transmitted by relating a measured prosthesis variable to selected stimulation parameters. For example, the magnitude of the grasping force can be communicated using the magnitude or frequency of stimulation. Therefore, the user needs to learn to relate the stimulation parameters to the prosthesis state, and this requires training. The information about grasping force, slippage [12], hand aperture [13], finger flexion [14], and elbow angle has been previously encoded and transmitted through sensory feedback [7], [15].

The electrocutaneous stimulation is an attractive modality to restore feedback and it has been investigated intensively in the past [16]. The stimulation can be delivered using simple and compact circuits and electrodes [17]. Therefore, the electrotactile interface is convenient for providing multichannel feedback and integration into a prosthetic socket. Furthermore, since there are no moving mechanical parts, the stimulation parameters can be changed fast and independently. This allows eliciting rich and dynamic tactile sensations. Studies with able-bodied subjects and amputees have shown that electrotactile feedback can improve prosthesis control [18], [19].

Nevertheless, a disadvantage of electrocutaneous stimulation delivered through surface electrodes is that it can produce uncomfortable and even painful sensations. High voltage is needed for the stimulation to overcome the skin impedance, which can also vary depending on the conditions of the electrode-skin interface. To increase the dynamic range, between the sensation and pain threshold, larger electrodes are required. Importantly, these drawbacks may be overcome by placing the electrodes subdermally, as previously demonstrated [20], [21]. Subdermal stimulation can lead to substantially more compact feedback interfaces, since it is based on point electrodes (wire tip), and it can substantially decrease the required voltage and current consumption because skin impedance is bypassed. As a step in this direction, psychophysical measurements were conducted previously [21] to evaluate and compare the properties of the surface and subdermal stimulation.

Ideally, a feedback interface needs to produce stable and repeatable sensations. This is even more important when using subdermal stimulation since the electrodes are meant to stay within the tissue for its lifetime, contrary to surface stimulation where they will be reapplied with each donning and doffing of the prosthesis. The short-term stability of subdermal stimulation has been tested in our previous study for up to eight hours [22]. However, long-term stability plays an important role in achieving the long-lasting functional sensory feedback and verifying its usability in clinical applications for amputees [23], [24]. In general, the multiday variability of the commonly used psychophysical measurements has received less attention in the literature.

Therefore, the aim of this study was to investigate the variability of psychophysical measurements over the course of seven days when using subdermal versus surface stimulation in upper-limb amputees. The psychophysical measurements that were investigated systematically in the present study were

detection threshold (DT), pain threshold (PT), dynamic range (DR), just noticeable difference (JND), Weber fraction (WF) and the subjective quality of evoked sensations.

II. METHODS

A. Subjects

Nine male upper-limb amputees (33.6 ± 12.9 years old, 13.7 ± 11.1 years after amputation) were recruited from Railway General Hospital, Rawalpindi, Pakistan (Table I). Subjects provided written informed consent and the study adhered to the Helsinki Declaration. The ethical committee of Riphah International University (N-ref# Riphah/RCRS/REC/000121/20012016) approved the study protocol. All subjects had undergone traumatic amputation of their dominant hand/arm. None of the subjects abused cannabis, opioids or other drugs. They had no record of previous neurological, musculoskeletal or mental illnesses, lack of ability to cooperate, fear of injections; and they were all

TABLE I
DEMOGRAPHIC DATA OF THE SUBJECTS

Subject	Age	Years after amputation	Amputation level	Cause of amputation
1	59	31	Transradial	Trauma
2	29	15	Transradial	Trauma
3	19	14	Wrist disarticulation	Trauma
4	30	3	Partial hand	Trauma
5	52	2	Partial hand	Trauma
6	36	31	Wrist disarticulation	Trauma
7	32	7	Wrist disarticulation	Trauma
8	19	14	Partial hand	Trauma
9	26	14	Partial hand	Trauma

All subjects were undergoing dominant side amputation.

phantom pain-free. One subject was excluded from the study because a pain threshold could not be reached even with a current amplitude of 40 mA (the highest possible current to deliver) and at that high stimulation level, strong muscle twitches were evoked.

B. Experiment procedure

A single session was performed each day for seven consecutive days. The psychophysical measurements were collected in the order of DT, PT, JND and sensation evaluation in each session. All seven sessions were scheduled at the same time of the day. The subdermal electrode was disconnected after each session and it remained under the skin for the duration of the experiment. The insertion site and the wire were wrapped with a medical bandage between different sessions, to minimize displacement of the electrode during daily activities. The surface electrodes were disposed following each session. This protocol was selected to mimic the real-life application in which the surface electrodes are reapplied with each donning and doffing, while the subdermal electrodes will be placed permanently. The common ground electrode was also removed at the end of the session. The same common ground electrode was reused for three or four sessions depending on the stickiness and conductivity.

C. Stimulation

A programmable stimulator (ISIS Neurostimulator, Inomed, Germany) was used to generate biphasic, rectangular, symmetric pulses with a pulse width of 200 μ s. The stimulator was controlled by a custom-made program implemented in LabVIEW version 2015 running on a laptop.

Commercially available surface electrodes (Ambu Neuroline 700, 20 mm \times 15 mm) and subdermal fine wire electrodes were used to deliver the electrical stimulation. The subdermal wire electrodes were made of Teflon-coated stainless steel (A-M Systems, Carlsborg WA, diameter 50 μ m), with 5-mm tip exposed [21]. Each subject was checked to see if the stump of his forearm had enough normal skin (the skin without any visible scar and any abnormal sensation) for electrode placement. The two stimulation electrodes were positioned on the dorsal side of the proximal end of the stump. The subject was seated on a chair with their stump exposed, and the skin of the dorsal stump was shaved in the area of approximately 2 cm \times 3 cm. The skin location was cleaned with a 70% alcohol swab and the wire was inserted subdermally using a 25-gauge hypodermic needle. The rest of the wire electrode was fixed to the skin by Fixomull® stretch tape to avoid any displacement. The surface electrode was placed just next to the wire (Fig. 1).

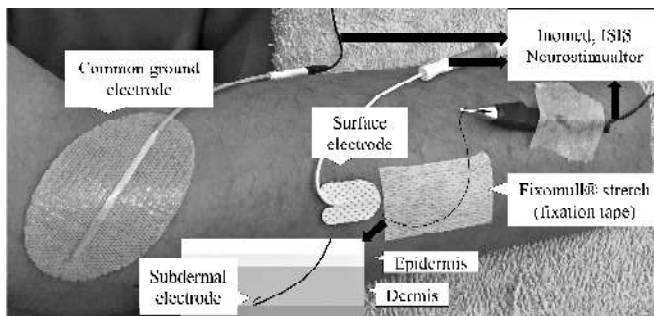


Fig. 1. Diagram of electrodes placement.

The pre-gelled common ground electrode (PALS Platinum, 40 mm \times 64 mm, oval) was applied to the dorsal side of the upper arm next to the elbow.

D. Psychophysical measurements

1) Detection threshold and pain threshold

The smallest stimulus that can be detected by the subject is called DT. The DT was measured using a staircase method by delivering single pulses with an inter-pulse interval of 2 s [25]. To initialize the staircase, an approximate DT was first determined using the method of limits [26]. The subjects received a series of pulses gradually increasing in steps of 0.3-0.5 mA for surface and 0.1-0.3 mA for subdermal stimulation. The steps were chosen randomly within the indicated range to avoid any anticipation bias by the subjects [22]. The amputee reported verbally when he first felt the stimulation. This amplitude was then used as the initial amplitude in the staircase procedure. During the staircase testing, a series of stimuli were delivered to the subjects with the amplitude that was adjusted adaptively based on subject responses. After each pulse, the subject reported if he felt the stimulation. If the subject detected the stimulus, the amplitude was increased, otherwise decreased

(in steps of 0.03-0.05 mA for surface and 0.01-0.03 mA for subdermal stimulation). The amplitude changes from ‘increase’ to ‘decrease’ or vice versa was defined as a ‘reversal’. The staircase procedure stopped after 10 reversals or after 30 stimuli were delivered. The DT was computed as the average of the last seven reversals.

The stimulus amplitude at which the subject starts to feel pain is referred to as the PT. The PT was measured using the method of limits [26] by delivering a single pulse with increasing amplitude in steps of 0.3-0.5 mA for surface and 0.1-0.3 mA for subdermal stimulation [22] and with an inter-pulse interval of 2 s. Three measurements were performed, and the PT was determined as the average of those measurements.

The DR was calculated by dividing PT by DT. A larger DR indicates that a wider range of electrical stimulation amplitudes is tolerated by the subject and may also generate a wider range of sensations (more room to operate).

2) Just noticeable difference

The smallest change in the stimulus amplitude that can be detected by a subject is called the JND. The JND was determined using the method of limits [26]. The amplitude of the baseline stimulus was set at $3 \times DT$ in both surface and subdermal stimulation. If this intensity was higher than the PT, a lower amplitude of $2 \times DT$ or $1 \times DT$ was used. Two stimuli were delivered sequentially and there was a 2-s break between the pulses. The first pulse was always set to the baseline amplitude whereas the amplitude of the second pulse was increased in steps of 0.01-0.11 mA for surface and 0.02-0.07 mA for subdermal. The pairs of pulses were delivered until the subject reported that he could feel the difference in the intensity. The difference was recorded as the JND. Finally, the procedure was repeated three times and the average of the three JNDs was used for data analysis.

The ratio between the JND and the baseline amplitude is called WF [18]. The WF was calculated using equation as follows:

$$WF = \Delta I / \Delta$$

where ΔI is JND and Δ is the baseline amplitude. According to Weber’s law, the WF should be approximately constant, and therefore, it can be used to estimate the JND for different baselines. Hence, the WF characterizes the resolution of the perceptual system.

3) Sensation evaluation

A computerized questionnaire was designed (Fig. 2) to collect the subjective experience of the stimulation [13]. The subjects were asked to report on the sensation quality, intensity, comfort, and location. The questionnaire included 12 pre-defined words that could be selected by the subject to describe the quality. For the stimulus intensity, the subjects were asked to indicate a number from a numerical rating scale (NRS), where 0 represented no stimulation and 10 represented the

maximum intensity. The stimulus comfort was reported using a Likert-type scale, where one indicated very comfortable, four neutral and seven very uncomfortable sensations. To describe the location of the perception, the subjects could select one of the three options, namely, 'local', 'radiation' and 'referred'. 'Local' represents that the sensation was just beneath the electrodes. 'Radiation' indicates that the sensation radiated out from the electrodes. 'Referred' represents that the sensation appeared at the other part of the body. All the answers were recorded on a computer via LabVIEW. The NRS and Likert scale were implemented using sliders and therefore the subject could indicate any number within the allowed range.

To evaluate the sensation quality, intensity, comfort, and location (questionnaire contents), the stimulation was delivered to the subjects in the form of 1-s pulse trains. The amplitude of the pulse trains was set to $3 \times DT$ and the frequency at 20 Hz and 100 Hz. These frequencies were selected as a) they elicit different sensations, 20 Hz elicits vibration and 100 Hz fused tingling, and b) they are within the range typically used for sensory feedback [27]. The amplitude of $1 \times DT$ or $2 \times DT$ was used if $3 \times DT$ was over PT. Each frequency was delivered to the subjects three times, and after each delivery, the subject was asked to fill in the aforementioned questionnaire. The stimuli at 50 Hz and 80 Hz were used as oddballs and delivered 2 times each. Twenty pulse trains (10 surface stimuli and 10 subdermal stimuli) were delivered to the subjects and the order of application of different frequencies was randomized. With sensation quality and location, the score was recorded as 1 if the specific word was selected; otherwise, the score was recorded as 0. Finally, the selection ratios (average scores of the 3 stimulation sequences) were used for data analysis for the sensation quality and sensation location of each item. With intensity and comfort, the average value of the three stimulation sequences was used for data analysis.

E. Data analysis

The coefficient of variation (CoV) was computed to evaluate the variability of DT, PT, WF, DR, intensity, and comfort across seven days. CoV was calculated as follows:

$$CoV = (Standard\ Deviation / Mean) \times 100$$

Finally, 8 CoVs (8 subjects) were obtained as a measure of within-subject variability across seven days for surface and subdermal stimulation. Then, the parametric paired sample t-test was used to compare CoVs between the surface and subdermal stimulation if the data were normally distributed, otherwise, the non-parametric Wilcoxon signed-rank test was used. The CoV values were expressed in percent.

One-way repeated-measures ANOVA was applied to detect if the psychometric parameters (DT, PT, DR, WF) changed significantly across the seven days when the data were normally distributed (Shapiro-Wilk test), otherwise, the Friedman test was used. In both cases, post hoc pairwise tests (Tukey's HSD criterion) were performed if a significant difference was detected across days.

Skilling-Mack test was used for difference detection across the seven days in sensation quality, intensity, comfort, and

Quality Q1: Please choose the words that best describe the sensation.

Pressure Tap Vibration Tingling

Pinprick Itch Pinch Pain

Muscle twitch Movement Warm Cold

Intensity Q2: Please rate the intensity of the stimulation.

0 1 2 3 4 5 6 7 8 9 10

Comfort Q3: Please rate the comfort of the stimulation.

1 2 3 4 5 6 7

Location Q4: Where did you feel the stimulation?

Local Radiation Referred

Fig. 2. Questionnaire for sensation evaluation.

location data since this test can be used in any block design and in the presence of missing data. Results are reported as mean \pm standard deviation ($M \pm SD$). Statistics were performed using IBM SPSS version 25 except the Skilling-Mack test, which was performed using Statext v3.0. The statistical significance threshold was set at $p < 0.05$.

III. RESULTS

A. PT, DT, and DR

The average CoVs of the DT and PT for surface and subdermal stimulation are shown in Fig. 3. There was a significant difference ($p < 0.05$) between the surface and subdermal stimulation in the CoVs of both DT and PT. The CoVs for DT were $13.41 \pm 5.11\%$ vs $22.30 \pm 5.06\%$ and for PT were $16.25 \pm 6.93\%$ vs $20.00 \pm 3.60\%$ in surface and subdermal stimulation, respectively. Therefore, both DT and PT were more variable in the case of subdermal stimulation.

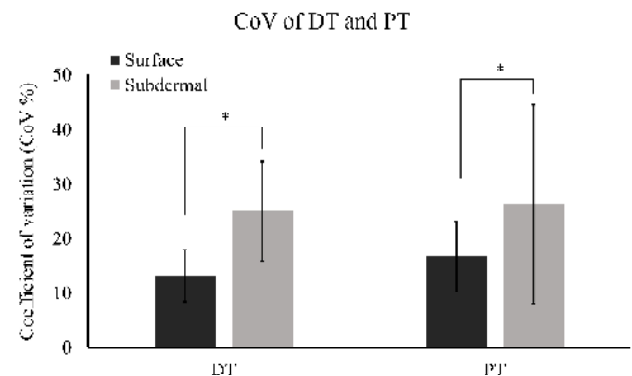


Fig. 3. The average (mean \pm standard deviation) coefficient of variation (CoV) for detection threshold (DT) and pain threshold (PT) across seven days for subdermal (grey) and surface (black) stimulation. * $p < 0.05$.

There was no significant difference across seven days in the mean DT of both surface and subdermal stimulation (Fig. 4 A and B). However, the PT in surface and subdermal stimulation increased across the seven-day period as shown in Fig. 4 C and D. The regression fit lines were significantly different from zero ($p < 0.05$). The mean PT of surface stimulation changed significantly across seven days, as detected by the Friedman test. The post hoc tests revealed that the PT of the second ($19.76 \text{ mA} \pm 4.59 \text{ mA}$) and third day ($20.60 \text{ mA} \pm 4.43 \text{ mA}$) was

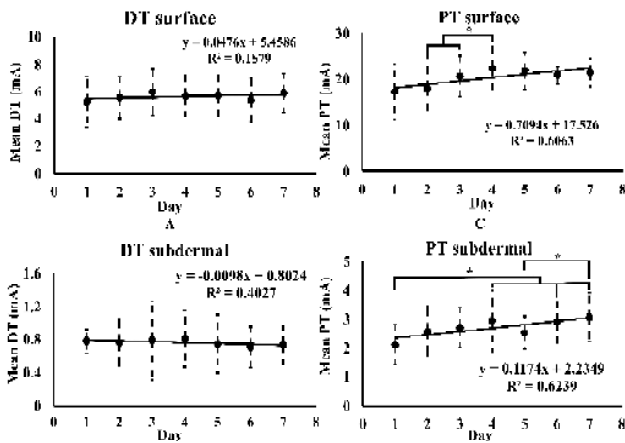


Fig. 4. The summary results (mean \pm standard deviation) of detection (DT) (Fig. 4 A and B) and pain threshold (PT) (Fig. 4 C and D) across days for surface and subdermal stimulation. The linear regression lines are shown as well as the respective coefficients of determination (R²). * $p < 0.05$.

significantly smaller than the PT of the fourth day ($22.38 \text{ mA} \pm 4.70 \text{ mA}$) ($p < 0.05$ for all, Fig. 4C). Likewise, a statistically significant change ($p < 0.05$) was detected across the seven days for the mean PT of subdermal stimulation using one-way repeated measures ANOVA. Post hoc tests revealed that the PT of the first day ($2.12 \text{ mA} \pm 0.71 \text{ mA}$) was significantly smaller than the PT of the fourth ($2.96 \text{ mA} \pm 1.07 \text{ mA}$), sixth ($2.91 \text{ mA} \pm 0.71 \text{ mA}$) and seventh day ($3.07 \text{ mA} \pm 0.85 \text{ mA}$). In addition, the PT of the fifth day ($2.55 \text{ mA} \pm 0.56 \text{ mA}$) was significantly smaller than the PT of the seventh day ($3.07 \text{ mA} \pm 0.85 \text{ mA}$) ($p < 0.05$ for all, Fig. 4D).

There was a significant difference ($p < 0.05$) between the surface and subdermal stimulation in the CoVs of the DR. The CoV was $18.46 \pm 6.68 \%$ for surface and $30.60 \pm 14.48 \%$ for subdermal stimulation (Fig. 5). Therefore, DR was more variable across seven days in subdermal stimulation. However, there was no significant change in the mean DR across seven days in both surface and subdermal stimulation, which means that both surface and subdermal stimulation were stable across days (no systematic trends).

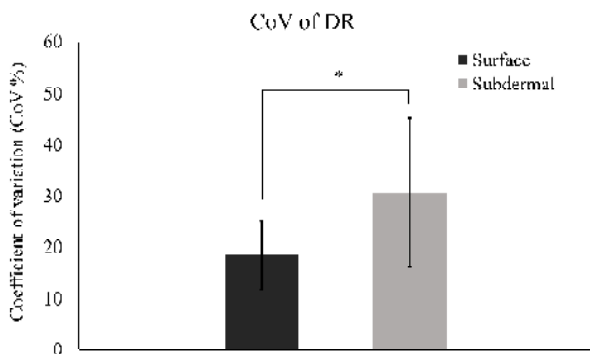


Fig. 5. The average (mean \pm standard deviation) coefficient of variation (CoV) for dynamic range (DR) across seven days for surface and subdermal stimulation. * $p < 0.05$.

B. WF (JND)

Although there was a large difference in the mean of the CoVs for the WF, there was no significant difference between

the surface ($64.66 \pm 45.52 \%$) and subdermal stimulation ($37.90 \pm 7.13 \%$), likely due to high variability of the CoVs across subjects in surface stimulation. There was no significant change in the mean WF of both surface and subdermal stimulation across the seven days, which means that both surface and subdermal stimulation were stable across days (no systematic trends).

C. Evoked sensation

1) Quality of sensation and perceived location

The sensation quality and perceived location for surface and subdermal stimulation exhibited a similar degree of variability across the seven days ($p > 0.05$ for all). As shown in Fig. 6, the selection ratios of pressure, vibration, tingling and movement for surface stimulation seem to be higher than for subdermal stimulation, while there is an opposite trend for the selection ratios of pinprick and warm sensations.

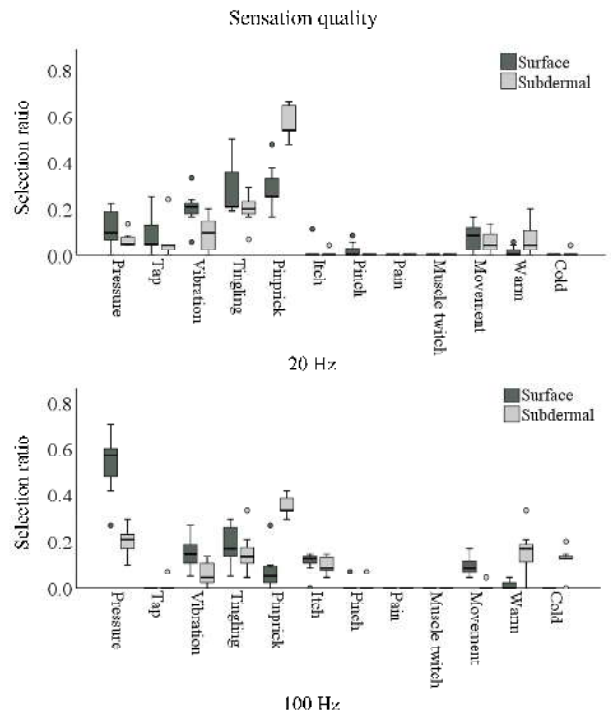


Fig. 6. The selection ratios (averaged across the seven days and eight subjects) of sensation qualities at 20 Hz and 100 Hz for surface and subdermal stimulation. The box plots depict median and interquartile range of selection ratios and the circles represent the outliers.

2) Intensity and Comfort

The average CoVs of intensity (mean \pm standard error) is shown in Fig. 7. There was a significant difference ($p < 0.01$) between the CoVs of surface ($11.56 \pm 5.31 \%$) and subdermal stimulation ($17.64 \pm 6.53 \%$) at the frequency of 100 Hz. However, there was no significant difference between the CoVs at 20 Hz ($14.04 \pm 6.02 \%$ vs $20.30 \pm 23.37 \%$). The CoVs for the comfort was similar ($16.42 \pm 9.66 \%$ vs $18.94 \pm 11.33 \%$ at 20 Hz and $21.29 \pm 13.85 \%$ vs $24.14 \pm 15.41 \%$ at 100 Hz) in surface and subdermal stimulation, respectively.

The intensity and comfort for surface and subdermal stimulation exhibited a similar degree of variability across the seven days ($p > 0.05$ for all).

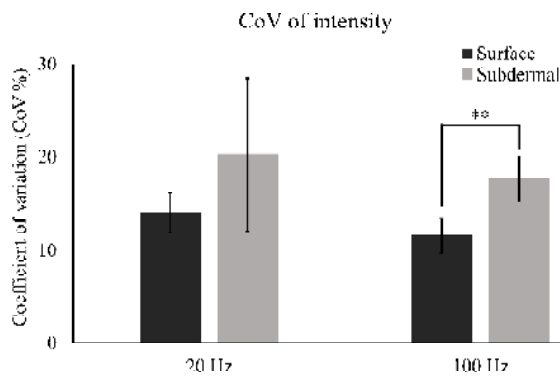


Fig. 7. The average (mean \pm standard error) CoVs for intensity across seven days for surface and subdermal stimulation. ** $p < 0.01$.

IV. DISCUSSION

In this study, two aspects of the psychophysical measurements were explored, one is variability (CoV) and the other is the stability of the mean (systematic trend). The variability of psychometric parameters across seven days was assessed for surface and subdermal stimulation delivered to the forearm of amputee subjects. As indicated by the CoVs, surface stimulation showed less variability in DT, PT, DR, and intensity at 100 Hz across the seven days compared to subdermal stimulation. Importantly, the higher variability of the subdermal stimulation was not due to a systematic change in the psychometric parameters across days. No significant trend across days was detected in the mean value of any of the parameters apart from the PT. Nevertheless, this does not indicate that systematic change will not happen in long term (e.g., months) due to for example encapsulation of the wire electrodes [28]. The mean PT increased in both surface and subdermal stimulation. From the viewpoint of sensory feedback, the increase in the PT is beneficial because this indicates that the subjects can tolerate the stimulation better. This was likely due to the subject getting used to the sensations elicited by the two types of stimulation [29], [30].

Therefore, it seems that the higher variability of the subdermal stimulation is due to intrinsic factors (versus systematic change), which can be related to the nature of the assessment and/or subject perception. One important point is that surface electrodes were replaced every session, while the subdermal wires were inserted in the first session and removed only after the experiment. As explained before, this reflects the way the interfaces would be applied clinically. Therefore, the psychophysical measurements might have been more stable because the impedance of the surface electrodes was always consistent, as a new pre-gelled electrode was placed on the skin each time. Nevertheless, certain variability is expected even in this case since, as demonstrated in [20], the sensation threshold and intensity may vary due to the repositioning error of the electrode. In subdermal stimulation, the wire electrode was maintained under the skin for seven consecutive days. Therefore, the environment in the tissue around the electrode might have changed, thereby influencing the psychophysical measurements. It was reported in the literature that one of the

three electrodes showed a change in threshold current between 3rd and 5th weeks post-implantation [20]. Therefore, we assume that the impedance change along with time will affect the evoked sensation post-implantation. Yet, this has to be identified in further experiments with long-term implantation. Another source of variability in subdermal stimulation could have been small displacements of the electrode within the tissue, as the subjects would perform daily life activities between the sessions with the electrode inserted. The wire was secured outside of the skin using a medical tape; however, this might have not prevented the movements of the part of the wire below the skin. Finally, the subjective experience and psychological reaction of the subjects to the stimulation delivered inside the tissue could also contribute to the variability. In fact, there was no re-insertion of the subdermal electrode during the seven days, as the re-insertion would be an additional source of variability. The final aim is to use permanently implant subdermal electrodes to avoid skin infection. The present manuscript demonstrates that clear advantages of subdermal stimulation related to potentially permanent placement below the skin, come with a disadvantage in terms of higher intrinsic variability.

In our previous study [22], we have assessed the repeatability of the subdermal and surface stimulation in short term (eight hours) in able-bodied subjects by testing for the systematic change in the mean value of the psychometric parameters. There were only three measurements and therefore the CoV was not computed. The DT of subdermal stimulation appeared to be more stable. There was no significant change in the mean DT of subdermal stimulation, while it decreased in surface stimulation. Similarly, the referred sensations increased for the surface stimulation. Contrary to the present experiment, the surface electrode was not replaced during the eight hours experiment, which is a likely reason for the changes in DT and referred sensations. The surface stimulation was more stable in PT and WF. The mean PT increased and WF decreased over time for subdermal stimulation. The stimulation modalities were equally stable in sensation quality, perceived intensity, and comfort. The present study demonstrates that psychometric parameters of the subdermal stimulation, apart from PT, do not exhibit systematic changes even when tested across a longer period of time (seven days versus eight hours).

Generally, higher stimulation frequencies are prone to evoke higher intensity under the same stimulation amplitude [21]. The present study shows that the intensity was less variable for surface stimulation at 100 Hz compared to subdermal stimulation, whereas no difference in variability was obtained at 20 Hz (Fig. 6).

In short, the present results do not favor subdermal stimulation over surface stimulation but, the applicability (e.g., permanent implantation, low power) of subdermal stimulation is indeed an advantage. Therefore, the subdermal stimulation can be an attractive alternative to surface and implanted (e.g. cuff [10]) solutions. It provides chronic placement with a simple procedure (needle insertion). However, contrary to surface and implanted methods that have been extensively investigated, the subdermal approach has received less

attention. Hence, the present study provides important information for future clinical applications of this approach.

From the viewpoint of implementing the sensory feedback in prosthetics, it is desirable that the perceived sensation is stable over time. As demonstrated here, both subdermal and surface stimulation are stable (no systematic change) but the psychometric parameters of the subdermal stimulation exhibit more intrinsic variability. The choice of the stimulation modality will therefore need to be based on the tradeoff, between variability and usability (e.g., compactness, lower power consumption or more permanent placement). The next step in this research is to evaluate the use of subdermal stimulation during online control task.

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