Psychophysical Evaluation of Subdermal Electrical Stimulation in Relation to Prosthesis Sensory Feedback

Bo Geng, Jian Dong, Winnie Jensen, Strahinja Dosen, Dario Farina, and Ernest Nlandu Kamavuako

***Abstract*— This study systematically evaluated the perceptual properties of subdermal electrical stimulation to test its efficacy in providing sensory feedback for limb prostheses. The detection threshold (DT), pain threshold (PT), just noticeable difference (JND), as well as the elicited sensation quality, comfort, intensity and location were assessed in 16 healthy volunteers during stimulation of the ventral and dorsal forearm with subdermal electrodes. Moreover, the results were compared with those obtained from transcutaneous electrical stimulation. Despite a lower DT and PT, subdermal stimulation attained a greater relative dynamic range (*i.e.*, PT/DT) and significantly smaller JNDs for stimulation amplitude. Muscle twitches and movements were more commonly elicited by surface stimulation, especially at the higher stimulation frequencies, whereas the pinprick sensation was more often reported with subdermal stimulation. Less comfort was perceived in subdermal stimulation of the ventral forearm at the highest tested stimulation frequency of 100 Hz. In summary, subdermal electrical stimulation was demonstrated to be able to produce similar sensation quality as transcutaneous stimulation and outperformed the latter in terms of energy efficiency and sensitivity. These results suggest that stimulation through implantable subdermal electrodes may lead to an efficient and compact sensory feedback system for substituting the lost sense in amputees.**

***Index Terms* — prostheses, sensory feedback, electrocutaneous stimulation, subdermal electrical stimulation**

I. INTRODUCTION

AFTER the loss of a limb, the majority of amputees usually rely on prostheses to replace the functionality of their missing limbs. Prostheses capable of effectively replacing biological limbs should not only allow the recovery of motor function but also recovery of the lost sensations. Sensory feedback plays a fundamental role in human motor control [1]. However, despite its widely recognized importance, the lack of sensory feedback remains a major obstacle towards a fully functional prosthesis [2], [3]. This is among the most cited reasons for abandonment of limb prostheses [4], [5].

While technologies for restoring natural sensory feedback via direct stimulation of peripheral nerves or the brain are promising [6]-[8], approaches to substitute the missing afferent pathways by artificially activating cutaneous afferents can be effective alternatives [9], [10]. The human skin has long been identified as a sensory input channel for transmission of information [11]. Tactile sense can be elicited by non-invasive external stimulation of the skin.

Among the non-invasive approaches, both mechanical and electrical stimulation of the skin have been extensively investigated. Mechanical stimulation can provide vibrotactile substitution using vibration motors [12] or modality-matched mechanotactile substitution by applying pressure to the skin using a liner pusher or a pressure cuff [13], [14]. Compared to mechanical approaches, electrical stimulation has certain advantages, including fast reaction and accurate modulation since the stimulation parameters can be independently controlled [9], [15]. In electrical stimulation, the electric current passes through the skin and evokes sensations by activating cutaneous sensory fibers or receptors [16]. The evoked sensations are dependent on multiple factors, including stimulus parameters (current, voltage, frequency, duration, waveform), electrode types (size, material, geometric contact area), and skin properties (thickness, location, hydration, receptor density) [17]-[19]. Information may be transmitted by means of parameter modulation or spatial coding [6].

Despite its advantages over mechanical stimulation systems, transcutaneous (or surface) electrical stimulation has practical limitations that impede its wider acceptance by users. The stimulation effectiveness strongly depends on electrode location and skin hydration [20]. Small repositioning errors induced by donning and doffing the prosthesis can lead to changes in the sensation thresholds and perceived sensation intensity [21]. Moreover, poor contact between the electrodes and the skin determines high electrode-skin impedance that can cause an uncomfortable sensation. These drawbacks may be overcome by using an implantable stimulation system.

This work was supported by The Danish Council for Independent Research under Grant 1337-00130.

Bo Geng is with SMI®, Department of Health Science and Technology, Aalborg University, Aalborg, Denmark (e-mail: bogeng@hst.aau.dk).

Jian Dong is with the Department of Orthopedics, The Second Hospital of Jilin University, Changchun, China, currently a guest researcher with the Department of Health Science and Technology, Aalborg University, Aalborg, Denmark.

Winnie Jensen is with SMI®, Department of Health Science and Technology, Aalborg University, Aalborg, Denmark.

Strahinja Dosen is with SMI®, Department of Health Science and Technology, Aalborg University, Aalborg, Denmark.

Dario Farina is with the Department of Bioengineering, Imperial College London, London, United Kingdom.

Ernest Nlandu Kamavuako is with the Centre for Robotics Research, Department of Informatics, King's College London, London, United Kingdom.

Stimulation of the nerves with implanted intraneural electrodes is the most direct way for restoring sensory information [6], [8], [22]. However, the neurosurgical procedure may not be accepted by all patients. In addition, placing electrodes around or inside the nerves may cause nerve irritation or further damage of the nerves.

A practical alternative to nerve implants is stimulation through subdermal electrodes, which would require a minimally invasive surgery for chronic implants. This approach has been previously suggested [23] but not thoroughly investigated. It has been shown that subdermal stimulation is more efficient in reaching detection threshold and more stable than surface stimulation [23]. Moreover, Riso and colleagues [20] proposed and tested coiled stainless steel wire electrodes and platinum-iridium disk electrodes to produce reliable tactile sensations. However, subdermal stimulation has not been studied with comprehensive psychophysical measures in comparison to surface stimulation.

The aim of this study was to systematically evaluate the psychophysical performance of subdermal electrical stimulation and to provide a knowledge base for its potential applications in sensory feedback for prostheses. Therefore, the detection threshold (DT), pain threshold (PT), and just noticeable difference (JND), as well as elicited sensation quality, intensity, comfort, and location, were assessed and compared to those measured during surface electrical stimulation.

II. METHODS

A. *Subjects*

The experimental protocol was approved by the North Denmark Region Committee on Health Research Ethics (N-20160021). Sixteen healthy volunteers (10 males and 6 females, 27.44 ± 4.95 years) recruited from Aalborg University participated in this study. All subjects signed an informed consent form prior to the experiment. The subjects had no visible broken skin or infections in the application area.

B. *Electrodes*

Two self-adhesive, surface electrodes (Ambu Neuroline 700, 20 mm × 15 mm) were used for surface stimulation. One was centrally placed on the ventral aspect of the non-dominant forearm midway between the elbow crease and the wrist joint. The other was positioned on the opposite (*i.e.*, dorsal) side of the forearm. Before the surface electrodes were attached, the skin was cleaned using a moisturized cotton swab to remove grease and improve conductivity. Gentle shaving was applied when needed.

Beneath the skin of each surface electrode site, a sterilized, custom-made fine wire electrode made of Teflon-coated stainless steel (A-M Systems, Carlsborg WA, diameter of 50 µm) was placed using a sterile 25-gauge hypodermic needle. The placement procedure consisted of lifting the skin and then inserting the needle nearly longitudinal. The needle was inserted until the tip of the wire was completely under the dermis and then removed to leave the wire electrode under the skin. The wire was uninsulated for 5 mm.

A self-adhesive electrode (PALS Platinum, 40 mm × 64 mm, oval) as common ground was positioned over the wrist of the same forearm. This larger common electrode was used to diffuse the flow of electric current so that the tactile sensations were evoked only via stimulating electrodes (*i.e.,* the smaller surface electrodes or the fine wire electrodes).

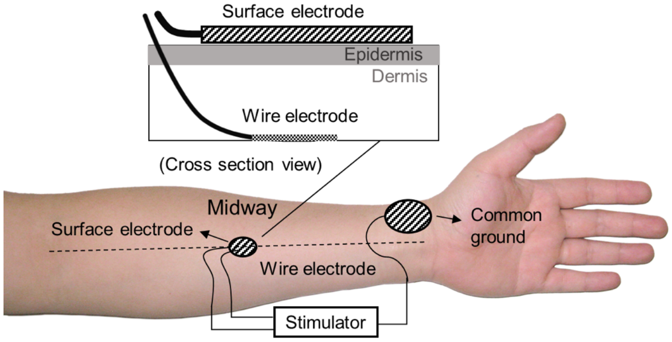


Fig. 1. Illustration of the electrode placement and stimulation setup. The other surface and fine wire electrode were on the opposite side of the forearm, which is not shown in this figure.

C. *Electrical Stimulation*

A symmetric, biphasic, rectangular waveform was used for its lowest total charge among the commonly used waveforms according to a previous study [24]. The duration of each phase was 100 µs. For evaluation of elicited sensations, the frequency below 100 Hz was considered because earlier studies found that low frequency was the most useful range for sensory communication [27]. The sensation elicited at10 Hz and 100 Hz, representing a lower and higher frequency in this range, respectively, were thus evaluated. The stimulus amplitudes were standardized across subjects by using two and three times DT of individual subjects.

The stimulation was applied via either the surface electrode to the forearm skin, or via the subdermally located fine wire electrode to the tissue surrounding the dermis. A commercial constant current stimulator (ISIS Neurostimulator, Inomed; Emmendingen, Germany) was used to generate the studied stimuli. The stimulator was controlled by a customized LabVIEW (version 2015) program. The electrode placement and stimulation setup are illustrated in Fig. 1.

D. *Measure of DT and PT*

The DT and PT of the ventral and dorsal forearm were measured for surface and subdermal stimulation, respectively. The DT was defined as the stimulus current amplitude producing just detectable sensation. The PT was defined as the current amplitude at which a subject began to feel pain.

DT was measured using a staircase procedure [25]. A rough estimation of the DT was first obtained by delivering a series of ascending stimuli at a relatively large step size (0.1 mA and 0.3 mA for subdermal and surface stimulation, respectively). The last amplitude that was not detected was then chosen as the first stimulus in the 'staircase'. This first stimulus was then delivered. If the subject could not perceive the stimulus, the amplitude of the next stimulus increased by a small step size (0.01 mA and 0.03 mA for subdermal and surface stimulation, respectively). Otherwise, the amplitude of the next stimulus decreased by the same small step size, and this event was registered as a 'reversal'. This procedure continued until at least 10 'reversals' were reached, or 30 stimuli were delivered. The first three 'reversals' were ignored, and the DT was determined as the average of the amplitude values corresponding to the remaining reversals.

PT was measured by the method of limit [26]. A series of ascending-amplitude stimuli was delivered until the subject reported a painful sensation. This procedure was repeated three times. The step size in the three repeated measurements varied in the range of 0.2 - 0.4 mA and 0.5 - 0.8 mA for subdermal and surface stimulation, respectively, to reduce the potential bias due to anticipation. The PT was determined as the average of the three measures. The dynamic range was calculated as the ratio PT/DT.

E. *Measure of JND*

To compare a subject's sensitivity to the change of stimulus level between stimulation modalities, the JND, defined as the minimum amount of change in current amplitude that produced a noticeable difference in elicited sensation, was measured for the ventral forearm.

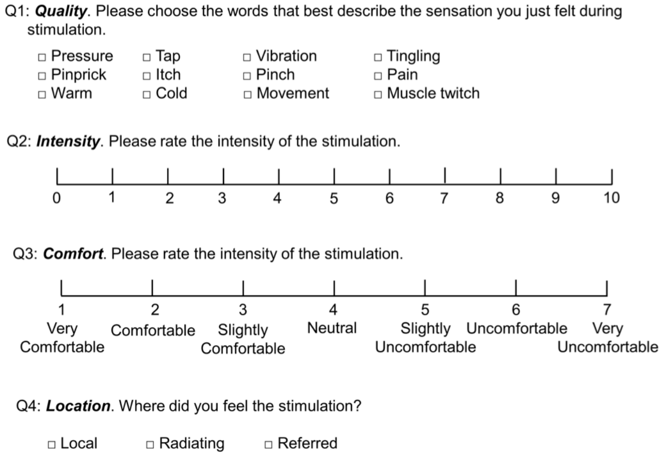
The method of limit was adopted to measure the JND [22]. For this purpose, a reference stimulus I_0 was first delivered and was followed by a comparison stimulus I after 2 s. If the subject could not detect the difference between the reference and comparison stimuli, another pair of stimuli were delivered in the same order but with the amplitude of the comparing stimulus increased by 0.01 mA and 0.03 mA for subdermal and surface stimulation, respectively. This process continued until the subject perceived the difference in the sensation elicited by the pair of stimuli. The difference in stimulus amplitude $\Delta = I - I_0$ was then determined as the JND at I_0, which reflects the subject's sensitivity to the change in stimulus amplitude at I_0.

Three reference amplitude levels (2×, 3×, and 4×DT) were tested and the JNDs were accordingly denoted as *JND-2*, *JND-3*, and *JND-4*. Each measure was repeated three times and the JND was determined as the average of the three measures. Current levels exceeding a subject's PT were excluded.

F. *Sensation Evaluation*

To evaluate and compare elicited sensation, four stimuli with the following stimulation parameters were selected to span the useful range of perceptions: single pulse with amplitude 2×DT (2×DT@1 Hz); single pulse with amplitude 3×DT (3×DT@1 Hz); 1-s pulse train at 10 Hz with amplitude 3×DT (3×DT@10 Hz); and 1-s pulse train at 100 Hz with amplitude 3×DT (3×DT@100 Hz). The current amplitudes beyond a subject's pain threshold were though excluded from the evaluation to avoid pain.

Each stimulus was presented to the subject three times, and a total of 12 stimuli were delivered in a random order. Once a stimulus was delivered, a psychophysical questionnaire was displayed on a computer monitor, and the subject answered it using a mouse. When the subject was finished with the questionnaire, the next stimulus was then immediately delivered, and the answers were registered for later analysis. Fig. 2 shows the questionnaire for evaluation of the elicited sensation consisting of four questions concerning sensation quality, intensity, comfort, and location.



Q1: ***Quality***. Please choose the words that best describe the sensation you just felt during stimulation.

☐ Pressure	☐ Tap	☐ Vibration	☐ Tingling
☐ Pinprick	☐ Itch	☐ Pinch	☐ Pain
☐ Warm	☐ Cold	☐ Movement	☐ Muscle twitch

Q2: ***Intensity***. Please rate the intensity of the stimulation.

Q3: ***Comfort***. Please rate the intensity of the stimulation.

Q4: ***Location***. Where did you feel the stimulation?

☐ Local ☐ Radiating ☐ Referred

Fig. 2. The psychophysical questionnaire for evaluation of elicited sensation quality (Q1), intensity (Q2), comfort (Q3) and location (Q4).

The sensation quality was assessed by a multiple-choice question. The answer consisted of 12 predefined descriptors, selected based on previous studies [27]-[29] and explained to the subjects before the experiment. The subjects were instructed to choose one or more words that best described the quality of the elicited sensation or to report that none of the words in the list accurately described the sensation.

The sensation intensity was measured by a numerical rating scale (NRS), with the left end '0' representing 'no sensation' and '10' representing 'the sensation at pain threshold'. The subjects were allowed to rate the intensity by moving a slider along the scale. The average of the three repeated measures was determined as the perceived intensity for a particular stimulus.

The comfort level of the perceived sensation was assessed by a Likert-type scale with seven anchors (1: Very comfortable, 2: Comfortable; 3: Slightly comfortable, 4: Neutral, 5: Slightly uncomfortable, 6: Uncomfortable, 7: Very uncomfortable). The subject rated the comfort level by moving a slider along the scale. Likewise, the average of the three repeated measures was determined as the comfort level for a stimulus.

The perceived location was evaluated by a multi-choice question with three predefined answers: local, radiating, and referred. 'Local' was defined as the sensation confined to the stimulation site. 'Radiating' was defined as the sensation spreading from the stimulation site to another site along the forearm. ‘Referred’ was defined as the sensation perceived at a location other than the stimulation site (*e.g.*, in the hand).

G. *Experimental Procedure*

The experiment started with the psychophysical evaluation of surface stimulation. The DT and PT were first measured, followed by measurement of JND. Sensation evaluation was subsequently performed. Measures for the ventral and dorsal forearm were alternated to avoid habituation. When the measurement for surface stimulation was completed, the surface electrodes were removed. After a 10-minute break, the fine wire electrodes were placed and the same procedure was performed with subdermal stimulation. The time duration for the entire experiment was approximately 2 h.

H. *Statistical Analysis*

According to the Shapiro-Wilk test, DT and PT data were normally distributed, whereas dynamic range data (*i.e.*, PT/DT) did not follow a normal distribution. Therefore, paired t-tests were used to compare DT and PT, and the non-parametric Wilcoxon signed rank tests were used to compare the dynamic range and the JND between surface and subdermal stimulation. The Wilcoxon signed rank test was also used to compare the sensation intensity score and the comfort score since they are ranking data. McNemar’s test was used to compare the proportion of trials in which the subjects perceived a particular sensation quality or location between the two types of stimulation. The significance level was 0.05.

III. RESULTS

A. *DT and PT*

Table 1 shows the mean and standard error (SE) of DT and PT, as well as the median and the interquartile range (IQR) of the dynamic range PT/DT for surface and subdermal stimulation of the ventral and dorsal aspect of the forearm. Significantly lower DT and PT were observed in subdermal stimulation. This result was expected since in surface stimulation electrical current needs to flow through the outermost layer of the skin (stratum corneum) which has a high electrical resistance. The high resistance likely leads to the requirement of a larger amount of electric charges adequate to activate the afferent fibers.

TABLE 1

MEAN ± SE OF DT AND PT, AND MEDIAN (IQR) OF DYNAMIC RANGE PT/DT

	Ventral		Dorsal	
	Surface	Subdermal	Surface	Subdermal
DT (mA)	3.18±0.24	0.62±0.08	3.82±0.26	0.89±0.07
PT (mA)	18.61±2.47	5.50±0.97	20.12±1.80	7.57±1.13
PT/DT	5.50(2.67)	7.59(7.82)	5.88(2.86)	7.48(6.00)

Statistical comparison indicated a significant difference between surface and subdermal stimulation in DT ($p < 0.001$ for both ventral and dorsal), PT ($p < 0.001$ for both ventral and dorsal), and in a dynamic range at the ventral forearm ($p < 0.05$). A trend toward significance was also observed for the dynamic range on the dorsal side ($p = 0.079$).

B. *JND*

JND was measured for the ventral forearm. *JND-2*, *JND-3*, and *JND-4* data were from 15, 13, and 8 subjects, respectively, since in some cases the amplitude was beyond PT.

Fig. 3 shows the boxplot of the JND data. The data larger than Q3 by at least 1.5 times the interquartile range (IQR), or smaller than Q1 by at least 1.5 times the IQR were represented as outliers. The statistical comparison indicated a significantly smaller JND in subdermal stimulation for the three reference amplitudes ($p < 0.05$ in all cases). The subdermal stimulation exhibited a greater sensitivity to stimulation amplitude than the surface stimulation. Similar JNDs were obtained irrespective of the reference stimulus, contrary to our expectation of a proportional increase in JND with increasing reference amplitude [26].

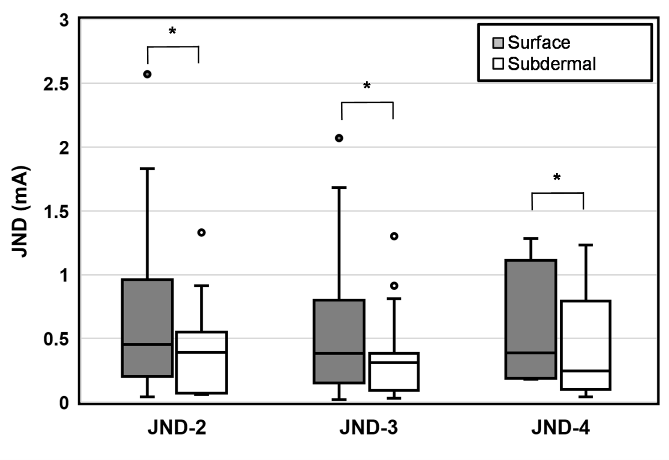


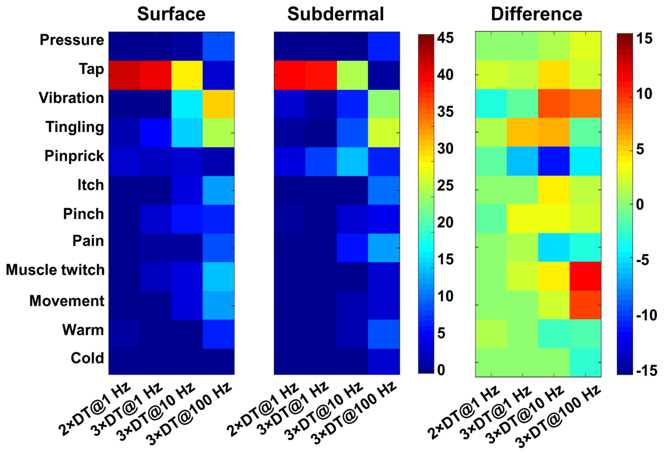
Fig. 3. Boxplot of JNDs for three reference amplitudes: JND-2, JND-3, JND-4 (representing 2×DT, 3×DT and 4×DT, respectively), $*p < 0.05$.

C. *Elicited Sensation: Quality*

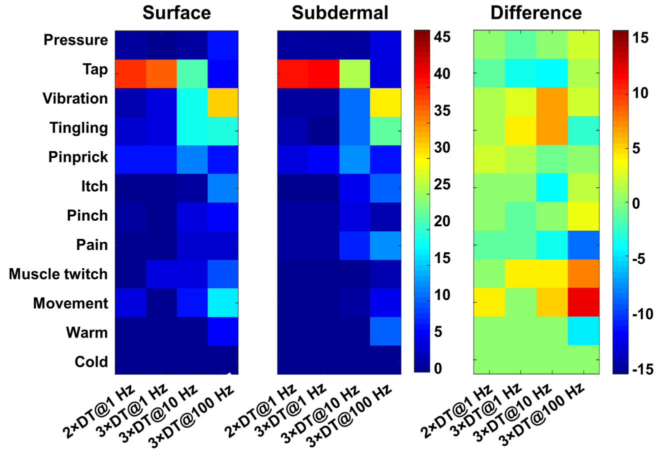
Heat maps were used to illustrate the overall number of stimulation trials, wherein a particular sensation quality was reported by the subjects (Fig. 4). A heat map of the ‘difference’ in the number of positive responses between surface and subdermal stimulation is also shown in Fig. 3. Because each of the four investigated stimuli was presented to the subjects three times, a total of 48 trials for each stimulus was tested on each side of the forearm.

Based on the pattern of the heat maps, the elicited sensations appeared qualitatively very similar in surface and subdermal stimulation, especially when the stimuli contained only a single pulse. For example, the ‘tap’ sensation was dominant in both single-pulse surface and single-pulse subdermal stimulation.

In other cases, the differences in sensation quality were observed but without statistical significance. For example, 'muscle twitch' and 'movement' were reported 25% and 21%, respectively more often, in response to the surface stimulation compared to subdermal stimulation of the ventral forearm at 100 Hz. This is most likely because the stimulation amplitude and electrode size in surface stimulation was much higher than it in subdermal stimulation, which increased the likelihood of activating muscle fibers. 'Pinprick' was reported 25% less often in response to the surface stimulation than subdermal stimulation of the ventral forearm at 10 Hz, likely due to a smaller electrode and thereby relatively higher current density.



(a) Ventral forearm

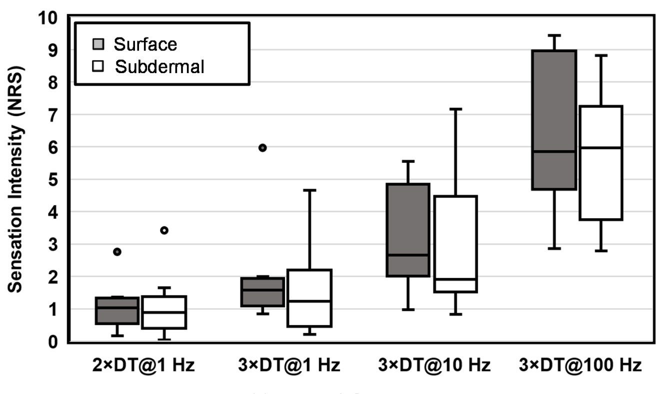


(b) Dorsal forearm

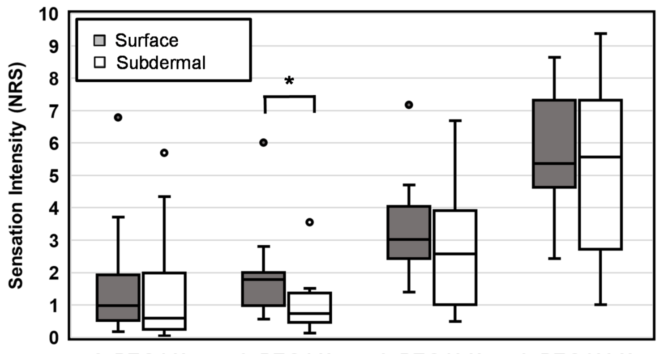
Fig. 4. Heat map illustration of perceived sensation quality in response to four stimuli: *2×DT@1 Hz*, *3×DT@1 Hz*, *3×DT@10 Hz*, *3×DT@100 Hz*. Colors indicate the number of trials in which a predefined sensation quality was perceived in surface stimulation (left) and subdermal stimulation (middle), as well as the difference in the number of trials between surface and subdermal stimulation (right). (a) Ventral forearm; (b) dorsal forearm.

D. *Elicited Sensation: Intensity*

Fig. 5 shows the boxplots of the numerical rating score of the perceived intensity for the four investigated stimuli applied to the ventral and dorsal forearm. In general, higher frequencies tended to elicit stronger perception. The perceived intensity was very similar between surface and subdermal stimulation with no statistically significant differences. The only exception was a significantly higher intensity perceived during single-pulse surface stimulation compared to subdermal stimulation of the dorsal forearm at the amplitude of 3 times DT ($p < 0.05$). This result suggests that in most cases subdermal stimulation was able to produce as strong sensation as surface stimulation but with a significantly smaller amount of electric charge.



(a) Ventral forearm



(b) Dorsal forearm

Fig. 5. Boxplots of elicited sensation intensity (NRS, numerical rating score) in response to the four stimuli applied to (a) ventral forearm and (b) dorsal forearm, *$p < 0.05$.

E. *Elicited Sensation: Comfort*

Fig. 6 shows the boxplots of the comfort score of the four investigated stimuli. For both the ventral and dorsal forearm, higher frequencies appeared to result in higher scores, hence more discomfort. The sensation elicited by the stimuli at 100 Hz was reported to be the least comfortable in both surface and subdermal stimulation. There was no statistically significant difference in the comfort level between surface and subdermal stimulation, except that the perception of surface stimulation was significantly less comfortable compared to the subdermal stimulation at 100 Hz on the ventral forearm ($p < 0.05$).

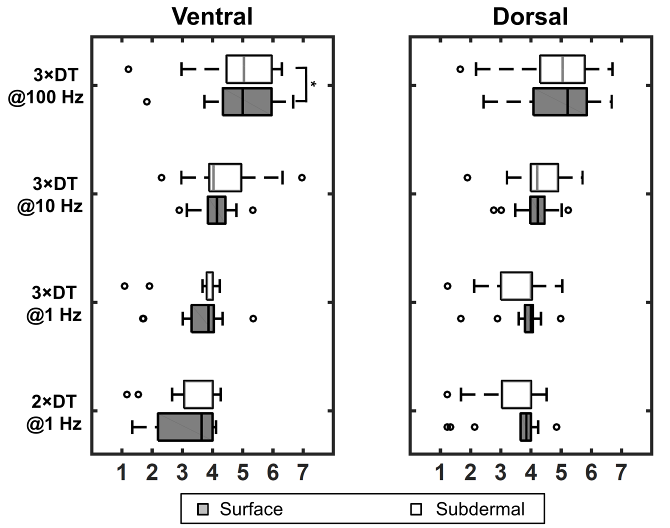
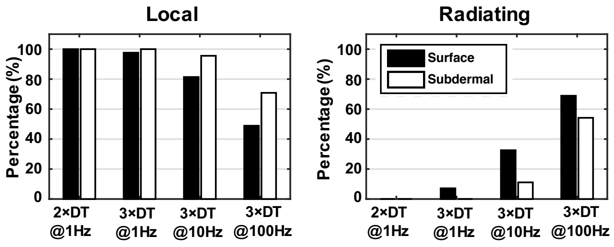


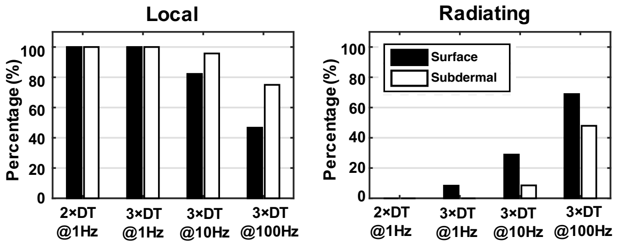
Fig. 6. Boxplots of comfort score in response to four stimuli on the ventral (left) and dorsal (right) forearm, $*p < 0.05$. Scores: 1-Very comfortable; 2-Comfortable; 3-Slightly comfortable; 4-Neutral; 5-Slightly uncomfortable; 6-Uncomfortable; 7-Very uncomfortable.

F. *Elicited Sensation: Location*

Fig. 7 shows the percentage of the stimuli reporting ‘local’ and ‘radiating’ in response to the four studied stimuli. ‘Referred’ sensation is not included since it has not been reported in our experiment. The majority of single-pulse stimuli elicited local sensations, whereas ‘radiating’ was more often reported during pulse-train stimulation of both the ventral and dorsal forearm. Higher stimulation frequency appeared to associate with higher percentage of stimuli perceived as ‘radiating’.



(a) Ventral forearm



(b) Dorsal forearm

Fig. 7. Bar plots of the percentage of stimuli reported as ‘local’ or ‘radiating’ in response to the four stimuli. (a) Ventral forearm; (b) Dorsal forearm.

In general, subdermal stimulation elicited more ‘local’ and less ‘radiating’ sensation, compared to surface stimulation, due to low current amplitude required. In spite of the clear trend, no statistically significant differences were observed in this result between subdermal and surface stimulation, possibly because of the small sample size.

IV. DISCUSSION

We systematically evaluated the psychophysical properties of subdermal electrocutaneous stimulation through fine wire electrodes. Specifically, DT and PT, JND for stimulus amplitude, and elicited sensation quality, intensity, comfort, and location were assessed. The same set of assessments was also performed for surface electrocutaneous stimulation of the same sites on the forearm.

A significantly larger dynamic range (PT/DT) and lower JND were attained with subdermal stimulation. Moreover, ‘muscle twitch’ and ‘movement’ were more frequently observed in surface stimulation, especially for stimulations at 100 Hz. Subdermal stimulation of the ventral forearm was more comfortable than surface stimulation at 100 Hz. Based on these results, subdermal stimulation may be a promising approach to provide sensory feedback for limb prostheses.

In this study, subdermal stimulation was delivered via fine wires. Fine wires are routinely applied for intramuscular recording and stimulation. They were used chronically demonstrating long-term stability (from months to years) with minimal risk of infection [30]-[32]. However, for chronic application, subdermal electrodes can also be realized using percutaneous micro-dermal implants. This is commonly used in cosmetics, and a recent study has demonstrated application of a percutaneous disc electrode implanted semi-chronically (weeks) in an able-bodied subject for EMG recording [33]. The implantation of such electrodes is simple and does not require surgery (contrary to electrodes for direct nerve or brain stimulation). In addition, the subdermal electrodes could be used as components of a fully implanted system. In this case, a surgical procedure is required but not on neural structures.

The skin has impedance properties that vary over time and with location; thus, the effect of surface stimulation strongly depends on location [16]. Repositioning errors in surface stimulation may cause poor consistency in sensation threshold and elicited sensation quality or intensity [20]. Stimulation through subdermal electrodes can potentially overcome this problem. Moreover, since subdermal stimulation bypasses the stratum corneum, it requires considerably smaller electrical charges adequate to activate afferents. For example, in this study, the average DT of surface electrical stimulation was over five times larger than the DT measured from subdermal stimulation. In this respect, subdermal stimulation has an obvious advantage in power efficiency. Furthermore, subdermal stimulation was associated with greater sensitivity to increases in energy. Its larger dynamic range and smaller JND, compared to surface stimulation, suggest the possibility of encoding a larger amount of information. Despite the greater dynamic range, the subjective reports of sensation following stimulation were not significantly different between surface and subdermal stimulation, indicating a similar afferent flow determined by the two techniques.

The fine wire electrodes were placed under the skin with the guidance of a hypodermic needle. During the insertion, although we attempted to control the depth of the electrode placement by lifting the skin, it was difficult to ensure that the wire electrodes were consistently placed under the skin. There was a chance that the electrodes were in fact placed within the dermis or the subcutaneous tissue. This problem may have caused some variability in the elicited sensation.

'Muscle twitch' and 'movement' were elicited 25% and 21% more often on the ventral forearm and 17% and 25% more often on the dorsal side in surface stimulation at 100 Hz compared to subdermal stimulation. The more frequent activation of efferent axons in surface stimulation was presumably due to the greater stimulus amplitude levels used with respect to subdermal stimulation. The higher amplitude resulted in a larger amount of electrical charges delivered to the tissue with each stimulus, which was enough to reach the threshold of motor activation. In the application of electrically generated sensory feedback for prostheses, such externally induced muscle activations should be avoided since they can contaminate the muscle signals for predicting a user's motion intention and thus potentially have a harmful impact on the accuracy of prosthetic control.

The subjects were encouraged to report the elicited sensation if it was not included in the predefined descriptors. However, this did not occur throughout the experiments with all subjects. This might suggest that the descriptor list covered the vast majority of the electrically elicited sensations. On the other hand, a multiple-choice question might have biased the subjects to choose from the given answers.

This study showed promising results for the use of subdermal stimulation in prosthesis; however, it should be noted that all investigations were carried out on able-bodied subjects. Whether the advantages are practically relevant can only be assessed with amputee patients since the density of sensory nerve endings may vary with the amputation site and the scar conditions. Many amputees can still feel the missing hand (termed phantom hand). When certain sites of the residual limb are being stimulated, they often perceive the stimulation also in the phantom hand [34]. It would be interesting to look into the difference in the perceptual properties between the two types of stimulation of those skin sites. Although the adopted experimental paradigm allowed for a minimally invasive procedure, the long-term stability and reliability of a subdermal chronic implant requires further extensive investigations. Nevertheless, an initial investigation in the present work was meant to pave the way for more practical and clinically oriented experiments.

V. Conclusion

This work aimed to provide psychophysical evidence for the potential application of subdermal electrical stimulation in sensory feedback for limb prostheses. By evaluation and comparison of its perceptual properties with surface electrical stimulation, the results showed that stimulation via subdermally located electrodes may be a promising substitute for the loss of sensation in amputees. In addition to prostheses, the potential applications may extend to other assistive technologies, such as reading and mobility aids for the blind or tactile vocoders for hearing impaired people.

References

[1] D. A. Rosenbaum, *Human motor control*. San Diego, CA: Academic, 1991.

[2] S. Lewis, M. F. Russold, H. Dietl, E. Kaniusas, "User demands for sensory feedback in upper extremity prostheses," in *IEEE International Symp. on Medical Meas. and appl. Proceeding (MeMeA)*, 2012, pp. 1-4.

[3] B. Peerdeman, D. Boere, H. Witteveen, R. Huis in'tVeld, H. Hermens, S. Stramigioli, H. Rietman, P. Veltink, S. Misra, "Myoelectric forearm prostheses: State of the art from a user-centered perspective," *J Rehabil Res Dev*, vol. 48, no. 6, pp. 719-738, 2011.

[4] E. A. Biddiss and T. T. Chau, "Upper limb prosthesis use and abandonment: a survey of the last 25 years," *Prosthet Orthot Int*, vol. 31, no. 3, pp. 236-257, Sept. 2007.

[5] K. Østlie, I. M. Lesjø, R. J. Franklin, B. Garfelt, O. H. Skjeldal, P. Magnus, "Prosthesis rejection in acquired major upper-limb amputees: a population-based survey," *Disabil Rehabil Assist Technol*, vol. 7, no. 4, pp. 294-303, Jul. 2014.

[6] S. D. Gurpreet and K. W. Horch, "Direct neural sensory feedback and control of a prosthetic arm," *IEEE Trans. Neural Syst Rehabil Eng*, vol. 13, no. 4, pp. 468–472, Dec. 2005.

[7] T. A. Kuiken, P. D. Marasco, B. A. Lock, R. N. Harden, J. P. Dewald, "Redirection of cutaneous sensations from the hand to the chest skin of human amputees with targeted reinnervation," *Proc Natl Acad Sci USA*, vol. 104, no. 50, pp. 20061–20066, Dec. 2007.

[8] S. Raspopovic, M. Capogrosso, F. M. Petrini, M. Bonizzato, J. Rigosa, G. Di Pino, J. Carpaneto1, M. Controzzi1, T. Boretius, E. Fernandez, G. Granata, C. M. Oddo, L. Citi, A. L. Ciancio, C. Cipriani, M. C. Carrozza, W. Jensen, E. Guglielmelli, T. Stieglitz, P. M. Rossini, S. Micera, "Restoring Natural Sensory Feedback in Real-Time Bidirectional Hand Prostheses," *Sci Transl Med*, vol. 6, no. 222, pp. 222ra19, Feb. 2014.

[9] A. Y. J. Szeto and F. Saunders, "Electrocutaneous stimulation for sensory communication in rehabilitation engineering," *IEEE Trans. Biomed Eng*, vol. 29, no. 4, pp. 300–308, Apr. 1982.

[10] P. B. Shull and D. D. Damian, "Haptic wearables as sensory replacement, sensory augmentation and trainer – a review, " *J Neuroeng Rehabil*, 12:59, 2012.

[11] F. A. Geldard, "Adventures of tactile literacy," *Am Psychol*, vol. 12, no. 3, pp. 115–124, Mar. 1957.

[12] C. Antfolk, M. D'Alonzo, B. Rosén, G. Lundborg, F. Sebelius, C Cipriani, "Sensory feedback in upper limb prosthetics," *Expert Rev Med Devices*, vol. 10, no. 1, pp. 45–54, Jan. 2013.

[13] S. G. Meek, S. C. Jacobsen, and P. P. Goulding, "Extended physiologic taction: design and evaluation of a proportional force feedback system," *J. Rehabil. Res. Dev.*, vol. 26, no. 3, pp. 53–62, Jan. 1989.

[14] P. E. Patterson and J. A. Katz, "Design and evaluation of a sensory feedback system that provides grasping pressure in a myoelectric hand," *J. Rehabil. Res. Dev.*, vol. 29, no. 1, pp. 1–8, Jan. 1992.

[15] M. Azadi and L. A. Jones, "Vibrotactile actuators: Effect of load and body site on performance," in *2014 IEEE Haptics Symposium (HAPTICS)*, pp. 351–356, 2014.

[16] E. A. Pfeiffer, "Electrical stimulation of sensory nerves with skin electrodes for research, diagnosis, communication and behavioral conditioning: a survey," *Med & biol Engng*, vol. 6, no. 6, pp. 637-651, Nov. 1968.

[17] K. A. Kaczmarek, J. G. Webster, P. Bach-y-Rita, W. J. Tompkins, "Electrotactile and vibrotactile displays for sensory substitution systems," *IEEE Trans. Biomed Eng*, vol. 38, no. 1, pp. 1–16, Jan. 1991.

[18] C. C. Collins and F. A. Saunders, "Pictorial display by direct electrical stimulation of the skin, " *J Biomed Syst*, vol. 1, no. 2, pp. 3-16, 1970.

[19] T. Tashiro and A. Higashiyama, "The perceptual properties of electrocutaneous stimulation: Sensory quality, subjective intensity, and

intensity-duration relation," *Percept Psychophys*, vol. 30, no. 6, pp. 579-586, 1981.

[20] R. R. Riso, A. R. Ignagni, M. W. Keith, "Electrocutaneous sensations elicited using subdermally located electrodes," *Automed*, vol. 11, 25-42, 1989.

[21] R. R. Riso, A. Y. J. Szeto, and M. W. Keith, "Comparison of subdermal vursus surface electrocutaneous stimulation," *in Proc IEEE Frontiers of Eng Health Care Conf*, 1982, pp. 343-347.

[22] P. M. Rossini, S. Micera, A. Benvenuto, J Carpaneto, G. Cavallo, L. Citi, C. Cipriani, L. Denaro, V. Denaro, G. Di Pino, F. Ferreri, E Guglielmelli, K. P. Hoffmann, S. Raspopovic, J. Rigosa, L. Rossini, M. Tombini, P. Dario, " Double nerve intraneural interface implant on a human amputee for robotic hand control," *Clin Neurophysiol*, vol. 12, no. 5, pp. 777-783, May 2010.

[23] F. A. Saunders and V. F. Saunders, "Intradermal recording during electrocutensou stimulation," *Federation Proceedings*, vol. 33, no. 3, Part 1 (1974).

[24] G. Kantor, G. Alon, H. S. Ho, "The effects of selected stimulus waveform on pulse and phase characteristics at sensory and motor thresholds," *Phys Ther*, vol.74, no.10, pp. 951-962, Oct. 1994.

[25] T. N. Cornsweet, "The staircase-method in Psychophysics," *Am J Psychol*, vol. 75, no. 3, pp. 485-491, Sep. 1962.

[26] G. A. Gescheider, *Psychophysics: The fundamentals*, 3rd ed. London: Lawrence Erlbaum associates, 1997.

[27] A.Y.J Szeto, J Lyman, R.E. Prior, "Electrocutaneous pulse rate and pulse with psychometric functions for sensory communication," Hum Factors, vol. 21, no. 2, pp. 241-249, 1979.

[28] C. N. Sang, M. B. Max, and R. H. Gracely, "Stability and reliability of detection thresholds for human A-beta and A-delta sensory afferents determined by cutaneous electrical stimulation," *J Pain Symptom Manag*, vol. 25, no. 1, pp. 64-73, 2003.

[29] B. Geng, K. Yoshida, L. Petrini, W. Jensen, "Evaluation of sensation evoked by electrocutaneous stimulation on forearm in nondisabled subjects," *J Rehabil Res Dev,* vol. 49, no. 2, pp. 297–308, 2012.

[30] J. M. Akers, P. H. Peckham, M. W. Keith, K. Merritt, "Tissue response to chronically stimulated implanted epimysial and intramuscular electrodes*," IEEE Trans. Rehabil Eng*, vol. 5, no. 2, pp. 207-220, 1997.

[31] W. D. Memberg, P.H. Peckham, G. B. Thrope, M. W. Keith, T. P. Kicher, "An Analysis of the Reliability of Percutaneous Intramuscular Electrodes in Upper Extremity FNS Applications," *IEEE Trans. Rehab Eng*, vol. 1, no. 2, pp. 126-134, Jun. 1993.

[32] K. L. Kilgore, P. H. Peckham, M. W. Keith, F. W. Montague, "Durability of implanted electrodes and leads in an upper-limb neuroprosthesis," *J Rehabil Res Dev,* vol. 40, no. 6, pp. 457–468, 2003.

[33] J. M. Hahne, D. Farina, N. Jiang, and D. Liebetanz, "A Novel Percutaneous Electrode Implant for Improving Robustness in Advanced Myoelectric Control," *Front. Neurosci.*, vol. 10, Mar. 2016.

[34] R. Melzack. "Phantom limbs," *Scientific American* vol. 266, no. 4, pp. 120-127, Apr. 1992.