International Journal of Physical Medicine & Rehabilitation

Geng et al., Int J Phys Med Rehabil 2016, 4:2
DOI: 10.4172/2329-9096.1000333

Commentary Open Access

Discrimination of Spatial and Temporal Parameters in Electrocutaneous Stimulation

Bo Geng*, **Senthoopiya Achuthan Paramanathan, Karina Faber Østergaard Pedersen, Mette Vandborg Lauridsen, Julie Gade, Eugen Romulus Lontis and Winnie Jensen**

Department of Health Science and Technology, Aalborg University, Fredrik Bajers vej 7D, 9220 Aalborg E, Denmark

***Corresponding author:** Bo Geng, Department of Health Science and Technology, Aalborg University, Fredrik Bajers vej 7D, 9220 Aalborg E, Denmark, Tel: 45 9940 8798; Fax: 45 9815 4008; E-mail: bogeng@hst.aau.dk

Received date: April 5, 2016; **Accepted date:** May 2, 2016; **Published date:** May 6, 2016

Copyright: © 2016 Geng B, et al. This is an open-access article distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited.

Abstract

This study aimed to investigate the human ability in discrimination of spatial and temporal parameters in electrocutaneous stimulation. Three surface electrodes were positioned on the ventral forearm of 14 able-bodied subjects. The subjects were instructed to discriminate between: (1) six different stimulation sites or site pairs, or (2) five different stimulation frequencies, or (3) hybrid parameters including both stimulation site and frequency, in three respective experiments. The results showed that two-site discrimination had a significantly lower success rate than one-site discrimination with a mean difference up to 12.1% ($p<0.01$). Temporal (frequency) discrimination appeared more challenging compared to spatial (site) discrimination. Moreover, the female subjects' performance was noticeably better than the males in all the three discrimination tasks with the mean difference up to 11.9% ($p<0.01$), 15.4% ($p<0.01$), and 16.7% ($p<0.001$), respectively. The findings may provide an insight into building an effective sensory feedback strategy in relation to development of functional hand prostheses and treatment of phantom limb pain.

Keywords: Sensory discrimination; Sensory feedback; Electrocutaneous stimulation; Amputee rehabilitation

Introduction

Electrical stimulation of the human skin can evoke a sensation by directly activating sensory nerve endings or sensory fibers located in the dermis [1,2]. The quality and strength of the evoked sensation are dependent on various factors, for example, the amount of electric charge, stimulus waveform, frequency, electrode size and material, stimulation site, skin thickness and degree of hydration [3,4]. Altering the value of appropriate parameters may possibly modulate and control the evoked sensation.

The electrically evoked sensation can be employed as sensory feedback in hand prostheses to improve the performance of prosthetic control and enhance agency of an artificial hand [5, 6]. While creating natural, intuitive sensory feedback to amputees is still very challenging, the approach that a sensory dimension (e.g., grip force) is encoded in a stimulation parameter (e.g., current amplitude), has often been used. By this approach, the prosthesis users learn to discriminate stimuli and mentally link different sensations, resulted from modulation of one or more stimulation parameters, with certain information. A number of studies have demonstrated that this encoding-based feedback increased the level of users' confidence in using hand prostheses and improved the incorporation of prostheses into body image [7-10].

The feasibility of an encoding scheme is highly dependent on the form of the feedback and the choice of the stimulation parameter to be varied. Therefore, the capability of discrimination between stimuli varied with respect to different parameters has been investigated in both able-bodied and amputee subjects. Christian et al. assessed the correct rate of discriminating between 2 levels of air-mediated pressure and 3 sites on the stumps of 12 trans-radial amputees and the forearms of 20 healthy subjects [11]. Another recent study examined the ability of healthy subject in discriminating vibrotactile stimulations on 3 forearm sites, and 3 amplitude discrimination, as well as discrimination of frequency-amplitude combinations [12]. These studies provided further evidence that encoding cutaneous stimulation information into haptic feedback could be a useful tool to enhance prosthesis use.

Apart from application in sensory feedback for prostheses, discrimination of external stimulations has also been used for sensory training to relieve phantom limb pain. Phantom limb pain has been found closely associated with cortical reorganization in the primary somatosensory zone [13,14]. External stimulation of the nerve stump can generate input to the cortical amputation zone. Providing intense behaviorally relevant sensory training may reverse the cortical reorganization and consequently alleviate phantom pain [15,16]. In an early study, amputee patients with phantom limb pain were trained with discrimination of location and frequency of electrical stimulation applied to the amputation stump. After two weeks training, the patients' discrimination ability was improved, accompanying with a significant decrease of phantom limb pain and reverse of cortical reorganization [17].

The aforementioned two applications of sensory discrimination (i.e., information encoding for prostheses and sensory training for phantom limb pain suppression), may be folded in one prosthetic device for amputees. A recent study provides important evidence showing that training with the use of a hand prosthesis that supplied encoding-based sensory feedback on grip force was effective in alleviation of phantom limb pain [18]. The aim of the present work is to examine a sensory discrimination scheme potentially suitable for both applications. The human ability of discriminating spatial and temporal parameters in electrotactile stimulation was evaluated in able-bodied subjects. The ultimate goal is to explore an effective sensory feedback strategy for hand prostheses, which can encode information, in the meantime suppress phantom limb pain.

Methods

Subjects

Fourteen able-bodied subjects (7 females and 7 males, aged 23-27 years, mean 24.4 years) participated in the study. All participants had no visible skin diseases in the arm and no known history of neurological disorders. Informed consent was obtained from all individual participants included in the study. The protocol was approved by the North Denmark Region Committee on Health Research Ethics (no. N-20110063) and have been performed in accordance with Declaration of Helsinki.

Experimental setup

A description of stimulation setup can be found in our previous study [17]. Three self-adhesive solid gel surface electrodes (Ambu Neuroline 700, skin contact size 20 mm × 15 mm) were positioned 5 cm distally to the elbow crease on the ventral aspect of the right forearm (Figure 1). The inter-electrode distance was 40-50 mm depending on the individual forearm sizes. The three electrode sites are referred to as S1, S2, and S3, respectively. A return electrode with a bigger contact area (PALS Platinum, 40 mm × 64 mm) was attached over the dorsal aspect of the wrist. The skin was cleaned with an alcohol pad to improve electrical conductivity. Gently shaving was applied when needed.

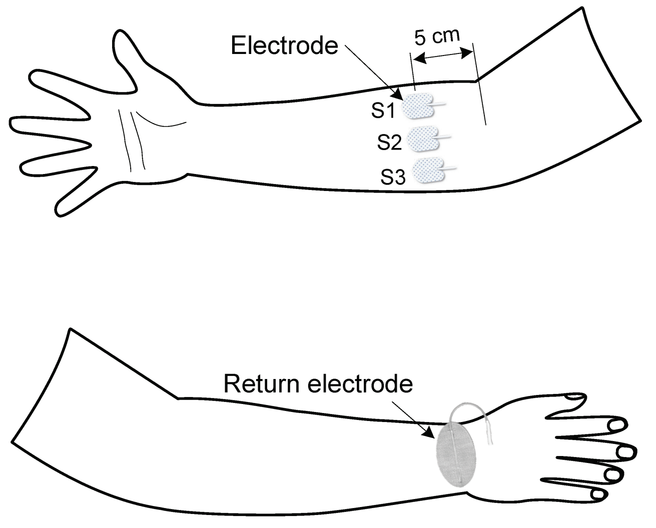


Figure 1: Placement of three active electrodes and return electrode on the forearm.

The waveform of stimuli was symmetric, rectangular, biphasic (positive following negative, 100 µs for each phase). The duration of each stimulus was 1 second. To determine the current amplitude to be used in sensory discrimination, sensory threshold for each stimulation site was first measured. The current amplitude for the three stimulation sites was then independently determined, ensuring similar strength of perceived sensation, that is, a score of 3-5 out of an 11-point numerical scale (0-no sensation, 10-upper limit of sensation). In the case of two-site stimulation, the current amplitude was individually tuned in order for the subjects to feel similar strength at the two sites. This procedure was done because the three sites usually had different sensory thresholds and the same current level could be perceived as different strength.

Experiment procedure

The experiment consisted of three parts: spatial discrimination, temporal discrimination, and hybrid discrimination, in which the subjects' discrimination performance was evaluated.

Spatial discrimination: Stimuli were delivered to a single site (i.e., S1, S2, S3) or simultaneously to a pair of sites (i.e., S1&S2, S1&S3, S2&S3). Once a stimulus was presented, the subject was asked to orally report in which site or site pair she/he perceived the stimulation. In total 60 evaluation trials with each site or site pair repeated 10 times were given to the subjects in a random order. To familiarize the subjects with the sensations related to stimulation at different sites or site pairs, a training session was provided before evaluation. A detailed description of training procedure can be found from our previous study [17]. All stimuli were delivered at a fixed frequency of 28 Hz. The performance was measured as the percentage of correctly recognized trials.

Temporal discrimination: Stimuli were delivered at five different frequencies: 10 Hz, 17 Hz, 28 Hz, 48 Hz, and 80 Hz (referred to as frequency level 1 to 5), logarithm distributed between 10 Hz and 80 Hz. This range was chosen because the just noticeable difference is relatively small in this range according to a previous study [18]. Once a stimulus was presented, the subject was asked to report the frequency level (1 to 5) that he/she perceived. In total 50 evaluation trials with each frequency repeated 10 times were given to the subject in a random order. A training session was carried out prior to evaluation. All stimuli were delivered to the site S1. Likewise, the percentage of correctly recognized trials was measured.

Hybrid discrimination: Stimuli at the above-described five frequencies were delivered to a single site (i.e., S1, S2, or S3). Thus, a number of 15 frequency-site combinations were used for evaluation. In total 60 evaluation trials with each combination repeated 4 times were given to the subjects in a random order. Once a stimulus was presented, the subject was asked to orally report both the site and frequency level that she/he perceived. The subject's answer was considered correct only if both site and frequency were successfully recognized. Again, a training session was provided prior to evaluation.

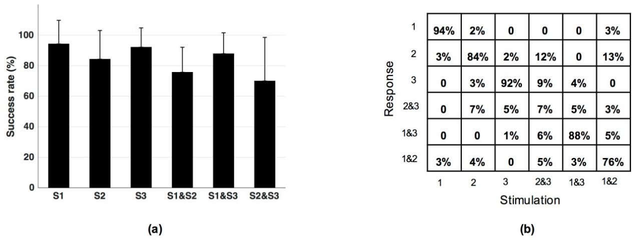
Statistical analysis

Paired *t-test* was used to compare the performance in one-site and two-site discrimination. Two-way ANOVA was used to test the effect of frequency and stimulation site on the performance in frequency discrimination. Paired *t-test* was also used to compare the performance between discrimination of frequency and stimulation site alone and discrimination of frequency together with site. Two-sample *t-test* was used to compare the performance between the female subjects and male subjects in the three discrimination tasks, respectively. Shapiro-Wilks test was utilized to analyze the data normality. For ANOVA, Levene's test was used to analyze the homogeneity of variance of the data.

Results

Spatial (site) discrimination

The overall performance in spatial discrimination was 83.9 ± 15.6%. The performance in discrimination of one site was 90.0 ± 12.8%, and 77.9 ± 16.2% in discrimination of two sites. Paired *t-test* indicated a significant difference between one-site and two-site discrimination ($p<0.01$). Figure 2a shows the success rate of discrimination of individual sites or site pairs. It appeared that the sites or site pairs involving S2 are associated with a lower success rate. Figure 2b gives a confusion matrix for site discrimination. It shows that the site pairs S1&S2 and S2&S3 were most frequently misrecognized. Both were most confused with S2.

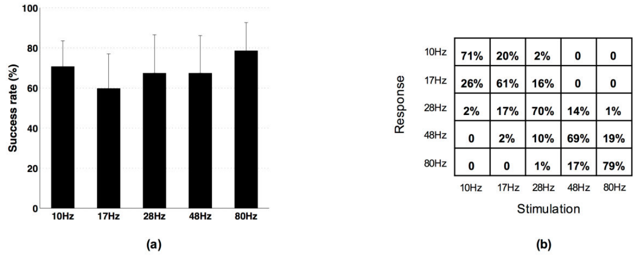


	1	2	3	2&3	1&3	1&2
1	94%	2%	0	0	0	3%
2	3%	84%	2%	12%	0	13%
3	0	3%	92%	9%	4%	0
2&3	0	7%	5%	7%	5%	3%
1&3	0	0	1%	6%	88%	5%
1&2	3%	4%	0	5%	3%	76%

Figure 2: Performance in spatial discrimination. a) Success rate for discrimination of six respective stimulation sites or site pairs. b) Confusion matrix.

Temporal (frequency) discrimination

The overall performance in temporal discrimination was 68.4 ± 13.8%. The frequency discrimination performance at individual sites was 66.6 ± 16.0% (S1), 70.0 ± 16.5% (S2), and 68.6 ± 16.4% (S3), respectively. Two-way ANOVA test indicated no significant effect of either frequency or stimulation site on the performance in frequency discrimination. Figure 3a shows the success rate of discrimination of individual frequencies. It appeared that the 10 Hz and 80Hz were associated with better performance, most likely because there is only one neighboring frequency to these two individual frequencies. Figure 3b gives a confusion matrix for discrimination of the five frequencies. It was not surprised that a particular frequency was mostly misrecognized by its neighboring frequencies.



	10Hz	17Hz	28Hz	48Hz	80Hz
10Hz	71%	20%	2%	0	0
17Hz	26%	61%	16%	0	0
28Hz	2%	17%	70%	14%	1%
48Hz	0	2%	10%	69%	19%
80Hz	0	0	1%	17%	79%

Figure 3: Performance in temporal discrimination. a) Success rate for discrimination of the five respective frequencies. b) Confusion matrix.

Hybrid (both site and frequency) discrimination

The average success rate in discrimination of both site and frequency was 69.8 ± 17.1%. The success rate of frequency and location discrimination was 70.7 ± 17.5% and 99.1 ± 1.6%, respectively. The rate of misrecognition of both parameters was only 0.4 ± 0.7%, suggesting that frequency discrimination contributed most to the misrecognition rate. Paired *t-test* indicated no significant difference in the performance between discrimination of frequency alone and discrimination of frequency together with location. In other words, discrimination of frequency alone seemed not influenced by the need of discrimination of an additional parameter (i.e., site). Paired *t-test* showed that site discrimination performance was significantly improved ($p<0.001$) in hybrid task compared to discrimination of location alone, largely because only three single-site locations were involved in this task.

Gender difference

The performance was compared between the female and male subjects. In all the three discrimination tasks, the females consistently achieved higher success rate than the males. Results of *t-test* for each of the three tasks indicated a significant gender difference in discrimination success rate with the mean difference up to 11.9% (location), 15.4% (frequency), and 16.7% (hybrid), respectively. Figure 4 shows the group mean and standard deviations of success rate in the three discrimination tasks. It is interesting that, the average performance of the females was improved by 4.3% (but not statistically significant) in hybrid discrimination tasks compared to discrimination of frequency alone, but nearly the same in the case of males.

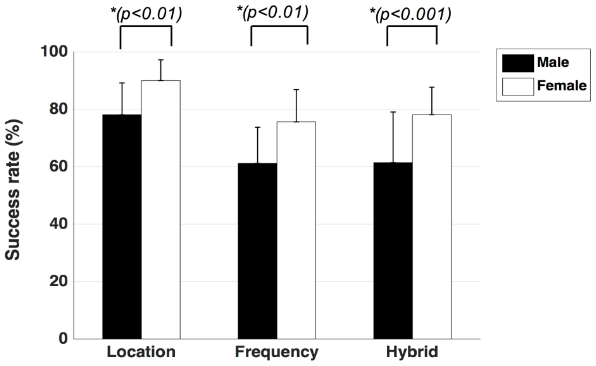


Figure 4: Performance in discrimination of spatial, temporal, and hybrid stimulation parameters for the female and the male group.

Variation between subjects

Typical subjects achieved the best performance in spatial (site) discrimination, a noticeably lower success rate in temporal (frequency) discrimination, and a slightly better performance in hybrid discrimination than temporal discrimination. However, it is worthwhile to note the variation between subjects. Figure 5 shows the discrimination performance of four particular subjects in the three discrimination tasks. Subject 1 exhibited excellent discrimination ability in all three experiments with a typical performance profile. Subject 2 achieved the best performance in hybrid discrimination. Subject 3 obtained lowest success rate in spatial discrimination, while subject 4 got considerably higher success rate in spatial discrimination than the other two tasks. This relatively small group of subjects contributed substantially to the deviations of the results.

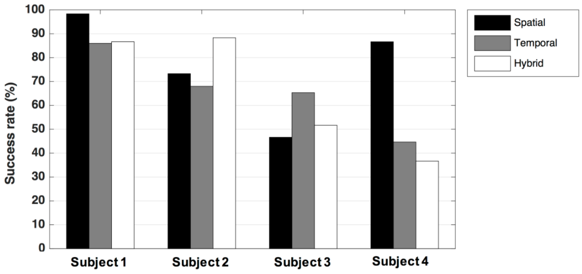


Figure 5: Discrimination performance of four particular subjects.

Discussion

The target population that the present study aimed to benefit is upper-limb amputee. In majority of upper-limb amputees, stimulation of the residual part of the arm can elicit phantom sensations referred to their missing hands (e.g. wrist, fingers, or joints [19-21]). Therefore, it was a natural choice to apply stimulation to the arm in relation to encoding sensory information of artificial hands, or providing input to the cortical region formerly representing the missing hand. The ventral forearm was chosen according to our previous finding that the ventral aspect has greater sensibility than the dorsal aspect [4]. It means that relatively smaller current amplitude is required to evoke moderate strength of sensation. Lower current level less likely produces motor activation, which should be minimized in the application of sensory feedback in prostheses.

During the experiment, we noticed that muscle twitch was more easily elicited in a few subjects than others. In this case lower current amplitude (i.e., score 3 out of 10 in the numeric rating scale) was used to minimize activation of motor neurons. For those subjects with a higher motor threshold, higher current level was used (i.e., score 5). Therefore, the subjects discriminated the evaluation stimuli based on different sensation strength. This may be one of the factors contributing to the relatively large standard deviations of discrimination performance. On the other hand, if muscle twitch was not minimized in the experiment, the discrimination performance is expected to be better since the subjects could distinguish stimuli based on a wider range of sensation quality.

The overall performance in spatial (i.e., site) discrimination was much better than temporal (i.e., frequency) discrimination (mean difference 15.5% and similar standard deviations). The human ability of discriminating another temporal parameter - the number of pulses - was investigated in our previous study [19]. Discrimination of the number of pulses achieved better performance than discrimination of frequency, suggesting that the former might be a more effective parameter to be modulated for sensory communication. However, frequency discrimination was highly dependent on the intervals between the selected frequencies. When the interval between two neighboring frequencies is adequately larger than the subjects' just noticeable difference, a better performance may be obtained. Besides, the number of frequency levels presented to the subjects also had an influence on the performance. A trade-off between the frequency range and the number of frequency levels is needed in order to approach the optimal sensory information coding by frequency modulation.

A training session was carried out before evaluation of the discrimination ability. We believe that this short-term training had a positive effect on the performance since this learning procedure enabled the subjects associate and interpret different stimulation frequencies or sites with particular sensations. It can be expected that a long-term training will further improve the discrimination performance. An early study demonstrated that an 8-9 days training improved the ability to perceive, interpret, and utilize information presented via the tactile sense by dual-channel electrocutaneous stimulation in healthy subjects [22]. Another study in amputee subjects demonstrated that the discrimination performance had been improved over a two-weeks training period [17].

Better discrimination performance in the females than the males suggested that females are likely more sensitive in both spatial and temporal modulation of electrical stimulation than males. During the procedure of determining stimulation amplitude, we found that the female subjects had lower sensation thresholds than the male subjects. The finding is in agreement with the results of our previous work [4] and a few other related studies [23,24]. Greater sensitivity might have contributed to overall better performance in the females. It should be noted that shaving applied more often to male subjects could have an impact on the perception and discrimination of stimuli. However, whether or not encoding-based sensory feedback in prostheses or sensory discrimination based treatment for phantom limb pain is more effective in female than male amputees remain to be further investigated.

Electrotactile and vibrotactile stimulation have their limitations due to unmatched sensation modality and relatively low selectivity in the application of sensory feedback for prostheses. These limitations to some extent have impeded the field to make significant progresses in recent decades. However, while promising neuron activation technology (e.g., direct nerve stimulation, targeted muscle reinnervation, and optogentics) are still at the early development stage, electrotactile and vibrotactile stimulation might remain non-invasive, economic alternatives. Moreover, integration of information encoding and sensory training in one prosthesis appears to be a promising solution for upper-limb amputee rehabilitation, which bridges sensory feedback technologies to the field of pain rehabilitation.

Conclusions

Development of functional prostheses and treatment of phantom limb pain are among the major concerns in amputee rehabilitation. Encoding sensory information by modulating electrical stimulation parameters remains a promising solution in spite of its constraints. Sensory training aiming for remodeling of brain circuits is still lacking of both neurophysiological and clinical evidence. Combination of sensory feedback in prostheses and sensory training in rehabilitation of phantom limb pain might be a new perspective to address the two concerns for amputees.

Acknowledgement

This work was funded by EU FP7 EPIONE project (no. 602547) and Danish council for independent postdoc project 'Multi-modality sensory feedback for phantom limb pain treatment' (no. 1337-00130B).

Conflict of Interest

The authors declare that they have no conflict of interest.

References

1. Szeto AY, Saunders FA (1982) Electrocutaneous stimulation for sensory communication in rehabilitation engineering. IEEE Trans Biomed Eng 29: 300-308.
2. Pfeiffer EA (1968) Electrical stimulation of sensory nerves with skin electrodes for research, diagnosis, communication and behavioral conditioning: a survey. Med Biol Eng 6: 637-651.
3. Kaczmarek KA, Webster JG, Bach-y-Rita P, Tompkins WJ (1991) Electrotactile and vibrotactile displays for sensory substitution systems. IEEE Trans Biomed Eng 38: 1-16.
4. Geng B, Yoshida K, Petrini L, Jensen W (2012) Evaluation of sensation evoked by electrocutaneous stimulation on forearm in nondisabled subjects. J Rehabil Res Dev 49: 297-308.
5. Schmidl H (1977) The importance of information feedback in prostheses for the upper limbs. Prosthet Orthot Int 1: 21-24.
6. Scott RN, Brittain RH, Caldwell RR, Cameron AB, Dunfield VA (1980) Sensory-feedback system compatible with myoelectric control. Med Biol Eng Comput 18: 65-69.
7. Peerdeman B, Boere D, Witteveen H, in 't Veld RH, Hermens H, et al. (2011) Myoelectric forearm prostheses: state of the art from a user-centered perspective. J Rehabil Res Dev 48: 719-737.
8. Patterson PE, Katz JA (1992) Design and evaluation of a sensory feedback system that provides grasping pressure in a myoelectric hand. J Rehabil Res Dev 29: 1-8.
9. Prior RE, Lyman J, Case PA, Scott CM (1976) Supplemental sensory feedback for the VA/NU myoelectric hand. Background and preliminary designs. Bull Prosthet Res Fall: 170-191.
10. Shannon GF (1979) A myoelectrically-controlled prosthesis with sensory feedback. Med Biol Eng Comput 17: 73-80.
11. Antfolk C, Björkman A, Frank SO, Sebelius F, Lundborg G, et al. (2012) Sensory feedback from a prosthetic hand based on air-mediated pressure from the hand to the forearm skin. J Rehabil Med 44: 702-707.
12. Cipriani C, D'Alonzo M, Carrozza MC (2012) A miniature vibrotactile sensory substitution device for multifingered hand prosthetics. IEEE Trans Biomed Eng 59: 400-408.
13. Ramachandran VS, Stewart M, Rogers-Ramachandran DC (1992) Perceptual correlates of massive cortical reorganization. Neuroreport 3: 583-586.
14. Chen R, Cohen LG, Hallett M (2002) Nervous system reorganization following injury. Neuroscience 111: 761-773.
15. Flor H (2002) The modification of cortical reorganization and chronic pain by sensory feedback. Appl Psychophysiol Biofeedback 27: 215-227.
16. Lotze M, Grodd W, Birbaumer N, Erb M, Huse E, et al. (1999) Does use of a myoelectric prosthesis prevent cortical reorganization and phantom limb pain? Nat Neurosci 2: 501-502.
17. Flor H, Denke C, Schaefer M, Grüsser S (2001) Effect of sensory discrimination training on cortical reorganisation and phantom limb pain. Lancet 357: 1763-1764.
18. Dietrich C, Walter-Walsh K, Preissler S, Hofmann GO, Witte OW, et al. (2012) Sensory feedback prosthesis reduces phantom limb pain: proof of a principle. Neurosci Lett 507: 97-100.
19. Geng B, Jensen W (2014) Human ability in identification of location and pulse number for electrocutaneous stimulation applied on the forearm. J Neuroeng Rehabil 11: 97.
20. Anani AB, Ikeda K, Korner LM (1977) Human ability to discriminate various parameters in afferent electrical nerve stimulation with particular reference to prostheses sensory feedback. Med Biol Eng Comput 15: 363-373.
21. Ramachandran VS, Hirstein W (1998) The perception of phantom limbs. The D. O. Hebb lecture. Brain 121: 1603-1630.
22. Szeto AY, Chung YM (1986) Effects of training on human tracking of electrocutaneous signals. Ann Biomed Eng 14: 369-381.
23. Maffiuletti NA, Herrero AJ, Jubeau M, Impellizzeri FM, Bizzini M (2008) Differences in electrical stimulation thresholds between men and women. Ann Neurol 63: 507-512.
24. Racine M, Tousignant-Laflamme Y, Kloda LA, Dion D, Dupuis G, et al. (2012) A systematic literature review of 10 years of research on sex/gender and experimental pain perception-part 1: are there really differences between women and men. Pain 153: 602-618 .

This article was originally published in a special issue, entitled: **"Neuroscience and Rehabilitation",** Edited by Fuminari Kaneko, Sapporo Medical University, Japan and Tadayoshi Asaka, Hokkaido University, Japan