2021 43rd Annual International Conference of the
IEEE Engineering in Medicine & Biology Society (EMBC)
Oct 31 - Nov 4, 2021. Virtual Conference

Modulation of sensation intensity in the lower limb via Transcutaneous Electrical Nerve Stimulation

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Abstract— **Commercially available lower limb prostheses do not restore sensory feedback in amputees. Literature suggests that Transcutaneous Electrical Nerve Stimulation (TENS) is a valid non-invasive, somatotopic technique to elicit tactile sensations, but no studies have been performed to investigate the capability of discriminating stimulus intensity via TENS in the foot. The aim of the study is to investigate how TENS can be used in order to restore sensations in the lower limb with different levels of intensity. Two experimental protocols were developed and tested on 8 healthy subjects: Mapping protocol is addressed to a fully characterization of the evoked tactile sensations; the Stimulus Intensity Discrimination one aims at investigating the best stimulation parameter to modulate for allowing the recognition of different levels of intensity. The results showed how elicited sensations were mostly described as an almost natural and superficial. A variation of the referred sensation (from nothing to vibration) and its intensity (ρ=0.6431) occurred when a higher quantity of charge was injected. Among the three modulated stimulation parameters, Pulse Amplitude (PA) has the best performance in terms of success rate (90%) and has a statistically significant difference with Pulse Frequency (PF) ($P_{PA\text{-}PF}$ = 0.0073<0.016). In the future, PA modulation will be tested on a larger number of healthy subjects and on amputees.**

I. INTRODUCTION

Every year more than 500.000 lower limb amputations occur in the world. In Italy about 1.000 individuals suffered from lower limb loss each year [1]. Current lower limb prostheses support walking, bending the knee joint, absorbing stance during walking, but they do not provide sensory feedback to the user [2]. The lack of sensory feedback causes an high risk of falls, low embodiment of the prosthesis and an increase of the physical and cognitive effort. These factors lead to an abandoning rate of a lower limb prosthesis of 60% [3]. Because of the aforementioned reasons, several solutions have been proposed in literature to restore sensory feedback in lower limb amputees.

Invasive techniques have allowed the elicitation of proprioceptive and tactile sensation in amputees increasing both walking speed and prosthesis embodiment, decreasing physical and mental fatigue [4]. Despite the good results, the proposed approaches present disadvantages related to invasiveness due to surgery, fibrotic reaction and weak long-term stability. Different non-invasive methods have been also tested. Although the obtained benefit in terms of gait symmetry and stability, most non-invasive systems are non-somatotopic since the elicited sensation is not felt in the missing leg but locally on the stump [5][6]. Conversely, the use of somatotopic approaches has to be preferred because of the intuitiveness, which allows for immediate and effortless integration of the feedback within the prostheses [7].

To this regard, Transcutaneous Electrical Nerve Stimulation (TENS) is a valid alternative since it uses superficial electrodes placed on the skin to electrically stimulate the underlying nerves evoking referred tactile sensations. The efficacy of TENS has been demonstrated in delivering touch and pain sensation [8][9] in upper limb amputees, allowing the recognition of objects' stiffness, shape and surface [10][11] during grasping with a prosthetic hand showing its efficacy in upper limb closed-loop prosthesis [12][13]: however, the use of TENS on lower limbs has not been deeply investigated, yet. It was only demonstrated its feasibility in eliciting haptic sensations in the missing foot of five transtibial amputees [14].

In this study two experimental protocols were developed and tested on 8 healthy subjects: the Mapping protocol is addressed to a fully characterization of the evoked tactile sensations and the Stimulus Intensity Discrimination protocol aims at investigating which is the best parameter allowing the recognition of different levels of intensity. The final purpose of this paper is to investigate how TENS is able to restore sensation in the lower limb with different level of intensities.

The paper is organized as follows: Section II describes the experimental setup and protocol. Section III reports and discusses results and Section IV is dedicated to conclusions and future work.

II. MATERIALS AND METHODS

A. Experimental setup

8 healthy subjects (3 males and 5 females) with a mean age of 27.0±1.8 years were recruited for the study. The study was authorized by the Ethic Committee of Università Campus Bio-Medico di Roma in accordance with the Helsinki Declaration.

The experimental setup is represented in Fig.1.A. It was composed of a proprietary control software and electrical stimulator (1 and 2), two superficial electrodes (3) and a Graphic User Interface (GUI) (4).

The electrical stimuli were delivered by a fully programmable stimulator (STG4008, Multichannel System MCS

This paper was partly supported by the European Union's Horizon 2020 research and innovation programme under grant agreement No 899822 (SOMA project), and partly by INAIL prosthetic center with the WiFi MyoHand project (CUP: E59E19001460005) .

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GmbH, Reutlingen, Germany). The proprietary software (MC_Stimulus II) of the stimulator allows generating arbitrary waveforms. Two square (50 mm side) commercial auto-adhesive and superficial electrodes (TensCare Ltd, Epsom, United Kingdom) were applied on the subject's left leg to stimulate the tibial nerve. The choice of stimulating the left leg rather than the right one has been arbitrary due to the symmetry of the human body with respect to the sagittal plane. A symmetric biphasic square wave was used because it prevents galvanic processes that can cause tissue damage and it is the most used in literature [8]-[15]. The stimulation parameters taken into account are the Pulse Amplitude (PA), the Pulse Width (PW) and the Pulse Frequency (PF). During the experimentation the subject sat in a chair in a comfortable position with his/her left leg in a rest position. A custom-developed GUI implemented in C# was used to record the main features of the elicited sensations in the foot: the naturalness, the depth, the quality, the intensity of the sensation and pain. The naturalness was assessed using five-point scale ranging from unnatural to natural. The depth was assessed choosing between superficial, deep and both [16]. In order to asses the quality of the sensation, the subject was able to choose one or more options selected on the basis of a previous study [8]. The intensity and the pain of the sensation were reported in a scale from 0 to 10. Moreover, the subject has to indicate the location of the sensation using two pictures representing the foot instep and sole. The elicited in-loco sensation has not been recorded since the optimal electrodes positioning evoked a negligible local sensation.

The experimental protocol is composed of two main sections: the Mapping protocol and the Stimulus Intensity Discrimination protocol.

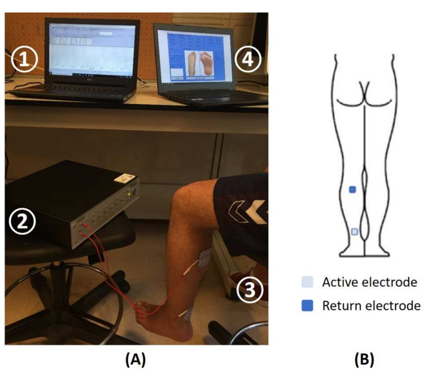

Fig. 1: A Experimental setup: proprietary control software and electrical stimulator (1 and 2), two superficial electrodes (3) and a graphic user interface (4); **B** Electrodes positioning.

B. Mapping protocol

The Mapping protocol was composed of three phases: electrodes positioning, charge and frequency modulation.

The first phase was aimed at identifying the optimal position of the electrodes along the superficial path of the tibial nerve. In this phase, the following parameters have been used: PW=500 μs, PF=500 Hz and the PA was incremented from 1 mA with a step of 0.1 mA until a value of PA at which the subject reported a well-defined and comfortable sensation. This value of amplitude is above the sensation threshold, below the motor one and was kept constant during the whole Mapping protocol.

In the second phase, a charge modulation was carried out. PF was fixed at 150 Hz and the PW was varied in the range 100 - 500 μs with a step of 40 μs between a stimulus and the following one. At the end of the modulation, PW_m was selected. PW_m is a value of PW at which the reported sensation intensity was at least 3.

In the last phase, a frequency modulation was carried out. PW was settled to PW_m and the PF was varied in the range 50 - 500 Hz with a step of 50 Hz from 50 to 200 Hz and a step of 100 Hz from 200 to 500 Hz between a stimulus and the following one. The stimulation duration was settled to 1 s and kept constant during Mapping protocol.

In accordance to the results obtained in this phase, three levels of intensities (low, medium and high) for each parameter (PA, PW and PF) and for each subject were chosen.

C. Stimulus Intensity Discrimination protocol

The Stimulus Intensity Discrimination protocol was divided into two phases: familiarization and validation.

During familiarization, each level of intensity of a single parameter was delivered for two times in a predefined order (low-medium-high). During validation, each level of intensity of a single parameter was provided for ten times in a random way. The subject, blindfolded and acoustically shielded, had to recognize the level of stimulus intensity and said it orally. This protocol was repeated in the same way for the PA, PW and PF (90 trials in total for each subject) in a random order. During the modulation of one parameter, the other two were kept constant to their highest values: in this way it will be guaranteed the elicitation of a well-defined sensation for each intensity. The stimulation duration was settled to 1 s and kept constant among all the trials.

III. RESULTS AND DISCUSSION

A. Mapping results

In this section, the results obtained during the Mapping protocol are reported.

The mean value of maximum current amplitude delivered to the participants was 8.7±1.2 mA. During the whole protocol, sensations were mainly described as almost natural for charge modulation (40%) and possibly natural (38%) for the frequency one. The stimulation evoked mostly superficial and painless sensations described as tingling, vibration and a mix of them: 27%, 4%, 22% and 25%, 11%, 42% for charge and frequency modulation, respectively.

Fig.2 shows, for all the involved subjects, the relationship between the injected charge and the perceived quality, whereas Fig.3 shows the connection between the injected charge and the referred sensation intensity. When a higher quantity of charge is injected, a variation of the perception (from nothing to vibration) occurred. A similar behaviour is reported also for the relationship between injected charge and referred sensation intensity (ρ=0.6431, Pearson coefficient).

The Weber fraction was calculated in order to estimate subjects' capability to distinguish among different stimuli [17]. It is equal to 0.16±0.08 and it is in accordance with another study regarding PW modulation of transcutaneous electrical stimulation [18].

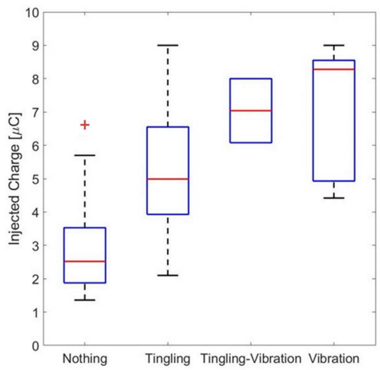

Fig. 2: Relationship between the injected charge and the perceived quality. The + sign represents the outlier.

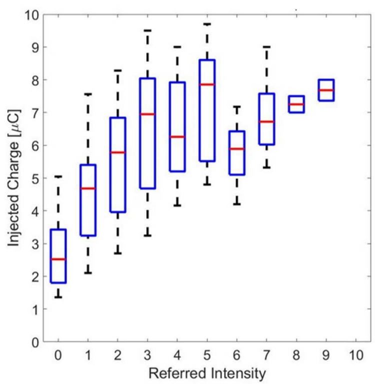

Fig. 3: Relationship between the injected charge and the referred sensation intensity during charge modulation.

The elicited regions experienced during the charge and frequency modulation of the tibial nerve stimulation are represented in Fig.4. The regions referred by the subjects were overlapped in order to obtain a single picture indicating the mean region reported for three different levels of the stimulus intensity.In order to evaluate the inter-subjects variability, the Structural Similarity Index (SSIM) [0-1] was reported in Fig.4 and it resulted more than 0.75 for each condition [19]. Morover, it was analysed the variation of the size of the elicited region between the three levels of stimulus intensity. In particular, between the minimum and the maximum level of intensity, a mean increase of 70% and 30% of the referred area was respectively reported for PW and PF modulation. The variation of elicited regions was not analysed for the insteps because the subjects mostly referred not sensations in this area.

B. *Stimulus Intensity Discrimination results*

During the Stimulus Intensity Discrimination protocol, the subject had to recognize the perceived level of stimulus intensity. A Success Rate (SR) was introduced to evaluate

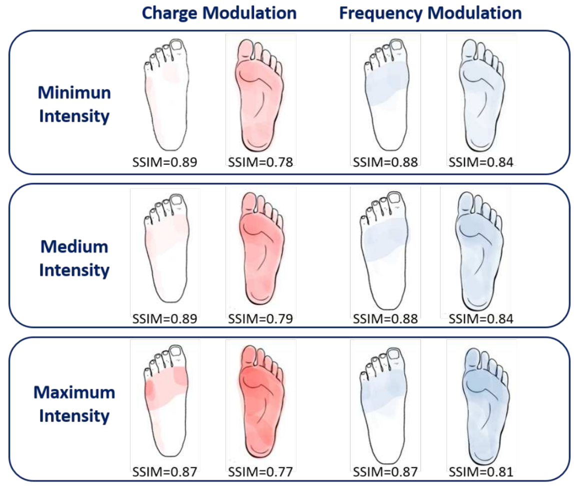

Fig. 4: Regions reported by the subjects after the charge (red) and frequency (blue) modulation. The areas depicted with a more vivid colour indicate the regions with a higher number of occurrences than others. Minimum intensity is PW=260 μs and PF=100 Hz; medium intensity is PW=380 μs and PF=300 Hz; maximum intensity is PW=500 μs and PF=500 Hz. The mean SSIM among the subjects is reported for each of 12 regions [0-1].

the number of times the subject correctly discriminate the level of intensity (low, medium or high) for each stimulation parameter. Fig.5 report the normalized confusion matrices of the SRs of PA (A), PW (B) and PF (C) modulation.

Confusion matrices show the promising results of the stimulus intensity discrimination during PA and PW modulation: more than 80% in the former and 73% in the latter for each level. In PF modulation, low level discrimination presents good accuracy. Conversely, worst results are obtained for medium and high level discrimination ($P_{\text{low-high}}$ = 0.0017<0.016 and $P_{\text{low-med.}}$ = 0.0693>0.016, Mann–Whitney U test with Bonferroni correction). This bad performance could be due both to difficulties encountered by the subjects already during the familiarization phase and to a greater adaptation phenomenon caused by PF with respect to PA and PW as already noticed in literature [20]. This is confirmed in Fig.6 where the median success rates among all the subjects are represented. PA modulation is the technique with the best success rate (90%), followed by PW (80%) and PF (70%). The statistical analysis pointed out a significant difference between PA and PF ($P_{\text{PA-PF}}$ = 0.0073<0.016). No statistically significant differences were found for the other comparisons ($P_{\text{PA-PW}}$ = 0.4204>0.016 and $P_{\text{PW-PF}}$ = 0.0872>0.016).

The obtained results in discriminating stimulus intensity via TENS in the foot are in line with those regarding the upper limb. These achievements would lead to the employment of intensity modulation of PA or PW for converting force information in a electrical stimulus. This application is straightened by the already obtained results in upper limb prosthesis, which mostly apply PA [10][11] or PW [12][13] modulation for encoding algorithms to restore force feedback. For this reason, future studies will be devoted to the application of TENS for the development of a closed-loop lower limb prosthesis.

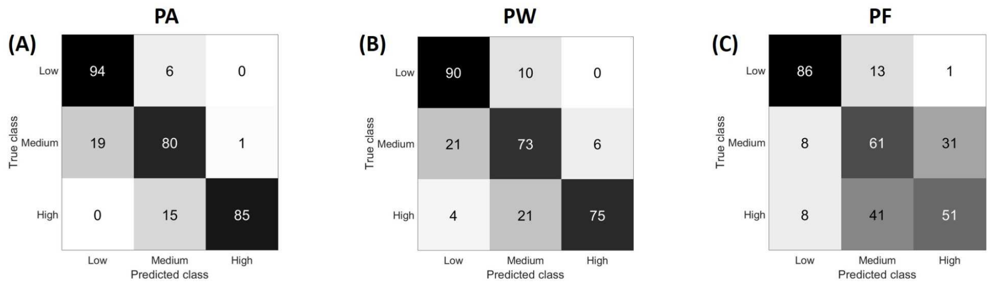

Fig. 5: Normalized confusion matrices of the SR of PA (**A**), PW (**B**) and PF (**C**) modulation.

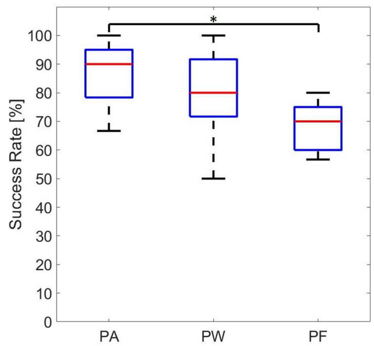

Fig. 6: Success Rate of the PA, PW and PF modulation. * indicates a statistically significant difference ($P_{PA\text{-}PF}$ = 0.0073<0.016, Mann–Whitney U test with Bonferroni correction).

IV. CONCLUSIONS

The final purpose of the study is to investigate how TENS can be used in order to restore sensation in the lower limb with different level of intensities.

The results of the Mapping protocol showed how TENS is able to elicit referred superficial and almost natural sensations in the foot. In terms of quality, the subjects mostly described them as a tingling. A variation of the perception (from nothing to vibration) occurred when a higher quantity of charge is injected. An analogue trend is reported also for the relationship between injected charge and referred sensation intensity (ρ=0.6431). The size of the elicited region proportionally increased with the stimulus intensity due to the increase of PW and PF in the two modulation phases.

The results of the Stimulus Intensity Discrimination protocol demonstrated how the subjects were able to discriminate three different levels of stimulus intensity. Among the three stimulation parameters modulation tested, PA has the best performance in terms of success rate: 90% compared to 80% and 70% of PW and PF, respectively. Moreover, a comparative analysis pointed out a statistically significant difference between PA and PF (Mann–Whitney U test with Bonferroni correction, $P_{PA\text{-}PF}$ = 0.0073<0.016). This preliminary study noticed how PA modulation is the best technique for restoring in the foot sensations with different intensities via TENS.

Further studies will be devoted to test a larger number of healthy subjects and transtibial amputees where the onset of dysmethabolic pathologies, the presence of scar tissue and the neural reorganization due to the amputation could modify the tissue impedance and thus the effectiveness of the whole system. Future improvements will make the system suitable for patients with different level of amputation and test it in static and dynamic settings in order to evaluate whether the elicited sensations in the foot depend on lower limb joint angle.

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Competition eligibility: *Student must be a current member of IEEE EMBS*

I. Nominee Information (student author contact information) by student's faculty advisor:

1.	Name of the Award: **EMBC 2021 SPC Award**	2.	Date of Nomination: July 30th, 2021
3.	Nominee (Student) Name: Andrea Demofonti	4.	IEEE EMBS Student Member No: 96129398
5.	Email address: a.demofonti@unicampus.it	6.	Telephone: 3392983258
7.	Present Affiliation: Research Unit of Advanced Robotics nd Human-Centred Technologies (CREO Lab), Università ampus Bio-Medico di Roma, Rome, Italy	8.	Paper Number: 1630
9	Paper Title: Modulation of sensation intensity in the lower limb via Transcutaneous Electrical Nerve Stimulation		
10.			YES, I wish to have my paper withdrawn in the event I am not selected as a Finalist
	✓		NO, I do NOT wish to have my paper withdrawn in the event I am not selected as a Finalist

II. Justification for Nomination: *(please do not exceed the space provided below)*

The lack of sensory feedback in commercially available lower limb prostheses is one of the main causes of their abandonment by the patients. Different invasive techniques (intraneural or epineural stimulation) have been proposed for the restoration of tactile information but they present drawbacks such as the need of an implant, the onset of a fibrotic reaction and a weak-long term stability.
In this study, the student proposes the use of a non-invasive strategy (Transcutaneous Electrical Nerve Stimulation, TENS) that has not been deeply analysed yet. The aim was to investigate how TENS is able to restore sensation in the lower limb with different level of intensities.
The student developed and tested on 8 healthy subjects two experimental protocols: the first is addressed to a fully characterization of the evoked tactile sensations and the second one aims at investigating the best stimulation parameter to modulate for allowing the recognition of different levels of intensity.
The obtained results show how TENS is able to elicit in the foot superficial and almost natural tingling whose intensity and region increase with the injected charge. Among the three modulated stimulation parameters, Pulse Amplitude (PA) has the best performance in terms of success rate (90%) and has a statistically significant difference with Pulse Frequency (Pulse Frequency).
Student's work is the first study concerning the stimulus intensity discrimination via TENS in the foot and it could pave the way to the development of encoding algorithms aiming at the conversion of ground reaction force exerted during gait and posture in a PA modulation.

III. Nominator (Advisor) Information

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