Model-based Transcutaneous Electrical Nerve Stimulation

Gloria Araiza Illan
EPSRC Centre for Doctoral Training in Future Autonomous and Robotic Systems
Bristol Robotics Laboratory
University of Bristol
Bristol, UK
Email: ga13414@bristol.ac.uk

Chris Kent
School of Experimental Psychology
University of Bristol
Bristol, UK

Jonathan Rossiter
Department of Engineering Mathematics
University of Bristol
Bristol, UK

Abstract—Transcutaneous electrical nerve stimulation (TENS) is a technique that allows the excitation of nerve fibres using electric-current pulses through electrodes on the skin. This work involves the development of an electrical stimulation simulation environment that can be used for studying and designing TENS systems, as well as defining the excitation patterns. Using an eight-electrode array implementation, it is shown how nerves located at different depths and with different orientations respond to specific injected currents, allowing the replication of reported experimental findings and the formulation of new hypotheses about the tactile sensations associated with certain stimulation patterns and selective nerve stimulation. The electrical stimulation simulation environment is compared to a documented mechanical stimulation simulation environment using the Generalized Victor-Purpura metric. Two sets of stimuli targeting selective nerve stimulation are developed in the simulation environment, validated through the aforementioned metrics and evaluated through psychophysical experiments using the hardware implementation of the TENS system.

I. INTRODUCTION

Tactile sensations, such as texture, pressure and vibration, result from the stimulation and activation of cutaneous mechanoreceptors, which transform the mechanical stimuli on the skin into electrical signals. It is known that once the receptor has been excited over a certain threshold (i.e. its membrane potential rises above a specific value), an action potential is induced and the signal is transmitted to the Central Nervous System (CNS).

Transcutaneous electrical nerve stimulation (TENS) is an established technique that has been used to study its effect, with different research purposes, when applied on different body parts in neuroscience, amongst which it is worth mentioning the production of tactile sensations in extremities [1], [2], [3], [4], [5]. TENS systems involve less complex hardware than mechanical stimulation systems, as well as lower production and maintenance costs. Controlling nerve selectivity in mechanisms based on TENS, offer the possibility to increase the amount of information that systems could supply for medical, teleoperation, industrial and gaming applications; i.e., providing haptic feedback. Human-machine interfaces, such as haptic feedback will enable multiple technologies to become more useful, intuitive and trustworthy.

This work involves the development of a TENS system in a simulation environment, its comparison with a mechanical stimulation system also in a simulated environment and the evaluation of the hardware implementation of the TENS system through psychophysical tests. The main objective is to study the dependency on the excitation patterns (electrical input) related to selective nerve stimulation and different tactile sensations.

II. METHODS

A. Electrical Stimulation Simulation Environment

The electrical stimulation (ES) simulation environment consists of a finite element electrical model (FEM) of a human finger developed in connected to a cable model-based representation of the nerve response. The FEM was developed using Elmer (https://www.csc.fi/web/elmer) and Gmsh (http://www.gmsh.info) software. The simulation environment the calculation of the behaviour of a nerve fibre when a specific distribution of stimulation currents are applied at the surface of the skin. The FEM has a cylindrical geometry and a spherical fingertip modelled to be in contact with an eight electrode array TENS system. The electrode spacing is 1 mm and each electrode has dimensions 1 mm×8.5 mm. The total sum of the currents is set to be equal to zero, constraint that ensures that no currents will flow deeply in the human body, which can lead to tissue damage [6]. The model provides a simultaneous visual representation and calculation of physical parameters for the evaluation and virtual prototyping of TENS systems.

The FEM is divided intro three main materials, each with a specific conductivity: bone, fat and skin. The skin is set to be dry and capacitive effects are neglected (they have been found to have a minor influence on nerve activation in TENS systems [5]. The model also has three nerve fibres, two of them set to run parallel to the skin (representing those connected to Merkel and Pacinian receptors) and one running perpendicular to the skin at first, to then change to run parallel to the skin (representing nerve fibres connected to Meissner receptors [7], [8]).

All myelinated nerve fibres are represented by the electrical cable model, describing the nerve membrane as an electri-


cal circuit. They are modelled as a cylinder divided into nodes of Ranvier. Each node is locally represented by the Hodgkin and Huxley (HH) equations with the corresponding modifications for myelinated fibres [9], which can simulate a cathodic block (effect that is of a particular interest in this work), unlike the Frankenhaeuser-Huxley (FH) equations [10]. The solution of the HH equations was found using MATLAB (https://uk.mathworks.com/), representing each fibre as a two-block Simulink system. One block corresponds to the compartment model based on the cable model and the second one implements the HH equations, feeding its results into the first block.

The validation of the ES simulation environment is achieved firstly by evaluating the local and overall effect of the electrodes on just one fibre running parallel to the skin, with a cathodic and anodic stimulation using two active electrodes. The second test involves the activation of all eight electrodes, using random current values within a range of ±5 mA (as an electrical safety constraint, for it is known that larger currents may result in pain and discomfort for the user, possibly leading to injuries [11], [12]). The final test is directed to study selective stimulation of the modelled fibres activating all eight electrodes.

B. Mechanical Stimulation Simulation Environment

The mechanical stimulation (MS) simulation environment consists of the integrate-and-fire model developed by Kim, Sripati and Bensmaia [13], implemented in MATLAB. This model replicates the properties of three mechanoreceptive afferents: slowly adapting type 1 (SA1) fibres, rapidly adapting (RA) fibres and Pacinian (PC) fibres of the macaque’s hand. Using this model, timing of individual spikes resulting from mechanical vibrations in any of the three aforementioned fibres, can be accurately predicted. The model outputs a spike train corresponding to the defined mechanical input.

C. Comparison Between the ES and MS simulation environments

The comparison between the ES and the MS simulation environments is achieved evaluating the spike trains that each model outputs through the Generalised Victor-Purpura (GVP) metric [14], [15]. Since the MATLAB solver for the HH equations used a variable step, a dynamic time warping technique was needed to compare both spike trains. The GVP metric is implemented in MATLAB as a kernel that maps the spikes in one of the trains to the spikes in the other train, penalising the unmatched spike times. The metric outputs the distance between the spike trains involving the minimum cost of transforming one spike train into the other.

Since the GVP metric allows fast clustering and dynamic programming algorithms, an optimiser is used to minimise the differences between the spike trains generated through ES and MS in the simulation environments. This is achieved by adjusting the values of the frequency and amplitude of the electrode currents to match the modelled response to specific simulated mechanical stimulation (selecting mechanical stimuli targeting the activation of fibres connected to Meissner and Pacinian receptors).

D. Hardware Implementation of the TENS System

In order to validate the results obtained from testing the ES simulation environment and the results from the comparison between the ES and MS simulation environments, the system physically implemented. The hardware to specifically drive the currents in each of the eight electrodes involves a digital to analog converter (DAC) and a voltage to current converter. The DAC circuit generates a digital pulse and amplifies before delivering it to the voltage to current converter. The voltage to current converter consists of a series of current mirrors that map the amplified pulse to a voltage range of ±200 V and ±5 mA.

E. Psychophysical Experiments

Two sets of stimuli targeting selective nerve stimulation are tested with five participants. One set is associated with the activation of a shallower fibre, while the other set is associated with the excitation of a deeper fibre. Two stimuli from each set are randomly selected to run a paired comparison test. The hardware is calibrated individually before running the paired comparison, finely tuning the amplitudes of all four stimuli so that the users can comfortably feel and distinguish them. The main aim of the experiments is to analyse whether the participants can differentiate and categorise them.

III. RESULTS

A. Validation of the ES Simulation Environment

Using two and eight active electrodes, the ES simulation environment showed that negative currents produce the depolarisation in the fibre and positive currents a polarisation. The overall effect of the injected currents through the eight electrodes can result in either the activation of the fibre (generating an action potential that will propagate towards the ending of the fibre, taken to go to the Central Nervous System), or the inhibition of the fibre.

Regarding the cases for selective stimulation, it was observed that when studying a fibre running parallel to the skin and one running firstly perpendicular and then parallel to the skin, the injected currents could be determined to selectively activate and/or inhibit the parallel one using an anodic and cathodic stimulation, but the fibre modelled with a first segment running perpendicular to the skin and then parallel to the skin was found to become activated with either of the stimuli. This case was based on the experimental findings by Yem and Kajimoto [16]. On the other hand, when analysing two fibres running parallel to the skin, motivated by experiments run by Kajimoto et al. [4], it was observed that the electrode currents could be arranged in such a way that one fibre would be activated while the other would be inhibited. The patterns of the injected currents were randomly created, to then form two sets to compare to the MS simulation environment and finally test in the ES hardware implementation.
B. Comparing the ES and MS simulation environments

The search for minimising the difference between the spiking trains produced by the ES and the MS simulation environments resulted in two clusters of specific stimuli, one targeting the excitation of a shallower fibre and one targeting the deeper fibre. The clusters contain different current arrays for the electrodes, but share common amplitudes and frequencies. From this data, the hypothesis of being able to produce different tactile sensations through electrical stimulation was formulated. In order to test it, the hardware implementation of the ES system was needed.

C. Psychophysical Experiments

The paired comparison test showed that the individuals could easily differentiate the two sets of stimuli, but could not easily distinguish the differences between two stimuli of the same set. They were also asked how they would better describe the produced sensation, and the response was that the stimuli from one set was very similar to a mechanical vibration, whereas the other set was perceived as a punctual warm and sharp object (resembling a needle).

IV. Conclusion

As demonstrated throughout the obtained results, the presented ES simulation environment is an important tool for studying and designing TENS systems, particularly regarding selective nerve stimulation. Despite the simplicity of the simulation environment, the cases involving selective stimulation proved the capacity and potential that the environment has. The GVP metric also demonstrated to be a significant method to compare time varying spike trains, which helped validating the ES model (matching its output to the documented MS model). Finally, the psychophysical tests showed that it is possible to produce different tactile sensations through electrical stimulation. It should be stated that these sensations do not necessarily have to be perceived exactly as those produced by a mechanical stimulation; however, the users can learn to associate them to specific information (e.g. visual cues, words, objects).

References