Proprioceptive feedback via dynamic stimulation patterns in closed-loop control of multi-DOF virtual prosthesis

Milica S. Isaković, Matija Štrbac, Minja Belić, Thierry Keller, *Member, IEEE*, and Strahinja Došen, *Member, IEEE*

***Abstract*—We present the system for evaluation of myoelectric control with electrotactile feedback in the closed-loop environment. This test bench was implemented in MATLAB Simulink, and relies on Mujoco HAPTIX virtual hand simulator and the Maxsens system for electrotactile stimulation. We selected a set of dynamic stimulation patterns to provide the user proprioceptive feedback from the multi-DOF virtual prosthesis regarding hand aperture and wrist rotation. The patterns were spatially coded and delivered to the user through a custom designed array electrode. Mujoco HAPTIX virtual reality hand simulator provided visualization of the prosthesis and task information. The results from the pilot test on one healthy subject suggest that the proposed dynamic patterns can be recognized with a high success rate and can be successfully exploited for controlling the extent of aperture and rotation of the multi-DOF myoelectric prosthesis.**

***Index Terms*—Electrotactile stimulation, array electrode, proprioceptive feedback, myoelectric control.**

I. INTRODUCTION

MYOELECTRIC prostheses can be used for partial restoration of motor functions lost after a hand amputation. The user can control the prosthesis by activating the wrist flexor and extensor muscles of the residual limb. The resulting electrical activity of activated muscles is recorded and converted into the control signals for the prosthesis [1]. An important drawback of the commercially available prostheses is the lack of somatosensory feedback, i.e. closing the control loop by transmitting the sensory information from the prosthesis. Providing the users with an artificial somatosensory feedback is considered essential for better integration and is stated as an important future goal by both the researchers and the users [2]. It could lead to improved control and the feeling of the embodiment, decrease of prosthesis rejection rate, and reduction of the phantom limb pain [3].

Different approaches have been proposed to restore missing somatosensory information [4]. The commonly employed approach is sensory substitution [5], based on collecting the sensory data from the prosthesis and delivering them to the user by activating remaining sensory structures. The most frequently used non-invasive methods include delivering feedback information by stimulating the skin over the residual limb using electrotactile [6, 7] or vibrotactile [7, 8] stimulation, or even combining them [9]. In the case of electrotactile stimulation [6, 7], tactile sensations are elicited by delivering low-intensity electrical current pulses to activate the skin afferents [10]. Information encoding can be achieved by modulating the stimulation parameters (i.e., pulse width, amplitude, and frequency modulation) and/or location of the active channel (spatial modulation). Spatial modulation requires the use of a multichannel interface [7], such as the one recently developed [11]. The stimulation parameters and active channels can be independently modulated, thus allowing the implementation of high-resolution multichannel interfaces with mixed information coding [12].

Most closed loop systems presented in previous studies investigated grasping force as a feedback variable [4]. The feedback on the grasping force assists the grasping process and improves the consistency of the force generation by providing the information that cannot be visually assessed. Additionally, it can be considered as an instrument for learning through repeated practice [13]. Nevertheless, proprioception is also necessary for the normal motor control [15] and could further increase the feeling of the embodiment. Some attempts to provide artificial proprioceptive feedback were made in the past [16] and also more recently [17], but far less compared to the studies investigating force feedback.

To provide real-time grasping force and proprioceptive feedback to prosthesis users, we developed a novel system for electrotactile stimulation including fully programmable stimulator, custom designed flexible electrodes and a set of dynamic stimulation patterns [11] communicating the state (proprioception and grasping force) of a multi-DOF

Milica S. Isaković is with the University of Belgrade – School of Electrical Engineering, 73 Bulevar kralja Aleksandra, 11000 Belgrade, Serbia and with Tecnalia Serbia Ltd, 13 Vladetina, 11000 Belgrade, Serbia (e-mail: isakovic@etf.bg.ac.rs).

Matija Štrbac is with Tecnalia Serbia Ltd, 13 Vladetina, 11000 Belgrade, Serbia and the University of Belgrade – School of Electrical Engineering, 73 Bulevar kralja Aleksandra, 11000 Belgrade, Serbia (e-mail: matija.strbac@tecnalia.com).

Minja Belić is with Tecnalia Serbia Ltd, 13 Vladetina, 11000 Belgrade, Serbia and the University of Belgrade, 1 Studentski trg, 11000 Belgrade, Serbia (e-mail: minja.n.belic@gmail.com).

Thierry Keller is with Tecnalia Research & Innovation — Health Division, 1 Mikeletegi Pasealekua, 20009 Donostia–San Sebastián, Spain (e-mail: thierry.keller@tecnalia.com).

Strahinja Došen is with Department of Neurorehabilitation Systems, Clinic for Trauma Surgery, Orthopedics and Plastic Surgery, University Medical Center Göttingen, 4 Von-Siebold-Straße, 37075 Göttingen, Germany (e-mail: strahinja.dosen@bccn.uni-goettingen.de).

prosthesis. The dynamic patterns, coded in an intuitive manner, were easy to adopt and identify by able-bodied subjects and transradial amputees [11, 18]. We employed the system for electrotactile stimulation for closing the loop in myoelectric control by providing the feedback on aperture and rotation of the Mujoco HAPTIX virtual hand [19]. In this manuscript we present the developed setup and the results of the pilot study on one healthy subject.

II. METHODS

A. System setup

The system setup comprised the following components: 1) multichannel EMG amplifier (INTEMG, OT Bioelettronica, Torino, IT), 2) multichannel electrotactile stimulation system (Maxsens, Tecnalia Research & Innovation, San Sebastian, ES), 3) a laptop PC (Intel(R) Core(TM) i5-4210U CPU at 1.70GHz, 6GB RAM), and 4) a 22" monitor. The block diagram of the system is presented in Fig. 1.

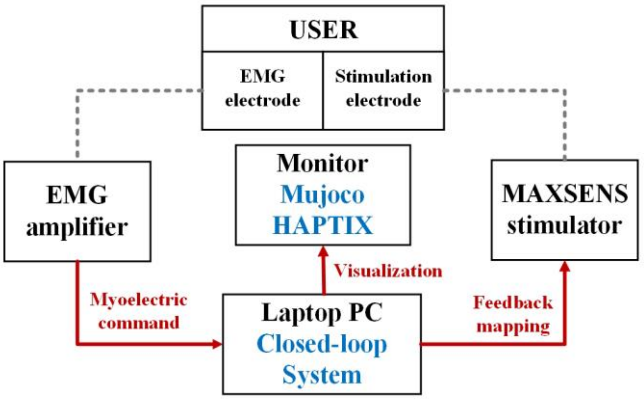

Fig. 1. A block diagram of the system setup. EMG amplifier records muscle activity of the user and gives out myoelectric commands to the virtual prosthesis simulated on the Laptop PC. Feedback on resulting movement of the virtual prosthesis is presented to the user in the form of electrotactile stimulation provided by the Maxsens stimulator.

EMG amplifier included four bipolar channels, two of which were used in the current study. The amplifier sampled the EMG signals at 1 kHz internally, segmented the data in 250ms windows with the 80% of overlap, calculated the mean absolute value (MAV) and sent it to the laptop PC via a USB connection. Standard pre-gelled Ag/AgCl electrodes (Skintact, Leonhard Lang GmbH, Innsbruck, AT) were used for recording EMG signals from the wrist flexor and extensor muscles in the bipolar configuration. Before placing the electrodes, the skin was prepared by applying a small amount of abrasive gel (everi, Spes Medica, IT).

The laptop PC ran the online control loop in the *Closed-loop System* - a flexible test bench for the evaluation of the human manual control systems, implemented using MATLAB Simulink (version R2016a, The MathWorks Inc., Natick, USA) and Real-Time Windows Target toolbox [19]. The simulated model of the prosthesis was implemented within the test bench, as a simple state machine emulating the prosthesis using an integrator (velocity-controlled system) or a pure gain (position-controlled system), depending on whether the prosthesis freely moves (closing/opening, rotation) or stalls (object contact), respectively. This reflects the operation of most of the myoelectric prostheses, and the model parameters have been adjusted using experimental data to emulate the operation of the Michelangelo Hand [12]. The test bench acquired the EMG signals from the amplifier, forwarded adequate commands to the simulated prosthesis, and based on the sensor data from the simulated prosthesis determined and updated feedback information, i.e. stimulation parameters for the electrotactile stimulator and/or Mujoco Haptix visualization.

The computer monitor was used for visualization of the prosthesis and providing task information and visual feedback to the subject, implemented using Mujoco HAPTIX virtual reality hand simulator [19]. The software is freely available at www.mujoco.org. This is an end-user product with full-featured GUI, which can be used as a generic simulator, or as a simulator customized for the needs of the DARPA Hand Proprioception & Touch Interfaces (HAPTIX) program. Mujoco HAPTIX provides the model of Modular Prosthetics Limb (MPL) [20].

The current state of the simulated prosthesis (aperture and rotation) was mapped to stimulation parameters and transmitted via Bluetooth to the stimulation system. The Maxsens system is a fully-programmable and integrated electrotactile interface comprising a stimulation unit and a flexible array electrode [11]. The electrotactile feedback was delivered to the user through the custom designed array electrode, which consisted of 16 circular cathodes and a single adjacent anode. It was designed to be placed circumferentially on the same forearm as the EMG electrode, 5 cm distal to the elbow joint. The size of the electrode was chosen in accordance with an average forearm circumference and the inter-pad distance satisfies the two-point discrimination threshold for electrical stimulation on the forearm [18]. The electrode was made of a polyester layer, an Ag/AgCl conductive layer, and an insulation coating covering the conductive leads. To improve the electrode-skin contact, the pads were covered with conductive hydrogel pads (AG730, Axelgaard, DK).

B. Dynamic stimulation patterns

The state of the prosthesis was communicated to the subject using the set of dynamic stimulation patterns presented in [11]. For the patterns to be intuitive, the design principle was to represent the spatial variables, such as rotation (pronation and supination) and aperture (opening and closing), using spatial coding. Furthermore, the spatial codes were designed so that they resemble the movement performed by the prosthesis.

The full range of the aperture (0 – 100%) was divided into four equal subranges i.e. aperture levels. Hand opening was represented by activating two pads starting in the center of the electrode (pads 8 and 9 – hand fully closed) and moving circumferentially further apart along the electrode (pads 5 and

12 – hand fully opened). Each pair of active pads represented an appropriate aperture level. Hand closing pattern was analogous to that for the hand opening, with opposite starting position and direction of movement of the active pads. Fully opened hand (pads 5 and 12) with null rotation was considered a neutral, starting state.

The full range of the rotation (-100 – 100%) was divided into nine equal subranges i.e. rotation levels. Wrist rotation was coded by activating two adjacent pads starting from the neutral state (active pads 5 and 12) and moving together clockwise or counter-clockwise to represent pronation or supination, respectively, until the end of the electrode.

The patterns were constructed so that they can be combined with one another, therefore providing feedback regarding two or more of the prosthesis states. For example, as the user closes the hand, the two electrodes come close together (aperture pattern). If the user then starts rotating the wrist, the two electrodes would start rotating around the forearm (rotation pattern) while maintaining the relative position (constant aperture).

The stimulation frequency was set to 20 Hz and the pulse width to 220 μs. The amplitude for each pad was individually calibrated to obtain clear and comfortable sensations of similar intensity for all feedback codes (force ranges).

C. Experimental protocol

The pilot tests were conducted on one healthy subject (female, 31 years, right-handed) with no known neuromuscular disorders. The subject was comfortably seated at the table, with the laptop PC and the monitor positioned in front of her. The EMG electrodes were placed on the wrist flexor and extensor muscles of the subject's dominant arm, and the stimulation electrode was positioned above them (closer to the elbow) on the same forearm.

The beginning of the experiment included EMG setup and a short training of myoelectric control. The subject was asked to perform the maximal voluntary contraction (MVC) of wrist flexor and extensor muscles, and the gains of the EMG electrodes were set so that the electrode output saturated at approximately 60% of MVC. During the EMG training, the subjects had the task to modulate the myoelectric signals in order to track a reference trapezoidal profile shown in real time on the monitor (pursuit tracking task [12]).

The myoelectric control was firstly evaluated individually for two DOFs of the myoelectric prosthesis – opening/closing (aperture) and rotation, and subsequently for their combination – sequential control of rotation and aperture. Therefore, the experimental session was organized in three blocks: 1) rotation, 2) aperture, and 3) rotation and aperture. Closing and opening of the virtual prosthesis were controlled by performing an appropriate contraction of wrist flexor and extensor muscles, respectively. Analogously, pronation and supination were controlled by activation of wrist flexor and extensor muscles, respectively. In the case of sequential control of two DOFs, the subjects performed cocontraction of the flexor and extensor muscles in to switch between the DOFs.

Each session included myoelectric control practice with visual feedback, electrotactile training with psychometric evaluation, and closed-loop myoelectric control with electrotactile feedback and target task. The aim of the control practice session using the visual feedback provided using Mujoco HAPTIX was to acquaint the subject with the control and the dynamic of the virtual myoelectric prosthesis. The subject was told to arbitrarily control the prosthesis while watching the model of the prosthesis presented on the screen.

Before starting the closed-loop control with electrotactile feedback, the subject underwent the feedback training during which she was trained to correctly interpret the dynamic stimulation patterns, i.e. the level of aperture and/or rotation. Electrotactile levels (four in the case of aperture, eight in the case of rotation – neutral state was excluded) were first presented to the subject from the lowest to the highest. Simultaneously, the appropriate visual feedback was presented. After that, 40 trials of reinforced learning were performed. The patterns representing random state change of the prosthesis were delivered and the subjects were asked to identify the corresponding state, and the experimenter provided the correct answer. Each pattern lasted for 4 seconds, regardless of the range of the state change. Finally, the psychometric evaluation, in which no feedback about the actual state change was given to the subject, including 24 trials of randomly ordered electrotactile patterns was conducted.

During the closed-loop control with electrotactile feedback, the subject was provided with the visual information regarding target task on the screen, while the information on the state of the virtual prosthesis was delivered only through the stimulation. In each session, 24 trials were performed. The subject signified that she is satisfied with the performed movement by pressing the button on the computer mouse, thus signifying the end of the current trial. When controlling the aperture, the task was to close the prosthesis to the designated target level (each of the four levels randomly appeared as task six times). In the case of rotation, the four levels associated with supination were assigned. The directions of the two DOFs were chosen so that they resemble daily manipulation and grasping activities.

D. Outcome measures

The outcome measures were the same for all three sessions of the experiment. In the psychometric tests, the outcome measure was success rate (SR) of correctly identified feedback levels. In the myoelectric control task, the accuracy and precision of the control were assessed by the mean absolute error (MAE) and the standard deviation of the absolute error (STDAE), respectively. The absolute error was computed for each trial as an absolute value of the difference between the target and the applied aperture/rotation. In the third session (rotation and aperture), the outcome measures were calculated separately for the two DOFs.

III. RESULTS

The results of the psychometric evaluation are presented in Table 1. The subject was able to recognize the electrotactile patterns with a high success rate, even for the combination of two DOFs.

TABLE 1
SUCCESS RATES IN RECOGNITION OF THE ELECTROTACTILE PATTERNS FOR THE THREE EXPERIMENTAL SESSIONS.

Session	Controlled DOF	Success Rate [%]
1	Rotation	92
2	Aperture	100
3	Rotation	96
3	Aperture	87.5

Absolute error (presented as mean ± standard deviation for 24 trials) between the target and performed aperture/rotation for three sessions are shown in Fig 2. For both DOFs, the performance is comparable when controlling them individually and in the combined task. The absolute error was slightly higher in the case of rotation (16.7±14.4% in Session 1 and 17.2±15.5% in Session 3) compared to aperture (13.7±9.2% in Session 2 and 13.3±6.6% in Session 3).

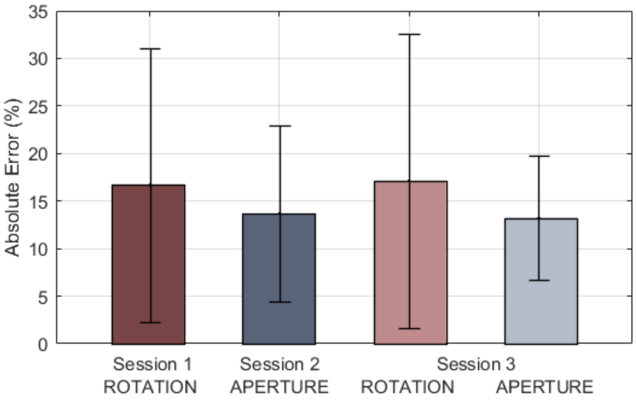

Fig. 2. Absolute error (MAE and STDAE for 24 trials) for three sessions: 1) rotation, 2) aperture, and 3) rotation and aperture.

IV. DISCUSSION AND CONCLUSION

For the evaluation of myoelectric control with the electrotactile feedback we have developed the closed-loop myoelectric control system based on the flexible test bench, implemented in MATLAB Simulink, Mujoco HAPTIX virtual hand simulator, and the Maxsens system for electrotactile stimulation. A set of dynamic stimulation patterns was used to provide the user of the multi-DOF prosthesis with real-time proprioceptive feedback. The dynamic patterns were spatially coded so they can be superimposed to transmit multiple feedback variables intuitively and simultaneously. Mujoco HAPTIX virtual reality hand simulator was used for visualization of the prosthesis and providing task information and visual feedback to the subject.

The subject was able to understand and identify the dynamic stimulation patterns with relatively high SR (<87.5%). As previously showed in [11], the success rate for recognition of eight patterns (hand opening/closing, pronation/supination, force increase/decrease, wrist flexion/extension) was 99±3% for able-bodied subjects, and 86±10%. However, in the previous study the subjects were presented with the pattern and only asked to identify the DOF and the direction (e.g. hand closing from fully open to fully closed). In this study, the aim was to recognize the extent of the proposed pattern (e.g. hand closed to level 1), which is by far a more complex task. Furthermore, the success rate did not decrease when the two DOFs were combined, confirming the hypothesis from [11] that the patterns can be superposed to transmit multiple feedback variables intuitively and simultaneously.

The subject was able to control the virtual prosthesis with acceptable absolute error (<17.2%) for both DOFs, individually and combined. Due to the resolution of the discrete feedback patterns, the absolute error can be up to 12.5% even if the correct level is reached. Therefore, the obtained errors are just above the minimal error.

We have previously evaluated understanding of electrotactile feedback on the grasping force and the quality of force control during the routine grasping task [14]. The results suggested that electrotactile feedback improves the performance in myoelectric control and also enables short-term learning of the feedforward control of the prosthesis. Although the long-term effects of the closed loop control remain to be investigated in a longitudinal study, electrotactile feedback can be exploited as a useful tool for learning and training of myoelectric control. The presented closed-loop system can be of great assistance in this process. We aim to further investigate the feasibility of the proposed system in able-bodied subjects and transradial amputees, and to include both grasping force and proprioceptive information feedback in more realistic tasks representing activities of daily living.

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