Evaluation of electrotactile feedback schemes in combination with electromyographic control – Closing the loop

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ABSTRACT
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I. INTRODUCTION

Introduction

The loss of an upper limb can be an incredibly traumatic and life-changing event with the consequence of a significantly reduced quality of life due to restrictions in function, sensation and appearance [1, 2]. In an effort to restore pre-trauma functionality, prosthetics of various functionality and complexity have been introduced to replace the missing limb [3]. However, despite advancements in prosthetic technologies 25% of users choose to abandon their myoelectric prosthetic device [4]. A major reason for the low user satisfaction is found in the lack of exteroceptive and proprioceptive feedback provided by commercially available devices [1, 5]. Presently, merely one commercially available device (VINCENT evolution 2, Vincent Systems Gmbh, DE), provides the user with feedback information of grasping force through a feedback interface [6].
The missing sensory feedback can cause the prosthetic hand to feel more unnatural and awkward [7]. Furthermore, the user mainly relies on visual feedback [7, 8], which is a need prosthetic users have shown a strong desire to decrease in order to enhance easiness and naturalness of use [9]. In a survey by Peerdeman et al. [5], it was found that secondly to receiving proportional grasp force feedback, prosthetic positional state feedback was of the highest priority. Visual independence can be achieved by providing the user with proprioceptive information through somatosensory feedback. This might facilitate the prosthetic device to be adopted by the user as an integrated part of their body, enhancing the feeling of embodiment and restoring the once physiologically closed loop [8, 10, 11, 12].
Various means of recreating the sensory feedback has been sought through either invasive and non-invasive approaches that translate information from sensors in the prosthesis to new sensory sites. Invasive methods, termed somatotopical feedback, aim to recreate the localization of the prior sensory experience by directly stimulating the nerves, which conveyed that particular sensory modality in the lost limb. This is, however, a complicated solution and multiple aspects, like long term effect, have yet to be investigated. [1, 8]. Substitution feedback utilizes various tactors (pressure, vibrational, temperature, electrotactile, etc.) and their use can either be modality matched using e.g. pressure as a substitute for grasp force [13] or non-modality matched via e.g. vibration for grasp force [14, 15]. Electrotactile feedback uses small electrical currents to activate skin afferents eliciting sensory sensations, which can be modulated in multiple parameters such as pulse width, amplitude, and frequency to convey feedback information along with the possibility of using multiple feedback channels [12]. As commercially available upper-limb prosthetics have multiple degrees of freedom (DoF's) [16] the need for multiple feedback channels is present to accommodate the amount of information which needs to be provided in a meaningful way.
In cases where two information variables are being conveyed e.g. grasping force and hand aperture using frequency and amplitude modulation in electrotactile stimulation [17] or pulse interval and stimulation frequency in vibrotactile stimulation [18], results have shown that one stimulator is not sufficient for users to distinguish between two modalities. In 2014, Witteveen et al. [19] provided sensory feedback of

grasping force and hand aperture through a single vibrator and an array of vibrotactile actuators, respectively. Results showed that identification of stiffness for four virtual objects was around 60 %. Although the percentage was rather low, the feedback configuration proved better compared to no feedback showing that multichannel feedback helps distinguishability when conveying feedback of more than one information variable. [19] However, the use of multiple vibrotactile actuators might be less feasible and practical to implement in prosthetics, due to their size and greater power consumption compared to electrotactile stimulation.

The flexibility of electrotactile stimulation makes is desirable and its use has earlier been proven useful in cases of conveying force feedback from pressure sensors on a prosthetic hand or from sensors in artificial skin [20, 21]. However, the possibilities in electrotactile feedback have also been investigated with regards to communication information on states of a multi DoF prosthesis. Strbac et al. [11] presented a novel electrotactile feedback stimulation interface, which could be used to convey information about the current state of a multi-DoF prosthesis. The system was comprised of four different dynamic stimulation patterns communicating the states of four different DoF's through a 16 multi-pad array electrode. The state of three different DoF's were communicated by altering the electrodes activated in a specific pattern. The fourth pattern communicated grasp force by modulating the stimulation frequency. Tests of the stimulation design showed that six amputees were able to recognize the stimulation pattern of the four DoF's with an average accuracy of 86 %. [11] However, it was not tested how well these stimulation patterns was aiding the user when combined with prosthetic control.

To the authors' knowledge, no one has fully closed the neural afferent/efferent loop, when investigating the usability of electrotactile feedback for restoring proprioceptive aspects during the use of a myoelectric prosthesis. Furthermore, based on the multiple parameters that can be modulated in electrotactile feedback, the question of which parameters that are most useful to convey tactile information on prosthetic motion states, is still unanswered. This study will, therefore, investigate how different electrotactile feedback modalities support prosthetic control when conveying proprioceptive sensory feedback of prosthetic states using a stimulation setup. Two novel stimulation configurations that delivered feedback regarding motion states of a two DoF virtual myoelectric prosthesis were investigated; one based on spatial activation of differently located pads in an electrode array, and one based on modulating the current amplitude of the electrode pads.

Info on the structure of the following chapters/sections.

II. METHODS

A. Experimental Protocol

To investigate the usability of the developed feedback schemes in combination with control an experiment was conducted which evaluated the usefulness of the feedback schemes when eliminating visual dependency. For this purpose 14 able-bodied subjects (12 male and 2 female - 13 right-handed and 1 left-handed with a mean age of 26.1 ± 2.4) were recruited. Included subjects signed an informed consent form and meet inclusion criteria stated in the experimental protocol, which was ethically approved by the ethical committee of Region Nordjylland, Denmark (approval number N-20150075). Each subject was introduced, trained and finally evaluated in understanding both the spatially based scheme and the amplitude based scheme. However, the order of which feedback scheme the subject would be trained/tested in was randomized. Figure 1 illustrates the chronological flow of stages in the experiment, where the first block focused on developing a subject specific prosthetic control system and the second block focused on training and evaluating the use of the sensory feedback schemes.

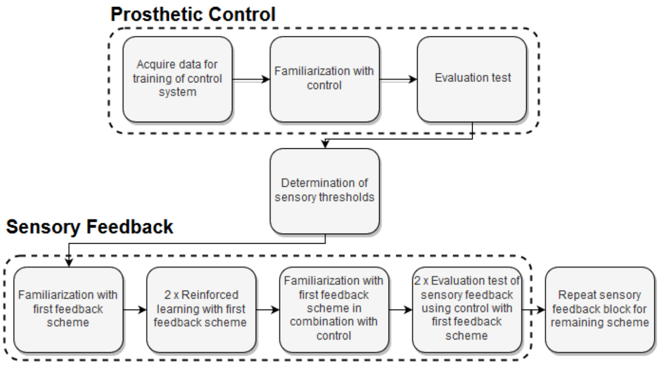

Fig. 1: Pipeline showing the stages of the experiment. The stages in the first block focused on developing and evaluating a subject specific simulated prosthetic control system. Then electrotactile sensory thresholds were determined. The second block focused on training the understanding of the feedback schemes and evaluating their use in combination with prosthetic control.

During the first block, EMG data was initially acquired and used to train a control system, which was used for a simulate prosthetic control. Subsequently, was a stage where the subject was made familiar with the control system. Finally, the achieved prosthetic control was evaluated through a target reaching test. Afterwards, a series of subjects sensory thresholds were determined for use of conveying electrotactile feedback. The subject then began the stages of familiarizing and training with a feedback scheme followed by re-familiarization of control in combination with feedback. Finally, a evaluation test of using the sensory feedback in combination for control was made. The entire sensory feedback block was then repeated using the remaining feedback scheme.

1 Feedback configurations

The main objective of the study was to evaluate two novel electrotactile feedback configurations' intuitiveness in providing proprioceptive information of a virtually simulated two DoF myoelectric prosthesis. The DoF's used were wrist rotation and closed hand, where each DoF was divided into four motion states, where a unique feedback was provided for the various states in each DoF. The electrode array used to deliver electrical stimulation can be seen in figure 2. The array consisted of 16 pads of which the activation and current amplitude could be modulated individually. It was placed around the contralateral lower arm of the dominant arm such that the end pads had a maximum gap of three cm centrally on the posterior side, when using a pronated arm as reference position. The following sections will present the two developed feedback configurations.

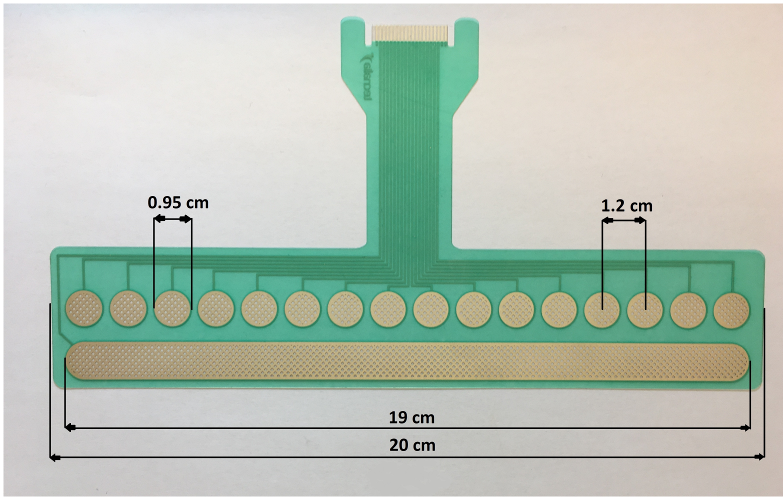

Fig. 2: Image of the 16 multi-pad electrode array used for stimulation. It consisted of 16 circular cathode pads, which each shared a common anode.

1.1 Spatial configuration

The motivation behind the spatial configuration was to spatially rotate the active electrode pads to communicate wrist rotation and to narrow the distance between pads to communicate closed hand. An illustration of the spatial configuration can be seen in figure 3.
The pads were divided two groups each responsible for conveying information about a single DoF. The anterior placed pads were allocated for wrist rotation and the posterior placed for closed hand. The pads were furthermore paired such that each pair would represent one of four motion states in one DoF. For wrist rotation the pads were connected in side by side pairs. For right handed subjects the activation of pads pairs would rotate laterally when increasing motion states during supination and rotate medially during pronation. The reversed activation was apparent for left handed subjects. For the closed hand DoF the pairs consisted of oppositely located pads on the me-

dial and lateral sides. When increasing motion states the active pairs would move posteriorly and the distance between active pads would become shorter.
When the virtual prosthesis was in a combined DoF state, the pads pairs corresponding to the level of the prosthetic state of each DoF would be active. Thus, a maximum of four pads could be active simultaneously.

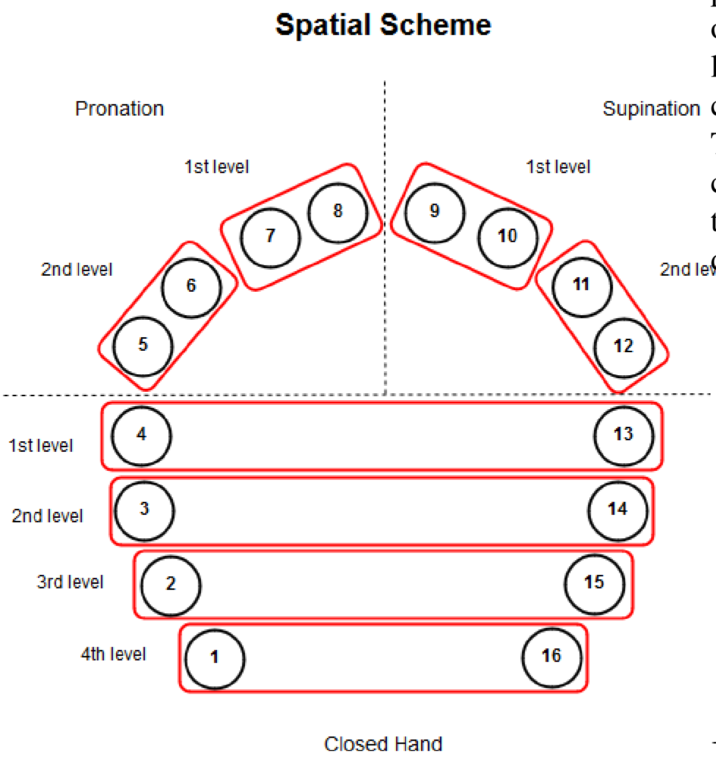

Fig. 3: Illustration of the developed spatial configuration. The levels written next to the pads pairs corresponded to the level of the prosthetic state; the higher the level, the more intense the prosthetic state of the given movement was. For left handed subjects the rotational states were reversed.

1.2 Amplitude configuration

The incentive behind the amplitude configuration was to convey information about the increase of prosthetic states by gaining the amplitude in electrode pad groups of four. An illustration of the amplitude configuration can be seen in figure 4.
The eight most anterior placed pads were used for wrist rotation and the four most posterior placed pads for closed hand. The eight pads used during wrist rotation were split such that the four most laterally placed were used during supination and four most medially placed were used during pronation for right handed subjects. The pad activation was reversed for left handed subjects. As the prosthetic state of a given movement would increase the the current amplitude in the pads corresponding to that movement would increase. When in combined DoF motion state, the pads corresponding to the level of the prosthetic state of each DoF would be active in the relative amplitude level. Thus, a maximum of eight pads could be active concurrently.
The choice of groups of four electrode pads was decided upon to exploit the highest number of pads in the electrode array, while maintaining a symmetric distribution of possible active pads.

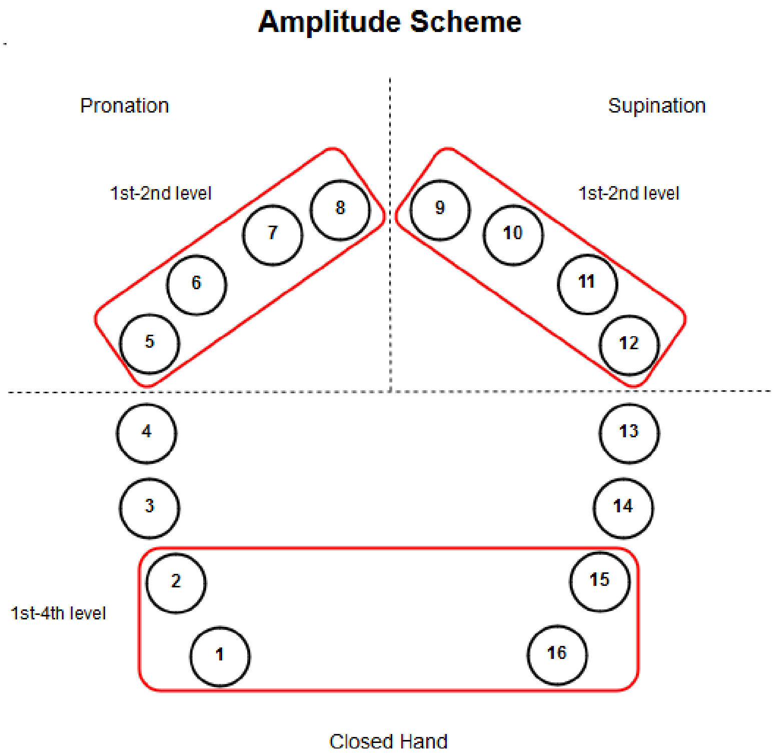

Fig. 4: Illustration of the developed amplitude scheme. Different groups of four electrode pads were active during supination, pronation and closed hand, respectively. The amplitude of the active pads would increase with the increase of the prosthetic state; the higher the prosthetic state level the higher the current amplitude of the given pads. For left handed subjects the rotational states were reversed.

2 *Virtual Closed-Loop Prosthesis*

Investigating the usability of the two sensory configurations in a closed-loop scenario required these to be interfaced with a prosthetic device, which accommodated the performance of rotational and open/closed hand DoF's. However, using an actual prosthesis would result in auditory feedback being provided to the subject, though prosthetic actuation sounds, eliminating the interest of solely exploring the impact sensory feedback. Hence, it was chosen to simulate a virtual prosthesis which enabled evaluation of the developed feedback schemes. In figure 5 is a depiction of a grid system and a black cursor symbolizing the different possible prosthetic states and the current prosthetic state, respectively. Each square corresponded to a prosthetic state of either a single DoF or combinations of two DoF's. Performing supination would make the cursor move to the right and opposite when performing pronation. Performing closed hand would make the cursor move downwards and upwards when performing open hand. The control was sequential only enabling the cursor move in one DoF at a time. When the cursor entered a square a specific electrotactile stimulation would be provided corresponding to the stimulation pattern for each scheme. In the neutral position (current location of cursor in figure 5), no sensory feedback was provided.

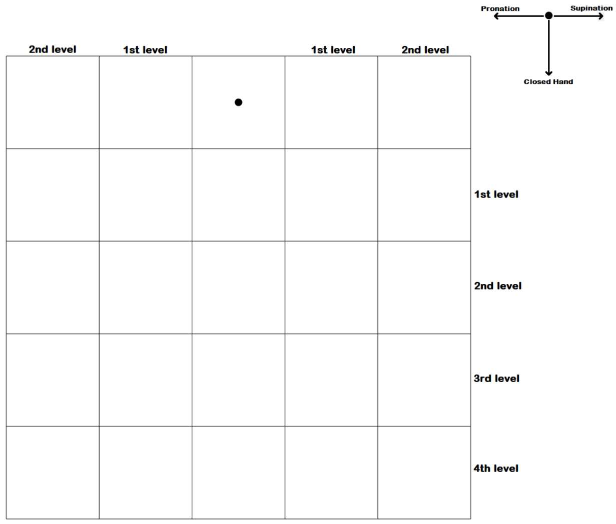

Fig. 5: Image of the grid map and cursor used in the experiment. Performing supination moved the cursor to the right, pronation moved it to the left and closing the hand moved it downwards. For left-handed subjects, the rotational movements were reversed. Opening the hand moved the cursor upwards, and was used as a correction movement if needed.

IV. RESULTS

V. DISCUSSION

VI. CONCLUSION

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References

[1] Jonathon S. Schofield et al. "Applications of sensory feedback in motorized upper extremity prosthesis: A review". In: *Expert Review of Medical Devices* 11.5 (2014), pp. 499–511.

[2] Kristin Østlie et al. “Mental health and satisfaction with life among upper limb amputees: A Norwegian population-based survey comparing adult acquired major upper limb amputees with a control group”. In: *Disability and Rehabilitation* 33.17-18 (2011), pp. 1594–1607.

[3] Purushothaman Geethanjali. “Myoelectric control of prosthetic hands : state-of-the-art review”. In: *Medical Devices: Evidence and Research* (2016), pp. 247–255.

[4] Elaine Biddiss and Tom Chau. “Upper limb prosthesis use and abandonment: A survey of the last 25 years”. In: *Prosthetics and Orthotics International* 31.3 (2007), pp. 236–257.

[5] Bart Peerdeman et al. “Myoelectric forearm prostheses: State of the art from a user-centered perspective”. In: *The Journal of Rehabilitation Research and Development* 48.6 (2011), pp. 719–738.

[6] VINCENT Systems. “VINCENT EVOLUTION 2”. In: *https://vincentsystems.de/en/prosthetics/vincent-evolution-2/* (2005).

[7] D Pamungkas and K Ward. “Electro-tactile feedback system for a prosthetic hand”. In: *22nd Annual International Conference on Mechatronics and Machine Vision in Practice, M2VIP 2015* (2015), pp. 27–38.

[8] Benjamin Stephens-Fripp, Gursel Alici, and Rahim Mutlu. “A review of non-invasive sensory feedback methods for transradial prosthetic hands”. In: *IEEE Access* 6 (2018), pp. 6878–6899.

[9] Diane J. Atkins, Denise C.Y. Heard, and William H. Donovan. “Epidemiologic Overview of Individuals with Upper-Limb Loss and Their Reported Research Priorities”. In: *Journal of Prosthetics and Orthotics* 8 (1996), pp. 1–11.

[10] Heng Xu et al. “Effects of Different Tactile Feedback on Myoelectric Closed-Loop Control for Grasping Based on Electrotactile Stimulation”. In: *IEEE Transactions on Neural Systems and Rehabilitation Engineering* 24.8 (2016), pp. 827–836.

[11] M Štrbac et al. “Integrated and flexible multichannel interface for electrotactile stimulation”. In: *Journal of Neural Engineering* 13.4 (2016), pp. 1–16.

[12] Bo Geng et al. “Evaluation of sensation evoked by electrocutaneous stimulation on forearm in nondisabled subjects”. In: *The Journal of Rehabilitation Research and Development* 49.2 (2012), p. 297.

[13] Sasha B. Godfrey et al. “Influence of Force Feedback on Grasp Force Modulation in Prosthetic Applications: a Preliminary Study”. In: *Conf Proc IEEE Eng Med Biol Soc.* (2016), pp. 1–8.

[14] Andrei Ninu et al. “Closed-loop control of grasping with a myoelectric hand prosthesis: Which are the relevant feedback variables for force control?” In: *IEEE Transactions on Neural Systems and Rehabilitation Engineering* 22.5 (2014), pp. 1041–1052.

[15] Muhammad Nabeel et al. “Vibrotactile stimulation for 3D printed prosthetic hand”. In: *2016 2nd International Conference on Robotics and Artificial Intelligence, ICRAI 2016* (2016), pp. 202–207.

[16] Francesca Cordella et al. “Literature Review on Needs of Upper Limb Prosthesis Users”. In: *Frontiers in Neuroscience* 10.May (2016), pp. 1–14.

[17] Ronald E. Prior et al. “Supplemental Sensory Feedback for the VA/NU Myoelctric Hand Background and Preliminary Designs”. In: *Bulletin of Prosthetics Reasearch* 101.134 (1976).

[18] Aniruddha Chatterjee et al. “Quantifying prosthesis control improvements using a vibrotactile representation of grip force”. In: *2008 IEEE Region 5 Conference* (2008), pp. 1–5.

[19] Heidi J.B. Witteveen et al. “Stiffness feedback for myoelectric forearm prostheses using vibrotactile stimulation”. In: *IEEE Transactions on Neural Systems and Rehabilitation Engineering* 22.1 (2014), pp. 53–61.

[20] C. Hartmann et al. “Towards prosthetic systems providing comprehensive tactile feedback for utility and embodiment”. In: *IEEE 2014 Biomedical Circuits and Systems Conference, BioCAS 2014 - Proceedings* (2014), pp. 620–623.

[21] M. Franceschi et al. “Preliminary evaluation of the tactile feedback system based on artificial skin and electrotactile stimulation”. In: *Proceedings of the Annual International Conference of the IEEE Engineering in Medicine and Biology Society, EMBS* (2015), pp. 4554–4557.