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STUDENT REPORT

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

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Part I

Paper

1 | Introduction

The loss of an upper limb can be 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]. The loss is additionally linked to the development of multiple mental health disorders [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 every 1/4 choose to abandon their myoelectric prosthetic device [4]. An explanation for the low user satisfaction should be found in the lack of exteroceptive and proprioceptive feedback provided by commercially available devices [5]. Presently, merely one device (VINCENT evolution 2, Vincent Systems Gmbh, DE), is commercially available providing 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], thus the user solely have visual feedback to rely on [8, 7], a need prosthetic users have shown a strong desire to decrease [9]. In a survey by Peerdeman et al. [5] it was found that secondly to providing proportional grasp force feedback, providing positional feedback was of highest priority. Visual independence can be achieved by providing the user with proprioceptive information through somatosensory feedback, possibly facilitating 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, translating information from sensors in the prosthesis to new sensory sites. Invasive methods, termed somatotopically feedback aims to recreate the localization of the prior sensory experience by directly stimulating specific nerves in the residual limb [1, 8]. Substitution feedback utilize various tactors (pressure, vibrational, temperature, electrotactile, etc.) and their use can either be modality matched using pressure as a substitute for grasp force [13] or non modality matched via 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 providing the possibility of using multiple feedback channels [12]. The relevance of employing multi-channel feedback is justified by commercially available upper limb prosthetics have multiple degrees of freedom (DoF's) [16].

The use of electrotactile feedback has earlier proven useful in cases of restoring force feedback through pressure sensors on a prosthetic hand or by the touch on artificial skin [17, 18]. However, the possibilities of electrotactile feedback have also been investigated in the case of improving prosthetic control. 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 comprised of four different dynamic stimulation patters 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 and the fourth, 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]
(Some great build up) investigate which types of electrotactile feedback is perceived more intuitive when conveying proprioceptive sensory feedback of the current prosthetic state. In this study we will present two different stimulation protocols to convey the before mentioned information; one based on activation of differently spatially located electrode pads, and another based on delivering different levels of amplitude.

Part II

Worksheets

2 | Background

2.1 Sensory Feedback Stimulation

It has been known for some time that vision alone does not provide a sufficient amount information to achieve efficient control of a prosthetic device. Hence, efforts have been put in investigating methods of providing proprioceptive and exteroceptive information of i.e. grasp strength and prosthetic state through the means of artificial stimulation. [1, 8] Presently, there are multiple ways of providing the user with a variety of sensory feedback. These can be divided into three categories: Somatotopically feedback, modality matched feedback and substitution feedback. [1]
This section will present general terms in sensory feedback stimulation and give a brief overview of the types of sensory feedback in order to give insight in the possibilities when providing the user of a prosthetic device with feedback.

2.1.1 Somatotopically feedback

Somatotopically feedback aims to provide the user with a sensory experience which is perceived as natural as what was felt by their missing limb, both in location and sensation. To achieve such an experience, somatotopically feedback uses invasive approaches by making use of invasive neural electrodes and targeted reinnervation. The former is known as peripheral nerve stimulation and relies on the invasive neural electrodes being interfaced with the original neural pathways preserved proximally on the residual limb. Currently, only two different types of electrodes have been exploited: One where a cuff is placed around a nerve fascicle and another where an electrode is implanted into the nerve fiber. But to this date, none of these methods have been comprehensively studied. Targeted reinnervation also enable the possibility of stimulating the original neural pathways from the missing limb. The corresponding sensory afferents are relocated to innervate new sites which can selectively be chosen and stimulated by non-invasive tactors. Somatotopically matched feedback is hypothesized to reduce the users cognitive burden due to its 'naturalness', facilitating increased compliance and less conscience attention. [1]

2.1.2 Modality matched feedback

In modality matched feedback, the type of sensory experience which would have been felt by the missing limb is communicated to the user. For instance, when pressure is felt in the palm of a prosthetic hand by pressure sensors, a proportional amount of pressure is delivered to the user somewhere on the skin. Thus, the sensation is not matched in location, but only in sensation. Mechanotactile feedback which conveys pressure information is utilized by the use of i.e. pressure cuffs or servomotors. These types of tactors are very useful for modality matched feedback, but have a disadvantage by being more power consuming compared to other stimulation types. [1, 19]

2.1.3 Substitution feedback

Substitution feedback methods convey information about the state of the prosthesis without regarding the type of sensation and location which would have been felt by the missing limb. Thereby, the sensory information is said to be non-physiologically representative. The feedback methods are often straightforward to implement, but demands a greater amount of user adaption to interpret what the feedback information represents. Often used methods for substitution feedback are vibrotactile and electrotactile feedback. [1, 19]

Vibrotactile stimulation

Vibrotactile stimulation utilizes small mechanical vibrators to convey information to a selected area of the skin which activates cutaneous mechanoreceptors. This method is most often used to transfer tactile information in prosthetic grasping tasks. [1] A recognizable sensation is evoked using frequencies between 10 and 500 Hz. The sensory threshold varies between users and location, resulting in the need for specific user threshold calibration. [19]

Electrotactile stimulation

In electrotactile feedback a sensory sensation is achieved by stimulating the primary myelinated afferent nerves with an electrical current. This creates what is often referred to as a tingling sensation. Electrotactile stimulation rely on small and lightweight electrodes to provide the electrical stimulation. When compared to other feedback methods as vibrational and pressure stimulation, which depend on heavier actuators and moving parts to provide the feedback, these properties can be seen as a drawback as prosthetic users strongly desire lightweight systems [8, 20]. Furthermore, through the use of electrotactile stimulation, multiple factors such as amplitude, pulse width, frequency and location of the stimulation can be controlled facilitating development of agile feedback schemes. This enables the possibility of varying the perceived feedback as either vibration, tapping or touch by modulating the signal waveform. The downside of using electrodes is the requirement for recalibration of sensory thresholds, pulse width and frequency to reproduce the same perceived stimulation every time the electrodes are placed on the user. In addition, interference between electrodes used for stimulation and recording have been found to result in noise in recorded EMG-signal used for myoelectric control. Concentric electrodes are able to limit the interference by limiting the spread of current. Concentric electrodes have also been found to increase localization and perceptibility of the induced stimuli. [1, 8, 19]

2.2 State of Art in Electrotactile Feedback

As presented in section 2.1.3 electrotactile stimulation offers a series of interesting properties which can be drawn upon when conveying complex tactile information. Therefore, the state of art methods using electrotactile sensory feedback in the current literature have been reviewed and will presented to ensure that the later derived feedback schemes extends recent evidence.

Multiple studies have investigated the use of electrotactile feedback regarding both how distinguishable sensations are evoked and how to convey sensory feedback in different coding schemes for improving myoelectric prosthetic control [8]. In 2015 Shi and Shen [21] investigated how subjects would perceive the effects of varying amplitude, frequency and pulse width of an electrical stimulation in various combinations. Results showed that appropriate sensations from electrical stimulation would be achieved by varying amplitude from 0.2 mA to 3 mA, pulse width from 0.2 ms to 20 ms and frequency from 45 Hz to 70 Hz. Furthermore, varying these ranges properly would make it possible to have proportionally increased stimulation grades felt by the subject. Additionally, the authors stated the importance of electrode size, as stimulation through to big or to small electrode diameters could result in sensations of pain or discomfort. [21]

Several studies [7, 10, 22, 23] using electrical stimulation have investigated its use in conveying grasping force/pressure feedback. Jorgovanovic et al.[22] investigated users' recognition of grip strength, when controlling a joystick controlled robotic hand, through varying the pulse width and keeping the frequency and intensity constant at 100 Hz and 3 mA, respectively. Results showed that providing electrotactile feedback improved the users' ability to move objects with the robotic hand. [22] Similar result were found by Isakovic et al. [23], who also showed that electrotactile feedback supported a faster learning than no feedback in grasp force control, and that electrotactile feedback might facilitate short-term learning.

A study by Xu et al. [10] tested and evaluated different types of pressure and slip information feedback through electrotactile stimulation and compared this to visual feedback and no feedback. The study recruited 12 subjects, 6 able bodied, and provided electrotactile feedback by keeping the intensity and frequency constant and then varying the pulse width between 0 μs and 500 μs indicating changes in grasp force. In this case, visual feedback was found to outperform electrotactile feedback. [10]

Pamumgkas et al. [7] also tested the use of electrotactile feedback to convey information from pressure sensors located in a robotic had. Their setup used six feedback channels corresponding to a pressure sensor in each of the fingers and one in the palm. Pressure information in the sensors were given in three discretized frequency levels of 100 Hz, 60 Hz and 30 Hz for the fingers and 20 Hz for the palm. Reported results stated that the subjects learned how to appropriately use the feedback when picking up objects of various sizes. Furthermore, the subjects reported that they preferred having electrotactile feedback accompanied by visual feedback opposed to only having visual feedback. [7]

The purpose of restoring the sensation that would be experienced by touch of the skin has also been pursued in more elaborate efforts through artificial skin [17, 18]. In these

cases, a grid of 64 pressure sensors were used to translate information of touch into 32 electrotactile electrodes placed on the arm of the subjects.
The use of electrotactile feedback has proven useful in cases of restoring the haptic feedback through pressure sensors on a prosthetic hand or by the touch on artificial skin. However, the possibilities of electrotactile feedback have also been investigated in the case of improving prosthetic control. In 2016, Strbac et al. [11] presented a novel electrotactile feedback stimulation system, which could be used to convey information about the current state of a multi-DoF prosthesis. The system comprised of four different dynamic stimulation patters communicating the states of four different DoF's through a 16 multi-pad array electrode, possibly restoring both proprioception and force. The state of the three of the DoF's were communicated by altering the electrodes activated in patterned fashion and the fourth DoF by modulating the stimulation frequency. Tests of the stimulation design showed that six amputees were able to recognize the four DoF's with an average accuracy of 86 %. [11]

2.3 Closing the Loop

The loss a limp does not only result in a loss of motor function, sensory function is also impaired. Providing an amputee with a prosthetic device, which does not provide sensory feedback, only restores one half of the one closed limb control loop. To close the loop the prosthetic device needs to contain proprioceptive and exteroceptive sensors, which recorded information needs to be conveyed to the amputee in a intuitive and meaningful way [24]. This can be achieved using the before mentioned methods of sensory substitution [**Schweisfurth2016**].
Closing the loop is a well recognized need of prosthetic users and might improve easiness of use and embodiment, possibly lowering rejection rates. Furthermore, the need for visual attention to correct prosthetic movement would be lowered. [11] However, the advantages of closing the loop by providing sensory substitution feedback have been contradictory [22]. In 2008 Cipriani et al. [**Cipriani2008**] investigated the use of vibroctacile feedback for improving grasp in a prosthetic and did not find any improvement using providing the sensory feedback. Later finding by Witteveen et al. [**Witteveen2012**] disproved this as they found providing information of grasp force and slip through vibrotactile feedback improved a virtual grasping task.
Even though most studies find closing the loop by providing sensory feedback helpful (review by Stephens-Fripp et al.) [8], currently one device, the VINCENT evolution 2 (Vincent Systems Gmbh, DE) is commercially available conveying grasp force feedback [6].

Actually, some researchers and commercial corporations (such as Otto Bock and RSL Steeper) have introduced automatic closed-loop control for certain prostheses. Some actuation mechanisms can automatically adjust grip force ac- cording to feedback information from sensors. This actually is a "local" autonomous loop based on sensing and actuating com- ponents within the prosthesis, in which users are not involved. The limitation is that these devices cannot provide amputees with tactile and proprioceptive feedback. [10]

2.4 Feedback Stimulation Setup

To elicit electrotactile stimulation in this project, the MaxSens stimulation device will be used along with a 16 multi-pad electrode. The following section will provide a short overview of the stimulation device and multi-pad electrode specifications.

2.4.1 Electrode

The 1×16 multi-pad stimulation electrode, can be seen in figure 2.1. It is made of 16 circular cathodes, which each share a common long anode. The electrode consists of a polyester layer, an Ag/AgCl conductive layer and a insulation coating. The electrode to skin contact is improved by applying conductive hydrogel pads to the electrode pads. [11]

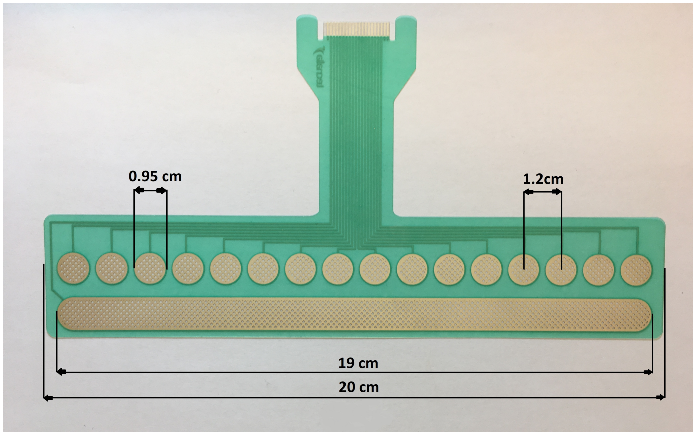


Figure 2.1: The 16 multi-pad electrode used for stimulation consisting of 16 circular cathode pads, which each share a common anode. The pads are numbered from 1 to 16 in a left to right order.

2.4.2 MaxSens stimulation device

The stimulation device is made by MaxSens, Tecnalia, San Sebastian, Spain. Communication between PC and the stimulation device can be achieved either through Bluetooth or USB serial connection. The device can be controlled through a series of commands. The MaxSens device allows for independent control of the 16 pads in the electrode. It generates biphasic stimulation pulses where the pulse width can be controlled within a 50 - 1000 μs range with 10 μs steps, frequency ranges from 1 - 400 Hz with 1 Hz steps and current amplitude ranges from 50 - 10000 μA with 0.1 μA steps. Whereas current amplitude and pulse width can be controlled independently for each pad, the pad frequency is set globally limiting all pads to have same frequency.

2.5 Electromyography

The control of a myoelectric prosthesis is based on recorded myoelectric signals. [3] Enabling the use of myoelectric signals for control of functional prosthetics requires a theoretical background knowledge of the signals origin and how it can be acquired. The following section will describe myoelectric signals and how they are acquired through the acquisition method of electromyography (EMG).

The process of executing a voluntary movement can be explained through electric potentials and the excitability of skeletal muscle fibers. The nerve impulse carrying excitation information of a voluntary muscle contraction will travel from the motor cortex down the spinal cord to a alpha motor neuron. The alpha motor neuron cell will activate and direct the nerve impulse along its axon to multiple motor endplates, which each innervate muscle fibers. [25] This initiates the release of neurotransmitters forming an endplate potential. The muscle fibers consist of muscle cells, which each are surrounded by a semi-permeable membrane. The resting potential over the membrane is held at a equilibrium, typically -80 mV to -90 mV, by ion pumps, which passively and actively control the flow of ion through the membrane. The release of neurotransmitters affects the flow through the ion pumps resulting in a greater influx of Na^+. This results in a depolarization of the cell membrane. However, only if the influx of Na^+ is great enough to create a depolarization surpassing a certain threshold, an action potential is formed. The action potential is characterized by the cell membrane potential, which changes from around -80 mV to +30 mV. After the depolarization a repolarization phase occurs and is followed by a hyperpolatization period, restoring the resting potential. The created action potential will propagate in both directions on the surface of the muscle fiber. The summation of this process and all its antagonist is in summation one motor unit. Hence, the action potential is also known as a motor unit action potential (MUAP), and it is the superposition of these across the muscle fibers, that is recorded through EMG. [25, 26]
Acquisition of EMG-signal can either be carried out through surface EMG or intramuscular EMG. The latter measures the MAUPs through needles inserted into the muscle and the former through electrodes on the skin surface. [27] Using surface EMG requires preparation of the skin surface to minimize impedance and maximize skin contact. Hence, the skin should be clean and dry before electrode placement. Often considered is removing excess body hair or flaky skin and cleansing the area using alcohol swabs. [25, 27]

2.5.1 Myo armband

To acquire EMG-signals the Myo armband (MYB) from Thalmic Labs is used. It contains eight dry stainless-steel electrode pairs placed inside the armband. The advantage of using dry electrodes is that they do not need to be disposed after use, in contrary to conventional gel electrodes. Thus, MYB can be reused for all subjects participating in the project, which provides less time consuming experiments. An additional usability advantage is that it communicates wirelessly to external devices via Bluetooth 4.0, leaving no loose wires to possibly limit mobility or distort connection.

MYB acquires EMG signals in an 8-bit resolution. Instead of acquiring the signal in millivolts, the output is scaled to decimal numbers between -1 and 1. However, the amplitude of the EMG signal output is still proportional to muscle contraction intensity. To avoid signal frequencies from the power grid to interfere with the EMG signal, an analogue notch filter at 50 Hz is built in the MYB. This is, however, the only analogue filter implemented in the MYB, and as it has a sample rate of 200 Hz, which is inside the EMG spectrum (10-500 Hz), the acquired EMG signal will likely be aliased. The implementation of a digital anti-aliasing filter would therefore be a trivial task and extracting features that represents the frequency content of the signal might not be useful. Additionally, MYB contains a 9 axes inertial measurement unit, but will not be utilized in this project and therefore not elaborated further.
During the initialization of using MYB the user has to follow two calibration steps: the warm up and the synchronization. In the warm-up step, MYB is establishing a strong electrical connection between the skin and the armband, which reduces skin-electrode impedance and enables the electrodes to transduce properly. This happens as the user's skin becomes more moist from light sweating, which works similar to the gel in conventional EMG electrodes. During the synchronization step the MYB determines its orientation in space, its position and on which arm it is placed, based on a wrist extension movement the user must perform. MYB works most optimally when tightly fit on the thickest part of the arm. To ensure a close fit, a set of clips can be used if necessary.

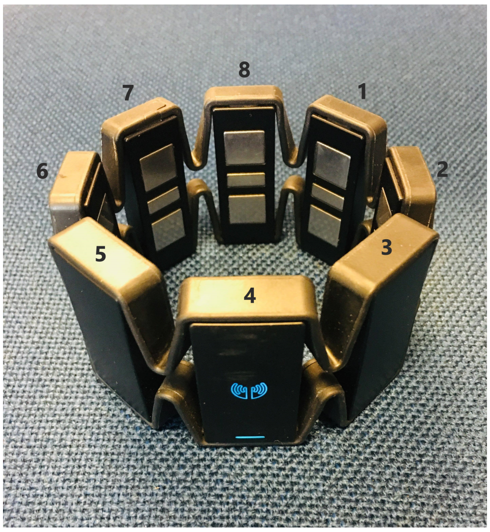


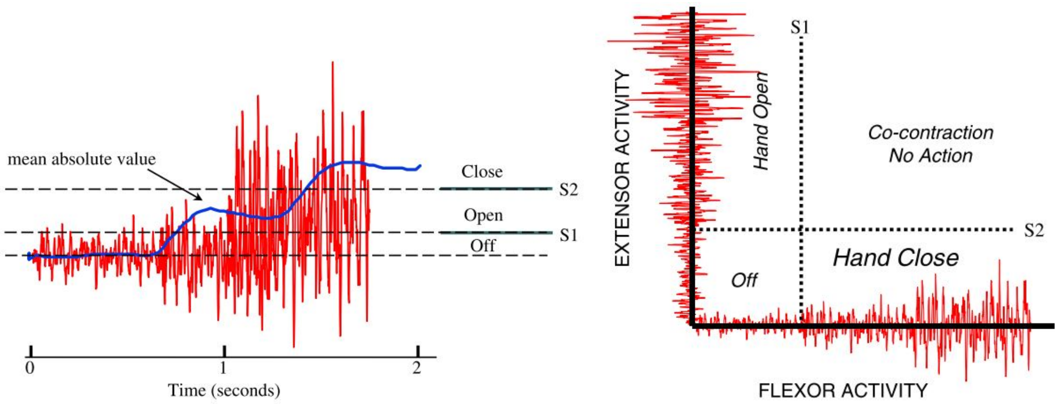
Figure 2.2

2.6 Prosthetic Control

Throughout the development of myoelectric prosthetics, different control schemes have been derived, tested and some implemented in commercially available devices. Complexity and dexterity are dependent on the control system and before choosing a method one must form an overview of the opportunities each presents. The following section will present fundamental concepts of the main control methods.

2.6.1 Direct switch-based myoelectric control

A Switch-based myoelectric is the conventional control method and is also known as on/off, crisp, binary or bang/bang control. [3] Signal preprocessing is simple and the signal is usually only rectified and filtered. Various sub-control schemes exist, which are either based on the EMG-amplitude of one or two channels. The user is able to control one DoF (e.g. open/closed hand), recorded from one channel, by surpassing a lower amplitude threshold for open hand and a higher closed hand. Alternatively the EMG-signal can be recorded from two independent muscles (two channels) and if a threshold is exceeded in one, the prosthesis would move in a predetermined direction. An illustration of both one and two-channel control schemes can be seen in figure 2.3. The actuation speed can be at a fixed speed or proportionally to the EMG amplitude. Multiple DoF's can be achieved by switching the DoF-mode by providing a quick mode-switch signal e.g. two quick contractions, or by physically pressing a switch on the prosthesis. [28, 29] The two channel direct switch-based control scheme can be found in the commercially available Michelangelo Hand [30].
Switch-based is a simplistic, but slow control approach. Furthermore, it quickly gets impractical and non-intuitive when increasing the number of DoF's to be replaced as the intended movement is unrelated to the acquisition site. Additionally, the methods relies on isolated muscle contractions, sensitivity might me decreased by channel cross-talk and muscle co-activation. [29]



(a) One channel threshold control. (b) Two channel threshold control.

Figure 2.3: Illustration of a direct one channel (a) and two channel (b) threshold control schemes using EMG amplitude to control open/close hand function. S denotes a threshold. Illustration taken from [31].

2.6.2 Sequential myoelectric control

To overcome the disadvantages of direct switch-based control in slow and not intuitive control, alternative control strategies relying on algorithms have been derived. Such algorithms could utilize classification-based pattern recognition to predict the intended movement of the user. Often signal from several electrodes are captured. An assumption is that given a consistent movement task is performed the muscles will exhibit a unique activation pattern, and that features extracted from each signal for each movement type can be used to distinguish between different movement types. Hence, complex EMG-signal patterns can be assigned to discrete movement classes, thus also allowing for control of several DoF's. [28, 29]
This approach is more intuitive as it does not demand the need for switching between DoF's, and lowering the amount of effort the user has to put in completing a task. A disadvantage of sequential control is lack of simultaneously controlling multiple DoF's at once allowing for a faster and more natural task execution. [28]

2.6.3 Simultaneous myoelectric control

Incorporating intuitiveness and naturalness in prosthetic control can be achieved through simultaneous control, where more than one DoF is controlled at a time. Pattern recognition methods predicting more than one movement type have been proposed, but naturalness through proportional actuation speed cannot be achieved independently for each DoF. Instead regression-based methods have been introduced. Compared to classification, which will output one class, trained regressors will continuously output the estimated value for each movement type. Choosing the two movement, which fit the regressors the best will provide simultaneous and proportional control. [32]

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A | Appendices