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STUDENT REPORT

Evaluation of Electrotactile Feedback Schemes in a Closed-Loop Myoelectric Prosthesis

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Project group: 19gr10407

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Abstract:

The implementation of intuitive and meaningful proprioceptive feedback of position states in myoelectric prosthesis is an important aspect in enhancing embodiment and user satisfaction, hence lowering the demand for visual attention for prosthetic control in everyday tasks. Therefore, two different configurations for conveying position state information of wrist rotation and hand aperture through electrotactile stimulation were developed and evaluated in a simulated closed-loop prosthesis. A spatially-based configuration was made conveying information by changing the activation of pads in an electrode array placed circumferentially around the non-dominant arm. The other scheme was amplitude-based and used various levels of amplitude from specific electrode pads to convey information of the position state of the prosthesis. 14 able-bodied subjects were evaluated through a Fitts' Law inspired target reaching test following a minimal training session. The amplitude-based and spatially-based configurations yielded mean completion rates of 93 % ± 6 % and 87 % ± 11 %, respectively. The amplitude feedback configuration yielded a slightly higher completion rate ($p = 0.044$) than the spatially-based and was also preferred by 64 % of the subjects. However, with such high completion rates both schemes can be regarded intuitive and was subjectively reported to be useful and easily comprehensible. This manifests that both developed feedback configurations allow subjects to perceive two feedback variables at the same time, despite being implemented in a compact stimulation interface.

Resume

Tabet på en overekstremitet kan være yderst traumatiserende og livsændrende og lede til signifikant nedsat livskvalitet grundet formindsket funktionalitet, sensation og udseende. Et aktiv med henblik på at genskabe den manglende funktionalitet hos trans-radialt amputerede findes i myoelektriske proteser. På trods af stor udvikling inden for proteseteknologier vælger 25 % af protesebrugere alligevel at undlade brugen af myoelektriske proteser. En rapporteret årsag til dette er, at de tilbudte kommercielle proteser mangler proprioceptiv og exteroceptiv feedback. Protesebrugerne er derfor bundet af visuelt feedback for at afgøre protesens position i rummet, og mangler taktil information, om hvordan protesens interaktion med omgivelserne føles. Grundet denne mangel opfatter brugerne derfor ikke protesen som en integreret del af kroppen.

Tidligere studier har forsøgt at genskabe disse sensationer, hvor vigtige aspekter dog er blevet negligeret. Manglen i disse studier omfatter simpliciteten af den simulerede feedback, den praktiske integration af stimulatortypen i en protese og manglende evaluering af feedback i kombination med myoelektrisk protesekontrol. For at imødegå disse aspekter blev der i dette studie evalueret anvendeligheden af to innovative stimulationskonfigurationer i en simuleret virtuel protese, der formidlede proprioceptiv feedback vedrørende to frihedsgrader (rotation af hånden og lukning af hånd) igennem et let integrerbart elektrotaktil feedback interface. De to frihedsgrader blev inddelt i fem diskrete intervaller, med en unik taktil feedback tilskrevet hvert interval. Da elektrotaktil feedback er multimodalt, var et yderligere fokus at evaluere hvilken modalitet, der kunne formidle taktil proprioception bedst muligt. De to modaliteter, der blev undersøgt, var spatial aktivering af forskellige områder i et elektrode array, og amplitude modellering af stimuleringen fra elektrode arrayet.

14 testpersoner blev rekrutteret og evalueret gennem en Fitts' Law inspireret test, som følge af en omtrent halv times lang træningssession i en af feedbackkonfigurationerne. Dernæst blev den anden feedbackkonfiguration trænet og evalueret. Hvilken konfiguration testpersonerne blev evalueret i først, var randomiseret. Indledningsvist blev testpersonerne trænet i at styre den virtuelle protese, da det var påkrævet at testpersonerne opnåede robust kontrol, før konfigurationerne kunne blive retfærdigt evalueret i en lukket motor/sensor loop protese.

Som resultat af evalueringstesten opnåede de amplitude og spatialt-baserede konfigurationer succesrater på henholdsvis 93 % ± 6 % og 87 % ± 11 %. Amplitude feedback konfigurationen opnåede en smule højere succesrate end den spatialt-baserede ($p = 0.044$), hvilket også var understøttet af testpersonernes subjektive vurdering, da 64 % favoriserede amplitude feedbacken. Succesraten for begge konfigurationer var dog betydeligt lavere end for visuelt feedback (99 % ± 2 %, $p < 0.001$). Synet er imidlertid en mere dominerende sans inden for motorisk læring end proprioception, og en identisk succesrate ville derfor aldrig være forventeligt.

Med så højt opnåede succesrater som følge af minimal træning, kan begge feedbackkonfigurationer anses som værende intuitive og let forståelige. Eftersom stimuleringssetuppet krævede minimal plads, vil det kunne integreres i en reel protese, hvilket potentielt kunne medføre en myoelektrisk protese, som brugere ville legemliggøre. Derudover havde især

den amplitude-baserede feedbackkonfiguration potentialet til nemt at kunne udvides til at formidle endnu mindre diskretiserede feedbackintervaller, hvilket kunne yderligere udbygge anvendeligheden.

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Part I

Paper

Evaluation of Electrotactile Feedback Schemes in a Closed-Loop Myoelectric Prosthesis

Christian Korfitz Mortensen* and Martin Alexander Garenfeld*

Abstract—**The implementation of intuitive and meaningful proprioceptive feedback of position states in myoelectric prosthesis is an important aspect in enhancing embodiment and user satisfaction, hence lowering the demand for visual attention for prosthetic control in everyday tasks. Therefore, two different configurations for conveying position state information of wrist rotation and hand aperture through electrotactile stimulation were developed and evaluated in a simulated closed-loop prosthesis. A spatially-based configuration was made conveying information by changing the activation of pads in an electrode array placed circumferentially around the non-dominant arm. The other scheme was amplitude-based and used various levels of amplitude from specific electrode pads to convey information of the position state of the prosthesis. 14 able-bodied subjects were evaluated through a Fitts' Law inspired target reaching test following a minimal training session. The amplitude-based and spatially-based configurations yielded mean completion rates of 93 % $\pm$ 6 % and 87 % $\pm$ 11 %, respectively. The amplitude feedback configuration yielded a slightly higher completion rate (p = 0.044) than the spatially-based and was also preferred by 64 % of the subjects. However, with such high completion rates both schemes can be regarded intuitive and was subjectively reported to be useful and easily comprehensible. This manifests that both developed feedback configurations allow subjects to perceive two feedback variables at the same time, despite being implemented in a compact stimulation interface.**

Index Terms—**Closed-loop, myoelectric prosthesis, electrotactile stimulation, sensory feedback, position state.**

I. Introduction

The loss of an upper limb can be an incredibly traumatic and life-changing event leading to a significantly reduced quality of life due to restrictions in function, sensation and appearance [1], [2]. In an effort to restore normal functionality, prostheses of various complexities 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 reason for the low user satisfaction is found in the lack of exteroceptive and proprioceptive feedback provided by commercially available devices [1], [5]. Presently, only one commercially available prosthesis (VINCENT evolution 2, Vincent Systems Gmbh, Germany), provides the user with feedback information of grasping force through a simple feedback interface using a single vibrator [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 prosthetic users have shown a strong desire to decrease. Removing visual dependency is expected 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 closed motor/sensory loop [8], [10]–[12].

Various means of providing the sensory feedback have been investigated through either invasive or 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 stimulation modalities (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 cutaneous skin afferents eliciting sensory sensations. The feedback can be modulated in multiple parameters such as pulse width, amplitude, and frequency 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 feedback 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 devices, due to their size and greater

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power consumption compared to electrotactile stimulation.

The flexibility of electrotactile stimulation makes it 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 communicating 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 coding schemes were comprised of four different dynamic stimulation patterns communicating the states of four different DoF's through a 16 multi-pad electrode array. 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 success rate of 86 % for amputees and 99 % for able-bodied. [11] However, the intuitiveness regarding feedback communicating combined DoF position states was not evaluated. Furthermore, it was not tested how well the stimulation patterns were 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 an online control task simulating prosthesis use. 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 position states, is still unanswered. This study will, therefore, investigate how different electrotactile feedback modalities support prosthetic control when conveying proprioceptive sensory feedback of position states of a prosthesis. Two novel stimulation configurations that delivered feedback regarding position 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.

In Section II a description of the two novel feedback configurations will be given, followed by the implementation methods and the experimental protocol. Results of the experiment will be reported in section III. Finally, the significance of this study and its results will be presented in Sections IV and V.

II. Methods

A. Novel Feedback Configurations

The main objective of the study was to evaluate the effectiveness of two novel electrotactile feedback configurations in providing proprioceptive information of a two DoF myoelectric prosthesis. The DoF's used were wrist rotation and hand aperture. The transmitted feedback was discrete, where the full range of each feedback variable was been divided into five segments. The electrode array used to deliver electrical stimulation can be seen in figure 1.

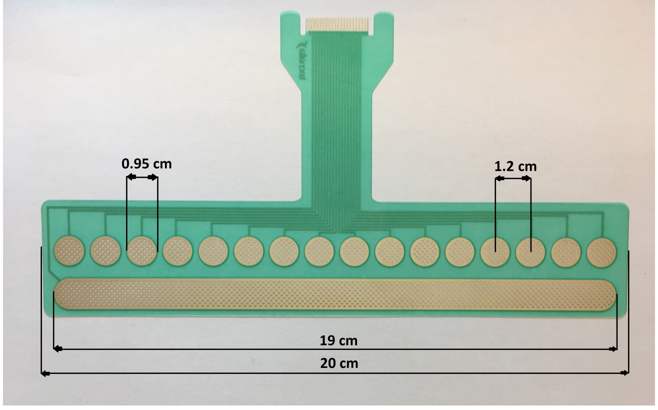

Fig. 1. Image of the 16 multi-pad electrode array used for stimulation. It consisted of 16 circular cathode pads, which each shared a common anode.

Fig. 2. The MaxSense stimulation device used for independently modulating each pad in the attached electrode array.

The electrode array consisted of a single anode pad and 16 circular cathode pads. The pads comprised of conductive Ag/AgCl traces imprinted in a 150 μm thick polyester layer. All pads were covered with conductive hydrogel (AG702, Axelgaard, Denmark) to enhance skin-electrode contact. A multichannel stimulation device (MaxSens, Tecnalia, Spain), seen in figure 2, generating biphasic pulses was connected to a standard desktop PC for individual modulation of pad activation. The pulse width and amplitude could be modulated independently for each pad whereas the frequency was modulated globally. The pulse width could be modulated 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. The electrode array was placed circumferentially around the non-dominant arm to avoid interference with the recording electrodes, which were fitted on the dominant arm. In a clinical application both interfaces should, however, be placed on the same arm (residual limb). The stimulation electrodes were fitted such that the end pads had a maximum gap of 3 cm centrally on the volar side. Hence, how distal the electrode array was placed towards the wrist depended on the diameter of the subject's forearm. The following sections will present the two developed feedback configurations.

1) Spatial configuration: The motivation behind the spatial configuration was to communicate wrist rotation by spatially rotating the activation of dorsally placed electrode pads and to communicate hand aperture by changing activation between volarly placed pads. This feedback design was chosen in order to intuitively mimic the directions of the motions in the included DoF's. An illustration of the spatial configuration can be seen in figure 3. The pads were divided into two groups each responsible for conveying information about a single DoF. The dorsally placed pads were allocated for wrist rotation and the volarly placed for hand aperture. The pads were furthermore paired such that each pair would represent one of four intervals of the position state feedback variable. For wrist rotation the pads were connected in side by side pairs. For right-handed subjects the activation of pad pairs would rotate laterally when increasing rotational states during supination and rotate medially during pronation. For hand aperture the pairs consisted of oppositely located pads on the medial and lateral sides. When increasing aperture states the active pairs would move volarly and the distance between active pads would become shorter. When both feedback variables were active, the pads pairs corresponding to the given level of hand aperture and rotation would be activated. Thus, a maximum of four pads could be active simultaneously. The reason for grouping adjacently placed pads to convey information about the rotational DoF was to improve sensation perception by stimulating a larger skin area, as shown in Dosen et al. [22].

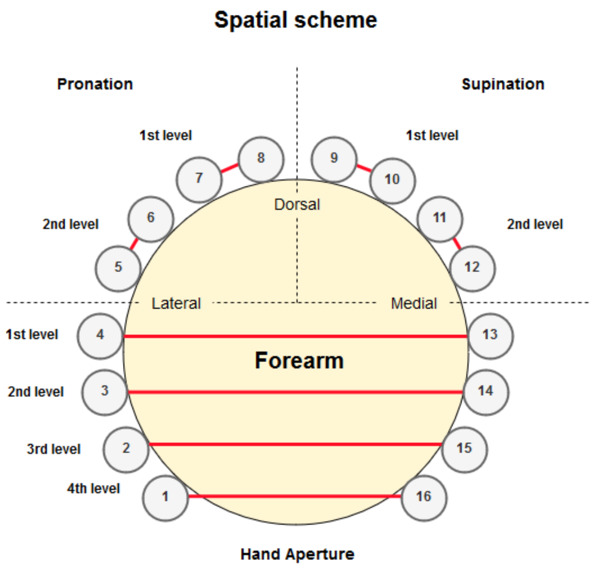

Fig. 3. Transverse view of the developed spatial scheme fitted on the left arm of a subject. The levels written next to the pads pairs corresponded to the level of the position state; the higher the level, the higher the position state of the given movement was. When fitted on the right arm medial and lateral sides were reversed.

2) Amplitude configuration: The incentive behind the amplitude configuration was to convey information by increasing the current amplitude as the position state increased. The feedback was provided in electrode pad groups of four. The areas of active pads allocated for the various motions was similar to the spatial configuration to intuitively resemble the prosthesis motions. An illustration of the amplitude configuration can be seen in figure 4.

The eight most dorsally placed pads were used for wrist rotation and the four most volarly placed pads for hand aperture. 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 position state of a given movement would increase the amplitude in the pads corresponding to that movement increased. When in combined DoF position states, the pads corresponding to the level of the position 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 grouping 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. Similarly to the spatial configuration this design was chosen to improve sensation perception [22].

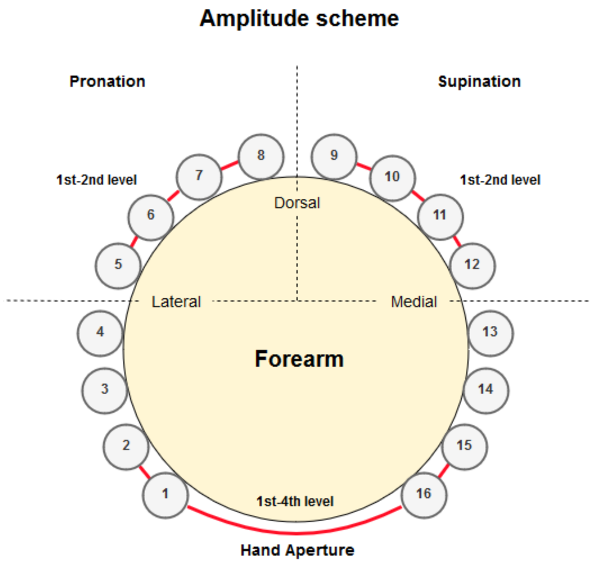

Fig. 4. Transverse view of the developed amplitude scheme fitted on the left arm of a subject. Different groups of four electrode pads were active during supination, pronation and hand aperture, respectively. The amplitude of the active pads would increase with the increase of the position state; the higher the position state level the higher the current amplitude of the given pads. When fitted on the right arm medial and lateral sides were reversed.

B. *Myoelectric Prosthetic Control*

In order for a subject to be able to control a virtual prosthesis, a prosthetic control system needed to be trained with acquired electromyographic (EMG) signals. For EMG data acquisition the Myo Armband (MYB) from Thalmic labs was used, which contained eight dry stainless steel electrode channels embedded on the inside of the armband. Furthermore, it could communicate wirelessly to external devices via a Bluetooth 4.0 unit, making it a highly practical recording device with minimum preparation time needed. However, it had a fixed sample rate of 200 Hz with the exclusive analogue filter being a 50 Hz notch filter. A study by Mendez et al. [23] showed, however, a similar mean classification accuracy of nine hand gestures in a Linear Discriminant Analysis (LDA)-based classifier, when comparing data acquired with electrodes that covered the entire EMG spectrum and the MYB acquired data. This justified the use of the MYB and only a 10 Hz cut-off second order Butterworth high-pass filter was implemented digitally to remove low frequency artefacts.

To account for the delay until steady state motions were reached, it was desired to train the prosthetic control system with both transient and steady state EMG data from each movement [24]. To achieve this, the subjects were to follow a trapezoidal trajectory, where they controlled a cursor that moved horizontally with time and vertically with EMG intensity. The recording was 11 seconds, where the trajectory had an incline/decline of three seconds and a plateau of five seconds, representing the transient and steady state, respectively. However, only data from the last second of the incline and first seconds of the decline was used to train the classifier to avoid active motion classes being misclassified with rest. The trajectory and cursor position was scaled relative to an initially recorded prolonged maximum voluntary contraction (pMVC) of 15 seconds. When performing the pMVC the subject was instructed in eliciting a strong voluntary contraction that could be held steady for 15 seconds. Data was acquired from three recordings per movement, where the plateau was 40, 50 and 70 % of the pMVC's, respectively. A last recording of 15 seconds rest was also performed.

For feature extraction, space-domain features designed by Donovan et al. [25] were applied. These were developed to enhance the classification accuracy when using the MYB for data acquisition by exploiting the relationship between EMG signals from neighboring electrode channels. The four non-redundant space-domain features of Scaled Mean Absolute Value, Correlation Coefficient, Mean Absolute Difference Normalized, Scaled Mean Absolute Difference Raw were extracted, along with the Hudgins feature Waveform Length to obtain an indirect representation of the frequency content [26]. Both offline and online features were extracted in windows of 200 ms with a 50 % overlap to obtain fast update time, while preserving robust classification accuracy [27].

The extracted features were used to train a sequential proportional control system. For sequential control, a LDA classifier was used and for proportional control multiple linear regression models were used.

The classifier was trained in distinguishing between five classes: wrist supination, wrist pronation, closed hand, opened hand and rest. A feature set was calculated for each of the eight electrode channels and subsequently concatenated resulting in a 40-dimensional feature matrix that was provided to the classifier. It was chosen to implement a LDA classifier due to it being fast to train, while still yielding robust control [28].

The proportional control model provided the control system with an actuation velocity proportional to the contraction intensity in a direction based on which movement class that was decided on by the LDA classifier. This was achieved by training four multiple linear regression models: one for each active movement class. The mean absolute value (MAV) was calculated in windows for all electrode channels and provided to the regression model as independent values, where the MAV scaled relative to the pMVC was provided as dependent values. During online control, the output was limited to a maximum velocity of 1 cm on the computer screen; corresponding to the intensity of the pMVC. Thus, the maximum velocity of the virtual prosthesis was 1 cm per update (100 ms). A full DoF would be completed from one extremity to another in two seconds, thus, achieving an actuation velocity similar to the commercially available Bebionic prosthesis [29]. A second restriction implemented was that a movement had to be performed with >15 % contraction intensity, for the virtual prosthesis to be actuated. This was included to get a more stable performance at rest.

C. 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 actuation of rotational and hand aperture DoF's. However, using a real prosthesis might result in auditory feedback being provided to the subject through prosthetic actuation sounds, eliminating the interest of solely exploring the impact of tactile feedback. Furthermore, simulating a virtual prosthesis would likely eliminate the output delay caused by motor actuation in a real prosthesis. Hence, it was chosen to simulate a velocity-based virtual prosthesis which enabled evaluation of the developed feedback schemes. In figure 5 is a depiction of a grid system, where the axes corresponded to the wrist rotation and hand aperture. The grid squares represented the discrete feedback variable intervals, and the cursor represented the current position state.

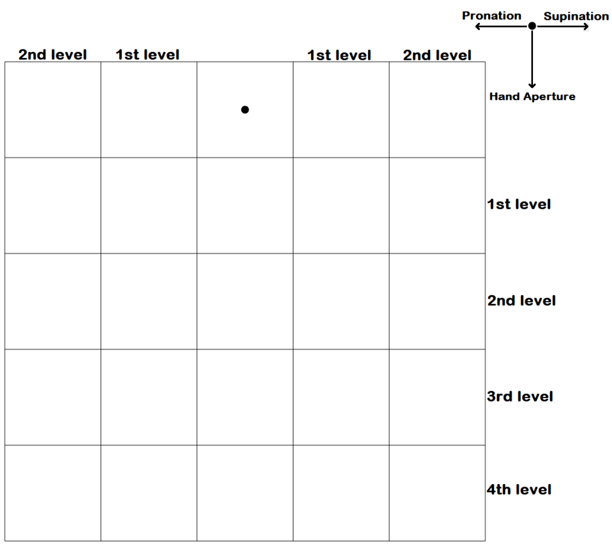

Fig. 5. Image of the grid map and cursor used in the experiment. Wrist supination moved the cursor to the right, pronation moved it to the left and closing the hand moved it downwards. For left-handed subjects, the rotational movements were reversed. Opening the hand moved the cursor upwards, and was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

Performing supination would make the cursor move to the right and to the left when performing pronation. Performing closed hand would make the cursor move downwards and upwards when performing open hand, resembling the change in hand aperture. Resting (relaxing the arm) would make the cursor stand still. Furthermore, the contraction intensity was

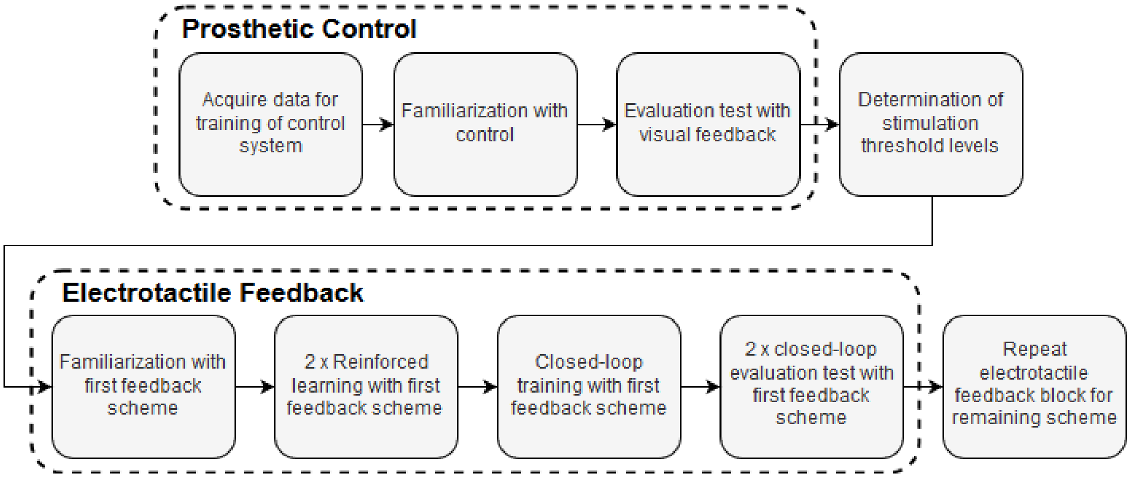

Fig. 6. Pipeline showing the stages of the experiment. The stages in the first block focused on developing a prosthetic control system, and evaluating the subjects' ability to control the prosthesis. Then stimulation threshold levels were determined. The second block focused on training the understanding of the feedback schemes and evaluating their usability in combination with prosthetic control. The electrotactile feedback block was repeated for the remaining feedback scheme.

made proportional with the actuation velocity, enabling the subject to have greater control of cursor movement. As the control was sequential the cursor could only move in one DoF at a time. The control scheme thereby resembled what is typically used in commercial prostheses [30]. When the cursor entered a given square a specific electrotactile stimulation would be provided corresponding to the stimulation pattern for each scheme. In the neutral position (location of cursor in figure 5), no tactile feedback was provided.

D. 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 feedback. 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 years) were recruited. Included subjects signed an informed consent form. The experimental protocol was approved by the ethical committee of Region Nordjylland, Denmark (approval number N-20150075). Each subject was introduced, trained and finally evaluated in the understanding of 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 6 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 electrotactile feedback schemes. The following text presents a brief chronological overview of the experimental protocol, and will be further elaborated on in the subsequent sections.

During the first block, EMG data was initially acquired and used to train a control system, which was used in controlling the simulated virtual prosthesis. In the subsequent stage, the subject was made familiar with the control system. The achieved prosthetic control was evaluated through a target reaching test. Afterwards, subject specific stimulation threshold levels were determined and used to convey electrotactile feedback. The subject then began the stages of familiarizing and training with one feedback scheme followed by re-familiarization of control in combination with receiving feedback. Finally, an evaluation test of using the electrotactile feedback in combination for control was conducted. The entire electrotactile feedback block was then repeated using the remaining feedback scheme. The duration of the experiment was approximately 2.5 hours.

E. Subject Control Training and Evaluation

The subjects were initially trained in controlling the virtual prosthesis via visual feedback. It was crucial for subjects to achieve robust control for the feedback configurations to be able to be evaluated in a closed-loop prosthetic control system. The subjects' control abilities were assessed empirically during trainings and quantitatively through a Fitts' Law inspired target reaching test. If a subject did not have a completion rate above 90 % and a mean time to reach a target at below 10 seconds the subject would be excluded.

The subject control training was divided into two runs of three minutes with a different visual feedback in each training. In the first training, the prosthesis was represented as a black cursor as seen in figure 5. The cursor position would update continuously with each control system output. In the second training, the cursor was invisible, and the visual feedback was instead the square containing the cursor being highlighted. This discretized visual feedback was implemented to equalize the visual and sensory feedback, and was used in the remaining training/test runs with visual feedback. During both training phases the subjects were instructed in practicing the ability to move the cursor in a desired direction and to transition from movement to rest.

During the target reaching test, the subjects had to reach targets (highlighted grid squares) visualized in a randomized order. The subjects had to match the discretized virtual prosthesis with the target and dwell in that position for 1.5 seconds for it to be deemed reached. The subjects had 30 seconds to reach a target. If either a target was reached or the time limit was reached, the virtual prosthesis would reset in neutral position. The test was finished when all grid squares had been highlighted, making a total of 24 targets.

F. Determination of Stimulation Levels

Providing meaningful sensory feedback required determination of four distinguishable subject specific stimulation threshold levels. Threshold levels were made solely amplitude dependent by keeping pulse width and frequency constant at 500 μs and 50 Hz, respectively. 1st level thresholds, termed perception thresholds, were determined for each pad by initializing the amplitude at 0 μA and then increase it in steps of 100 μA per second. The subject was instructed in reporting when stimulation could be perceived confidently. Subsequently, the amplitude values were readjusted by comparing the sensation intensity in neighboring pads to achieve homogeneous sensation intensities across all pads.

4th level thresholds, termed tolerance thresholds, were set using the same approach besides that the amplitude value was initialized at the perception threshold and increased in steps of 200 μA per second. The thresholds were determined when the subject reported that the sensation was on the onset of getting unpleasant, the stimulation was becoming functional or a maximum of 10,000 μA was reached. Amplitude values were again readjusted to achieve homogeneous sensation intensities. Throughout the process of determining values, the subject was faced away from the screen to avoid bias from observing the visual increase of amplitude values. Intermediate threshold levels 2 *lvl2* and 3 *lvl3* were calculated for the i^{th} pad based on the perception p and tolerance t threshold levels as:

$$lvl2_i = p_i + \frac{1}{3} \cdot (t_i - p_i) \quad (1)$$

$$lvl3_i = t_i - \frac{1}{3} \cdot (t_i - p_i) \quad (2)$$

G. Sensory Feedback Training

Following the determination of stimulation thresholds, the subject was trained in understanding a sensory feedback scheme. The sensory feedback training was divided into two phases: familiarization and reinforced learning.

The familiarization phase provided the subjects with a short and controlled introduction to the scheme. The cursor was visualized and moved by the investigator from the neutral position to a designated state incorporating the transition from one square to the next, thus, presenting the subject with the coherence between feedback variable level and position state for a designated state. Feedback variable levels in the top and bottom row and the middle column were presented actively, while the remaining 12 levels were presented indirectly as transition levels. Moving to feedback levels of 4th level hand aperture combined with either 1st or 2nd level wrist pronation and supination was done by first moving in the rotational DoF. Time spend in designated states was approximately four seconds and time spend in transition states was approximately two seconds. Recognition of single DoF position states was assessed to be most crucial for comprehension, hence, these were favored in the familiarization phase.

In the reinforced learning phase, the subject was asked to face away from the screen. The cursor was directed to a designated state and the subject then had to report what the current position state was based solely on the felt feedback variable. If the subject answered correctly, the cursor was reset to the neutral position and then moved to a new target. If the subject answered incorrectly, the correct state would be communicated to the subject before continuing. Each position state would be presented once and be moved to by taking the optimal path (move the cursor fully in one DoF before the other). However, which DoF the cursor would move in first was varied. Hence, the subject could utilize the transitions made when guessing the current state. The order of the designated states was predetermined by the investigators. Time spend in transition states was approximately two seconds. When all 24 position states had been trained, the subject was given a short break before repeating the reinforced learning. However, the order and paths were changed for the second run.

H. Closed-Loop Evaluation

The subject had until this point trained the prosthetic control and sensory feedback separately. The motor function and sensory feedback was now combined in a closed-loop prosthetic system. During this final evaluation test the visual feedback regarding the position state was eliminated. The subject then had to rely on the sensory feedback to assess the position state.

Before undergoing the test the subject was given a three minute training period to get reacquainted with the prosthetic control and to further train the understanding of the feedback scheme. The evaluation test was identical to the evaluation test with visual feedback presented in section II-E, besides that the virtual prosthesis was not visualized. Thus, the subject had to solely rely on electrotactile feedback, when reaching a target. The evaluation test was performed two times consecutively.

I. Statistical Analyses

The metrics extracted from the evaluation tests were number of reached targets, time spend per target and path efficiency. Paired comparisons were made between results from evaluation tests. Due to the sample populations not being normal-distributed based on one-sample Kolmogorov-Smirnov tests, comparisons were made using non-parametric statistics. Wilcoxon signed rank test was applied as comparisons was made on related samples obtained from a two block study design. A significance level of $p < 0.05$ was used.

III. RESULTS

A. Prosthesis Trajectories

Figure 7 illustrates two example prosthesis trajectories from the amplitude feedback evaluation test with combined DoF states as targets: one ideal trajectory (top figure) and one feedback-assisted path correction (bottom figure). The ideal trajectory indicates a total comprehension of the feedback, where no overshoots or detours were performed. The feedback-assisted path correction is an example of a subject overshooting the hand aperture level before performing supination. However, this was compensated for as the subject moved directly in the correct hand aperture level after reaching the correct supination level. This illustrated the subject's ability to utilize the feedback when correcting for an overshoot.

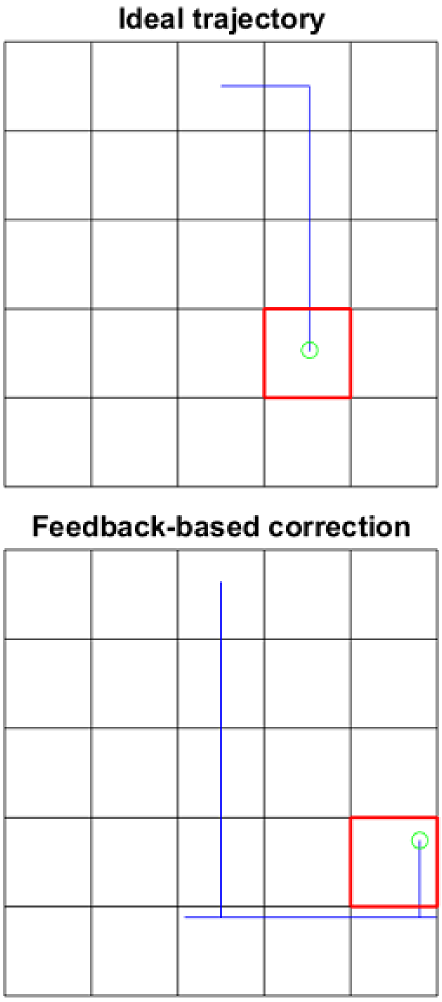

Fig. 7. Examples of two prosthesis trajectories when reaching a combined DoF target in the amplitude evaluation test. The top figure shows an ideal trajectory and the bottom figure illustrates a feedback-assisted path correction. The blue line is the prosthesis trajectory, the center of the green circle is the end position and the red square is the targeted state.

B. Evaluation Metrics

The evaluation metrics from first to second evaluation test in each feedback scheme did not yield significant difference ($p > 0.05$). Therefore, it was chosen to view these evaluation tests as one, by calculating the mean between the first and second evaluation test in both blocks, resulting in a single test result for the spatial feedback and a single test result for the amplitude feedback.

Figure 8 shows box plots of the extracted metrics for the visual, spatial and amplitude feedback evaluation tests. The mean completion rate for the amplitude evaluation test was 93 % ± 6 % and 87 % ± 11 % for the spatial evaluation test, which slightly favoured the amplitude feedback ($p = 0.044$). This quantitative result was also supported by the subjective opinion of the subjects as 64 % of the subjects favoured the amplitude feedback. However, all subjects struggled in choosing a favoured feedback scheme as they found both intuitive to understand. Worth noting was that visual feedback still outperformed electrotactile feedback both when spatially or amplitude modulated for the completion rate and time to reach a target metrics. However, these high completion rates along with the subjects' impression indicated a great usefulness associated with both schemes.

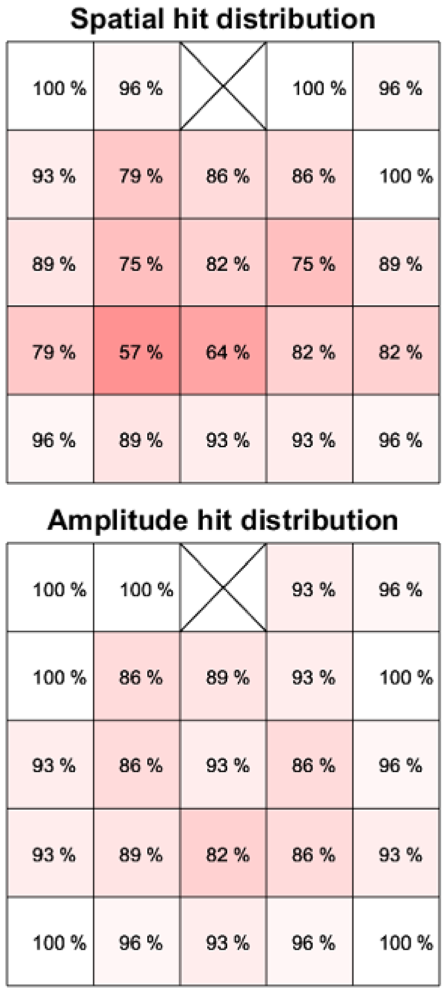

Fig. 9. Hit rate for each target in the spatial and amplitude evaluation test, respectively. The more transparent a target is, the higher the hit rate was. 100 % accounts for a total of 28 hits for each test.

C. Target State Hit Distribution

Figure 9 shows the hit distribution for all feedback variable intervals in both feedback schemes. Common for both feedback schemes was that the centered targets (targets not touching the outer boundary) were more troublesome to reach: mean completion rate for centered targets was 76 % ± 10 % with spatial feedback and 88 % ± 4 % with amplitude

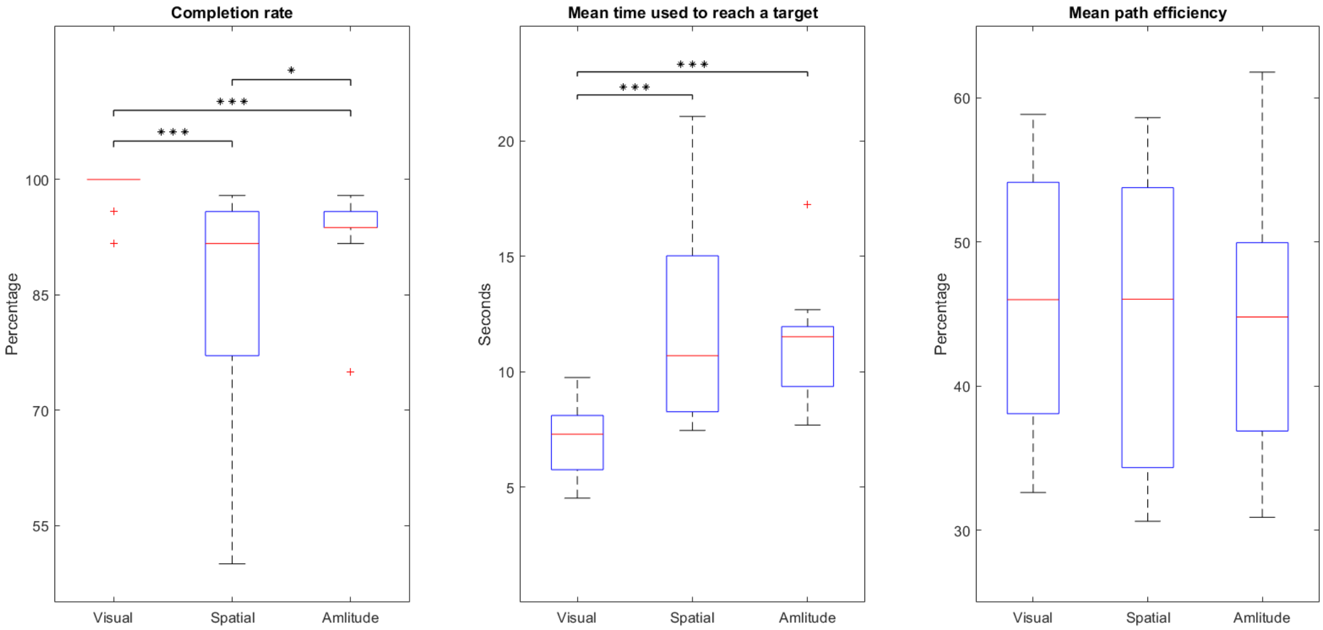

Fig. 8. Box plots of the metrics extracted from the visual, spatial and amplitude feedback evaluation tests. The two evaluation tests in the spatial and amplitude feedback block, respectively, were combined by calculating the mean between the two tests. One asterisk indicates p-value < 0.05 and three asterisks indicates p-value < 0.001.

feedback; mean completion rate for peripheral targets was 93 % ± 6 % with spatial feedback and 97 % ± 3 % with amplitude feedback. A possible reason for this finding is that the subjects had to achieve complete rest to dwell inside these targets. In the peripheral targets, the subjects did not necessarily need to achieve complete rest, as they could continue performing a movement and still be on the boundary of the target. This was due to the cursor being restricted to the outer limit in order to resemble practical prosthetic actuation.

Furthermore, combined DoF targets (all targets besides first row and third column targets), generally had a lower completion rate for the spatial feedback scheme: mean completion rate for single DoF targets was 90 % ± 12 % with spatial feedback and 93 % ± 6 % with amplitude feedback; mean completion rate for combined DoF targets was 85 % ± 11 % with spatial feedback and 93 % ± 6 % with amplitude feedback. This could indicate that the sensory feedback regarding combined position states in the spatial feedback scheme was slightly harder to interpret than in the amplitude feedback scheme.

Lastly, for both schemes a higher completion rate was achieved for rotational single DoF targets compared to hand aperture single DoF targets: 98 % ± 2 % for rotational single DoF targets during spatial feedback and 97 % ± 3 % with amplitude feedback; 81 % ± 12 % for hand aperture single DoF targets during spatial feedback and 89 % ± 5 % with amplitude feedback. This could indicate that either the feedback regarding wrist rotation was easier to comprehend, or the control for the rotational DoF was better.

IV. Discussion

Two intuitive electrotactile feedback schemes were developed for a two DoF velocity-based virtual prosthesis: one spatially modulated and one amplitude modulated. The schemes were integrated in an easy implementable 16 pad electrode array and tested in combination with sequential proportional myoelectric control. Unique sensory feedback was provided for four levels of position states in single DoF's and for 16 position states representing combined DoF's. The objective was to investigate the usability of the developed feedback schemes when removing visual dependency.

From the metrics extracted describing the subjects' performance in the evaluation test, only completion rate indicated a slight dominance in favor of the amplitude scheme compared to the spatial scheme (p-value = 0.044). However, with a mean completion rate of 93 % ± 6 % and 87 % ± 11 %, respectively, both feedback schemes can be deemed intuitive to utilize in combination with myoelectric control when removing visual dependency. Considering that these completion rates were obtained from a minimal training protocol (training time per scheme < 30 minutes), a completion rate close to visual feedback (99 % ± 2%) might be achieved if more training blocks were included. However, as stated in [31], vision is more dominant in motor learning than proprioception, and a completely equal performance should, therefore, not be expected.

Compared to the results of Strbac et al. [11] the results of recognizing four DoF stimulation patterns which achieved a success rate of 99 % ± 3% for able-bodied subjects, the usability of the derived schemes seems lower. However, Strbac et al. did not test the usability of their feedback schemes in combination with control. Furthermore, recognizability was only investigated for each DoF independently and not in combinations as in this study. We speculate, that eliminating these variables, similar results would be achieved when subjects were given adequate training time.

In the reinforced learning, the mean success rate for the spatial scheme was 73 % ± 17 % and 78 % ± 16 % for the amplitude scheme. This was a notably lower success rate than obtained from the closed-loop evaluation tests. This could indicate that when put into the intended application, a higher understanding of the feedback can be accomplished. If the training block had the same duration, but was solely closed-loop-based, an even higher success rate might have been achieved in the evaluation tests.

A. Sensory Threshold Levels

Some subjects reported that it was difficult to separate levels in both DoF's in the spatial scheme, due to a notable difference in sensation intensity between levels. A different approach in the determination of sensory threshold levels might have removed this confusion in the spatial feedback. The amplitude levels were determined by setting the threshold level for the electrode pads in a consecutive order. This might have caused a slight adaptation in the sensory perception of the subjects, which distorted the sensation intensity when applied in the sensory feedback training and the evaluation tests. By interleaving the order of designated electrode pads, or by making the determination of threshold levels more scheme related (setting threshold levels simultaneously for pads connected in the schemes), could have made the sensation intensities more homogeneous across all pads. A weak functional electrical stimulation due to summation of active stimulation pads was observed in few subjects during the amplitude sensory feedback training, and might also have been avoided by relating the determination of threshold levels to the schemes.

B. Future Works

As mentioned, even with a minimal training, the results indicated a clear intuitiveness in understanding both feedback schemes when tested in a simulated virtual prosthesis. However, as the ultimate aim is to develop a prosthetic device, which users can apply in daily life tasks without being reliant on visual feedback, some aspects needs to be taken into consideration before testing the feedback schemes in a real prosthesis.

The stimulation electrode setup used in this study might interfere with the recording electrodes when fitted on the same arm. In that relation, it should be considered to use concentric electrodes that minimize current leakage. Furthermore, the schemes were tested in a ideal non-delayed control system. When applied in a real prosthesis, the motor actuation will likely cause a delay that might lower the effectiveness of the feedback schemes.

For further improvement of the naturalness of the feedback schemes, it would be of great interest to investigate the performance of the feedback scheme concepts in a less discretized environment (increase number of feedback variable levels). With the electrode array used in this study, especially the amplitude scheme has a huge potential, as only the device restrictions and subjects' sensory discrimination abilities are a limit.

In the evaluation tests, only the active movement of the grasping DoF (closing the hand) was assessed, and the starting point was always resting state (no feedback received). In future studies, it could be investigated how the performance would be if the starting point was varied, e.g. by randomizing the starting point to resting state and highest level hand aperture, or by not resetting the position state when a new target state appeared. This would demand the subjects to more comprehensive understand the feedback, as they would not as rigidly be given reference states during the tests, and the test would be more transferable to practical prosthetic use.

Finally, as the schemes were easy comprehensible, an expansion of the scheme concepts to represent more feedback variables would be a large step towards producing a prosthetic device concept with the potential of enhancing the users' prosthetic embodiment. Since electrotactile stimulation allows for modulation of frequency, another feedback variable could be included enhancing the complexity and amount of information which can be conveyed. For instance, proportional grasp force feedback was the most important feedback to restore according to [5]. This could be restored using frequency in a similar fashion as done in [32], where grasp force was modulated via stimulation frequency.

V. Conclusion

This study investigated the intuitiveness of two novel electrotactile feedback configurations communicating proprioceptive information of a two DoF closed-loop myoelectric prosthesis: one modulating the spatial activation of electrode pads and one modulating the current amplitude. The evaluation tests showed that even with minimal training (< 30 minutes) a mean success rate of 93 % ± 6 % and 87 % ± 11 % can be achieved for the amplitude and spatial modulated configurations, respectively; and along with subjects reporting that both feedback schemes were easily comprehensible, the developed feedback schemes can be deemed highly intuitive. As the stimulation setup demanded scarce space, it could be easily integrated in a two DoF myoelectric prosthesis, potentially enhancing the prosthesis embodiment in users. Moreover, especially the amplitude feedback scheme had the potential to convey the position states even less discretely, which would further increase the naturalness of use.

Appendix

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Part II

Worksheets

1 | Background

The background chapter will outline the considerations that needs to be made when testing the usability of sensory feedback configurations in combination with myoelectric prosthetic control. The feedback will be given based on which position state a pattern recognition controlled prosthesis is in.

The main idea behind myoelectric prosthetic control is to translate recorded muscle signals (EMG signals) into a motion performed by the prosthesis. Often, if possible, EMG is recorded from the muscles which were used to perform movements with the biological hand and used for prosthetic control. A pattern recognition model can be trained to differentiate between a set of movement classes. When receiving a segmented part of an EMG signal, it then decides upon which movement class that most likely is being performed. In combination with the elicited muscle contraction level, this is used as input in the control system and the prosthesis should perform a corresponding motion. [1] In a closed-loop prosthesis, the position state the prosthesis is in can be coded to be equivalent to a certain sensory feedback. The should enable the user to interpret the sensory feedback and use as additional information to visual feedback about the prosthesis' position state. [2] A closed-loop prosthesis iteration can be seen in figure 1.1.

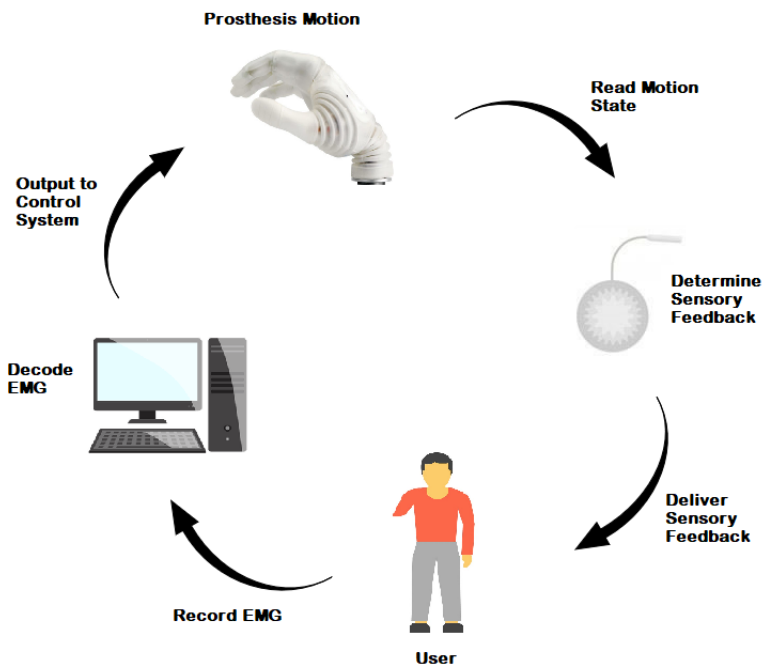


Figure 1.1: The figure shows the stages of a closed-loop prosthesis. First, EMG signals are recorded from the user. The signals are decoded and an output is relayed to the control system, which is used for the prosthesis to perform a motion. The position state is then read and sensory feedback is delivered to the user regarding which position state the prosthesis is in.

Regarding control the background chapter will explain the following: generation of EMG signals, data acquisition, data processing, pattern recognition and proportional control.

Regarding sensory feedback the following will be explained: types of sensory feedback, prior investigations on sensory feedback and sensory feedback configurations.

1.1 Sensory Feedback Stimulation

It is recognized that vision alone does not provide a sufficient amount information to achieve efficient daily life use of a prosthetic device, as the use requires full visual attention. In the effort of regaining the cutaneous sensations previously felt by the lost limb of a transradial amputee, stimulations of various sorts can be applied on the skin of the remaining stump. These stimulations mimic the information sensed by the lost limb by activating cutaneous receptors. It has been shown both in the acute phase and long term that providing the amputee with sensory feedback can reorganize neurological pathways or even recover original pathways during motor tasks, when trained amply. [3]
Hence, efforts have been put in investigating methods of providing proprioceptive and exteroceptive information of e.g. grasp strength and position state through the means of artificial stimulation. [4, 5] Presently, there are multiple ways of providing the user with a variety of sensory feedback. These can be divided into three categories: somatotopical feedback, modality-matched feedback and substitution feedback. [4]
This section will present general concepts in sensory feedback stimulation and give a brief overview of the types of sensory feedback in order to give insight in the possibilities and eventual disadvantages when providing the user of a prosthetic device with feedback.

1.1.1 Somatotopical Feedback

Somatotopical 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, somatotopical 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, 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 enables 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 cognitive attention. [4]

1.1.2 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 at another site. 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 e.g. on the residual limb. Thus, the sensation is not matched in location, but only in sensation. Mechanotactile feedback which conveys pressure information is utilized by the use of e.g. pressure cuffs or servomotors. These types of tactors are very useful for modality-matched feedback, but have a disadvantage by being more power consuming and less practical compared to other stimulation types. [4, 6]

1.1.3 Substitution Feedback

Substitution feedback methods convey sensory information 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. [4, 6]

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 mostly used to transfer tactile information in prosthetic grasping tasks. [4] 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. [6]

Electrotactile Stimulation

In electrotactile feedback a sensation is achieved by stimulating the primary myelinated afferent nerves with an electrical current. The sensation which the stimulation invokes has been reported to be tingling, prickling, itching, buzzing, physically touching and/or burning. [4] 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, this property can be seen as an advantage as prosthetic users strongly desire lightweight systems [5, 7]. 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. However, 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. [4, 5, 6]

1.2 State of Art in Electrotactile Feedback

Section 1.1 presented different types of sensory feedback from which the choice of stimulation in this project can be drawn upon. Somatotopical feedback might provide the most natural sensations, but is also the most complicated to implement. Modality matching the feedback should instead be sought, however present tactors are larger and more power consuming than electrodes uses in electrotactile feedback. Furthermore, the dimensions of stimulation electrodes facilitate easier integration with the prosthesis as these can be placed inside the socket, along with electrodes used for acquisition. However, this requires that a solution for leakage current is found. Modulating pulse width, frequency and amplitude in electrotactile feedback gives more possibilities for 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 previous investigations.

Multiple studies have investigated the use of electrotactile feedback regarding both how distinguishable sensations can be evoked and how to convey sensory feedback in different coding schemes for improving myoelectric prosthetic control [5]. In 2015, Shi and Shen [8] 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 0.3 to 3 mA, pulse width from 0.1 to 20 ms and frequency from 40 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 too large or too small electrode diameters could result in sensations of pain or discomfort. [8]

Several studies [9, 10, 11, 12] using electrical stimulation have investigated its use in conveying grasping force/pressure feedback. Jorgovanovic et al. [11] investigated users' recognition of grip strength, when controlling a joystick controlled robotic hand, through varying the pulse width and keeping the frequency and amplitude 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. [11] Similar result were found by Isakovic et al. [12], 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. Electrotactile feedback was provided by keeping the intensity and frequency constant and then varying the pulse width between 0 and 500 μs indicating changes in grasp force. In this case, visual feedback was found to outperform electrotactile feedback. [10]

Pamungkas et al. [9] also tested the use of electrotactile feedback to convey information from pressure sensors located in a robotic hand. 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, 60 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. [9]

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 [13, 14]. 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 proprioceptive recognition In 2016, Strbac et al. [2] presented a novel electrotactile feedback stimulation system, which could be used to convey information about the current position 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 feedback. The state of 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 % while able-bodied subjects had a success rate of 99 %. [2]

In summary, most studies have focused on using electrotactile feedback for exteroceptive means while only few have investigated its use for proprioceptive feedback. However, studies investigating proprioceptive feedback encourage further investigation into how electrotactile feedback can be utilized for providing meaningful proprioceptive feedback [2].

1.2.1 Sensory Adaptation in Electrotactile Feedback

Before implementing an electrotactile feedback interface, it is important to consider the effect electric stimulation might impose on the sensory system.

Adaption is defined as a changing sensory response to a constant stimulus, and all sensory systems have shown adaptive tendencies [15]. This could result in undesired effects during prolonged electrical stimulation. Hence, it is crucial to consider stimulation parameters which reduce adaption. Sensory adaption usually occurs within minutes, and reaches a maximum after 15 min. Furthermore, the adaption rate is related to the stimulation amplitude as adaption occurs faster when closer to the pain threshold. Low frequencies (<10 Hz) show less adaption compared to higher frequencies (>1000 Hz). The adaption response is found to be exponential in decay and recovery. [15, 16] However, sensory adaptation can be overcome by using intermittent stimulation, and preferably, stimulation interfaces should consider conveying feedback information through diversified patterns [16, 17].

Developed feedback schemes should consider using as low amplitudes as possible to reduce the rate of sensory adaption. Furthermore, continuously changing the site of stimulation should also facilitate less adaption.

1.3 Closing the Loop

The loss of a limb does not only result in loss of motor function as sensory function also gets impaired. Providing an amputee with a prosthetic device, which does not provide sensory feedback, only restores one half of the once closed motor/sensory loop. To close the loop the prosthetic device needs to extract proprioceptive and exteroceptive information, which should be conveyed to the amputee in a intuitive and meaningful way [18]. This can be achieved using methods of sensory substitution as mentioned in section 1.1.3.

Closing the loop is a well recognized need amongst prosthetic users and using substitutional sensory feedback holds the possibility of lowering need for visual attention to track correct prosthetic movement. This might furthermore improve easiness of use and embodiment, which could lower rejection rates. [2] However, the advantages of closing the loop by providing sensory substitution feedback have been contradictory [11]. In 2008, Cipriani et al. [19] investigated the use of vibroctacile feedback for improving prosthesis grasp function and did not find any improvement when providing the sensory feedback. Later findings by Witteveen et al. [20] disproved this as they found that when providing information of grasp force and slip through vibrotactile feedback improved a virtual grasping task.

Even though studies like [11, 20] found closing the loop by providing grasp force sensory feedback helpful, currently only one commercial feedback providing device, VINCENT evolution 2 (Vincent Systems Gmbh, DE), is available [21]. However, no devices have yet to implement means of proprioceptive feedback. Additionally, closed-loop control systems bypassing human interaction have also been investigated and implemented by commercial manufacturers i.e. Otto Bock and RSL steeper. Actuators are made to autonomously adjust grip force based on sensors located in the prosthetic hand, thereby not involving the user in the final execution of the task. [10] Such an approach might improve reliability of the prosthesis, but does not provide proprioceptive and exteroceptive feedback to the user, hence not promoting full naturalness.

1.4 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.

1.4.1 Stimulation Electrode

The 1×16 multi-pad stimulation electrode, can be seen in figure 1.2. 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 can be improved by applying conductive hydrogel pads to the electrode pads. [2]

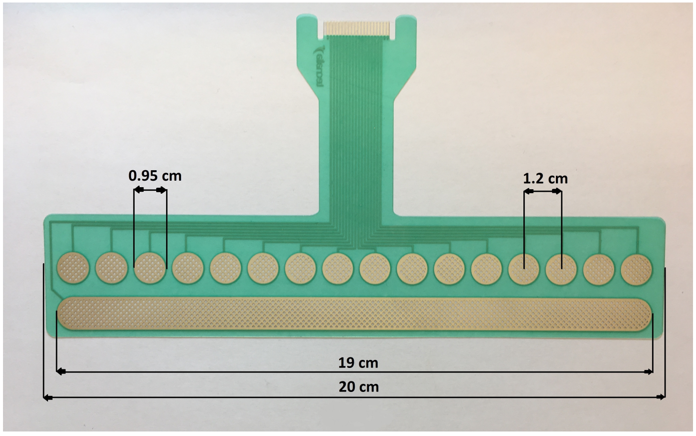


Figure 1.2: The 16 multi-pad electrode used for stimulation consists of 16 circular cathode pads, which each share a common anode.

1.4.2 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 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.

1.5 Electromyography

The control of a myoelectric prosthesis is based on recorded myoelectric signals. [22] 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 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 will activate and direct a nerve impulse along its axon to multiple motor endplates, which each innervate a muscle fiber. The motor neuron and the muscle fibers it innervates is in collection called a motor unit. [23]

The nerve impulse 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 at -80 mV to -90 mV, by ion pumps, which passively and actively control the flow of ions 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. The created action potential will propagate in both directions on the surface of the muscle fiber. This process happens across all muscle fibers in a motor unit. The action potential is also known as a motor unit action potential (MUAP), and it is the superposition of multiple MUAPs that is recorded through surface EMG. The action potential is still measurable on the skin surface, however, some limitations in surface EMG are that the recording is restricted to superficial muscles, that the amplitude of the EMG signal is affected by the depth of subcutaneous tissue and that the distinguishability of MUAP's from adjacent muscles is unreliable. [23, 24]

Acquisition of EMG signal can either be carried out through surface EMG or intramuscular EMG. The latter measures MUAPs through needles inserted into the muscle and can and collect MUAPs from single muscle fibers individually. Surface EMG is acquired through electrodes on the skin surface. [25] 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. To further minimize skin-electrode impedance removal of excess body hair or flaky skin and cleansing the area using alcohol swabs should be considered. [23, 25] In this project, MUAPs will be recorded through surface EMG. An example of a surface EMG recording of two different movements (pronation and supination of the wrist) can be seen in figure 1.3. Here, the surface electrodes are placed at the circumference of the forearm of the subject. It can be seen that some electrode channels are more or less active when comparing the two movements. This corresponds to different muscles being more or less contracted depending on which movement that is performed. This facilitates the distinguishability the recognition of which movement is being performed. A prerequisite for this to work is that the electrode placement must be identical throughout the recording. If not, the activation of the various channels shifts spatially, and the accuracy of the trained recognition system might be decreased.

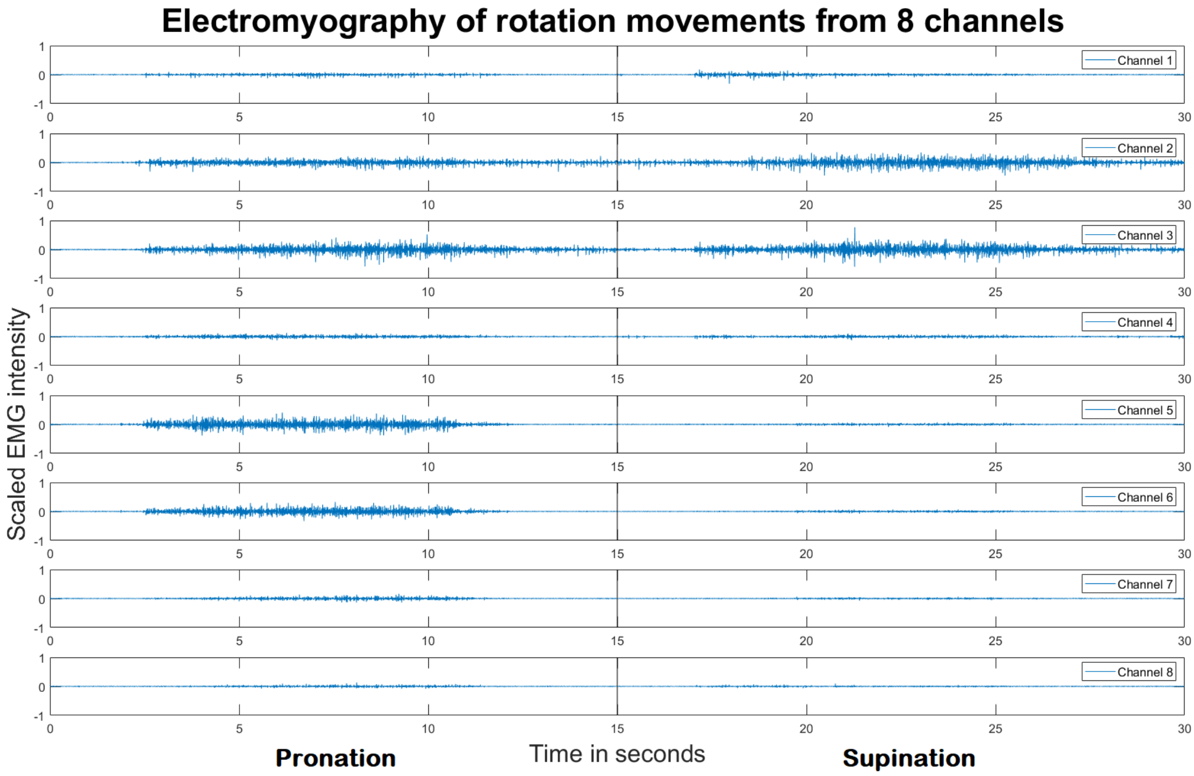


Figure 1.3: Illustration of an eight electrode channel surface EMG of the forearm during pronation (left side) and supination (right side) of the wrist. The recording was acquired using the Myo Armband, see figure 1.4. The 4th channel was placed on the thickest part of the forearm centrally on the dorsal side, when using a pronated arm as reference position, with the horizontal LED light faced laterally towards the wrist.

1.5.1 Data Acquisition

Before a user can utilize a myoelectric prosthesis the control system needs to be taught how certain movements look like represented as EMG signals. This process is called training the control system. The acquisition of training data from the user is therefore the first step in training the control system.

In the acquisition of EMG signals the Myo Armband (MYB) from Thalmic Labs will be used. It contains eight dry stainless-steel electrode channels 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, the MYB can be reused for all subjects participating in the project, which enables 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. [26]

The 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 50 Hz notch filter 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 an irrelevant task. However, a comparison study showed that using the MYB in a Linear Discriminant Analysis (LDA) control scheme can achieve similar performance accuracy compared to using conventional gel electrodes with a sample rate of 1000 Hz [27]. Additionally, the MYB contains a 9 axes inertial measurement unit, but will not be utilized in this project and will therefore not be further elaborated on. [26]

During initialization of the MYB the user has to follow two calibration steps: the warm up and the synchronization. In the warm-up step, the 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. The MYB works most optimally when tightly fit. To ensure a close fit, a set of clips can be used if necessary. [26]

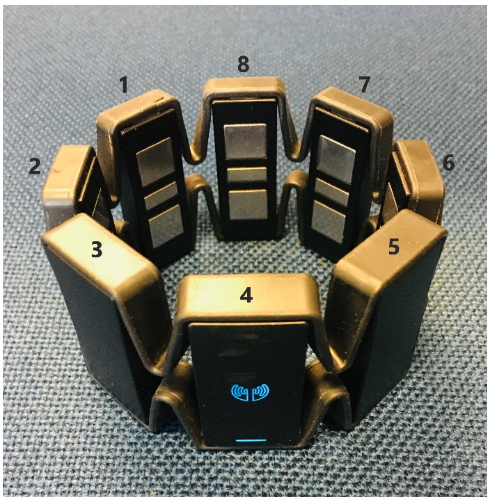


Figure 1.4: Image of the Myo armband from Thalmic Labs. Electrode channel 1 corresponds to the first output in the recording and electrode channel 2 as the second etc., as seen in figure 1.3.

1.6 Data Processing

In order to use the acquired data most optimally in the myoelectric prosthetic control scheme, the data must be processed. In this processing, undesired frequencies are filtered out and features that represents the data are extracted from segments of the data in order to obtain more information about the movement than only using the raw EMG signal. This data processing will be covered in the following sections.

1.6.1 Filtering

To remove unwanted frequencies from the EMG signal, it should be filtered. According to the Nyquist Theorem, the rate the signal is sampled with must be at least twice the highest frequency contained in the signal to achieve a non-aliased digital recording. However, as mentioned in section 1.5.1, the MYB samples with a rate lower than the highest frequency in the EMG spectrum, without having any analogue bandpass filter implemented. The rationale behind incorporating a digital anti-aliasing filter is therefore defeated. Implementing a digital high-pass filter with a corner frequency at 10 Hz to remove low frequency miscellaneous biological noise would, however, be desirable. [25]

1.6.2 Segmentation

The extraction of features are done in discretely segmented windows of data, instead of calculating the features from instantaneous values. In online control, the length of windows is a compromise between classification accuracy and delay in prosthetic control. Often an window overlap is implemented. This is a technique applied to ensure short delays, while still enabling a high classification accuracy. When applying an overlap values from the previous window is reused in the current window. The amount of overlap chosen is significant for the performance of the control scheme. Generally, it is recommended to have window lengths of 150-250 ms and use a 50 % overlap [28]. Choosing a large overlap will result in short delays, but worse classification accuracy and vice versa. When using the MYB it is important to take the low sample rate into consideration, as a window will contain less data compared to if the sampling was appropriate to the EMG frequency properties. [28] Short windows will therefore likely result in worse classification accuracy compared to appropriately sampled data segmented in an identical window length.

1.6.3 Feature Extraction

Instead of only utilizing the raw EMG signal in a control scheme, features are extracted to exploit more representations of the EMG signal that optimally results in robust control. Various independent features can be extracted from the signal either from the time domain, frequency domain or the time-frequency domain. Most commonly features from the frequency and time domain are used. When extracting frequency domain features it is required for the EMG signal to be transformed into the frequency domain. This takes more computation time compared to extracting features directly from the time domain. For this reason features in the time domain are usually favoured. [29] Especially used are the Hudgins features: Mean Absolute Value (MAV), Zero Crossings (ZC), Slope Sign Changes (SSC) and Waveform Length (WL) [30]. However, both ZC and SSC represent the frequency content of the signal, which most likely has been distorted by the low sample rate. When using the MYB for EMG acquisition an alternative set of features has been suggested by Donovan et al. [31]. These features are so called space domain features, since they exploit the relationship between the output from the electrode channels. When evaluating data acquired from the MYB the space domain features increased classification accuracy by 5 % in an LDA-based control scheme compared to using the Hudgins features [31]. A final consideration to make when choosing features is to avoid redundancy as these features would not provide additional information about the signal but increase the computation time while not increasing the classification accuracy.

1.7 Pattern Recognition

For a myoelectric prosthesis to know which movement to perform, it needs to know how to differentiate between the movements. For this purpose classification is a commonly applied model. The classification model, or classifier, is fed known data consisting of features extracted from the raw EMG signals, which were recorded while the user was performing different movements. If each of the known feature data sets related to each movement is known they can be labelled appropriately, and the classifier will then learn which data represents which movement. Each label is known as a class and the process of labelling the data is called supervised learning. The known data is also called training data, hence this process is called training the classifier. If the classifier is trained properly, it is able to categorize unknown data accurately into the correct class. This is what happens online in each segmented data window when using a pattern recognition-based myoelectric prosthesis. The classifier is, however, only able to categorize unknown data into one of the trained classes. [32]

A frequently used supervised classifier for myoelectric prosthetic control is the LDA classifier. An advantage of using LDA is that it enables robust control, while having a low computational cost [33]. LDA will be used in this project to determine motor function and an overview of the theory behind LDA will be given in the following section.

1.7.1 Linear Discriminant Analysis

LDA determines decision boundaries between the desired number of classes, where the distance between the decision boundary and the centroid of the class feature values is maximized. Such a decision boundary is defined as a linear combination of the feature values x:

$$g_j(x) = weight_j x + bias_j \tag{1.1}$$

where $weight_j$ decides the orientation of the decision boundary of class j, and $bias_j$ is a bias that decides the position of the decision boundary of class j in relation to origo.

The decision rule of an LDA classifier is based on which class that has the highest probability of having produced the input feature values; also called the posterior probability. Given this decision rule, LDA can be derived from the Bayes theorem, which expresses the posterior probability as:

$$P(\omega_j|x) = P(x|\omega_j)P(\omega_j) \tag{1.2}$$

where $P(x|\omega_j)$ is the class conditional probability, the probability that a feature value from class j appears, and $P(\omega_j)$ is the prior probability, the probability that class j

appears. This can be written as the function:

$$g_j(x) = P(x|\omega_j)P(\omega_j) \tag{1.3}$$

An constraint in LDA is that each class is Gaussian distributed and all classes share the same covariance matrix. The class conditional probability can therefore be written as the multivariate normal distribution, in which the class conditional covariance matrix can be written as the common covariance matrix. This leaves the following function:

$$g_j(x) = \mu_j \Sigma^{-1} x' - \frac{1}{2}\mu_j \Sigma^{-1} \mu_j' - ln(P(\omega_j)) \tag{1.4}$$

where μ_j and Σ^{-1} are the mean vector for class j and the common covariance matrix, respectively. The function in equation (1.4) can be written in the common linear discriminant classifier form as in equation (1.1). [34] Thus, a posterior probability is calculated for each class based on the decision boundaries, and according to the decision rule, the class with the highest probability of having produced the input feature values will be chosen as the determined motor function. However, LDA only determines the movement class, but does not enable control of the motion speed the actuator must perform. For this purpose an additional control scheme must be applied to activate the determined motor function in a proportional matter. [35]

1.8 Proportional Control

After the motor function has been determined, a mapping of the control output needs to be performed. The advantage of providing a continuous output to the actuator proportional to the contraction intensity compared to a one-speed controller is that the user has the possibility of grasping objects quickly, while still being able to perform more slow and dexterous tasks. Additionally, proportional control resembles the human neuromotor system, which makes it more intuitive. [35]

A widely used proportional control scheme is linear regression [35]. Here, a dependent output value can be calculated based on a function of an independent input value. In the case of using several electrode channels as when using the MYB, the output needs to be computed based on several independent values. For this purpose multivariate linear regression would be appropriate:

$$\hat{Y} = \alpha + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_i X_i + \epsilon_i \tag{1.5}$$

where $\hat{Y}$ is the control output and X_i is the independent input values, where the index i will correspond to the number of electrode channels in the MYB. α and β are the estimated value of $\hat{Y}$ at $X = 0$ and estimated regression coefficients, respectively. The absolute values of the recorded EMG signals can be used directly as the independents input value in such a proportional control scheme. [36] However, a regression model needs to be estimated for each motor function in the control system. Then the appropriate regression model will be selected based on the classification output.

1.9 Performance Evaluation

Evaluating the performance of a derived control system can be achieved through the completion of various tasks. If available, the system can be interfaced with a myoelectric prosthesis, and based on the completion of tasks mimicking daily life functionality (e.g. grasp and movement of objects), performance can be evaluated [37]. Otherwise, virtual environments have been widely used showing movements of virtual prostheses [38] or by moving a cursor to targets resembling motor function, where performance can be quantified through measurements based on Fitts' Law [34, 39, 40]. An obvious measure to observe is the completion rate (CR), which is the ratio of reached targets compared to the total number of targets. This describes the overall ability the user has when using the control system. Path efficiency (PE) can be used to observe how efficiently continuous movement control is achieved by comparing the distance travelled to reach a target to the most direct route. To observe how well the user can keep the system at rest and control velocity, stopping distance (SD) and overshoot (OS) can be measured. The former measures the distance travelled at times where no movement is intended, and the latter tracks the number of times the user reaches a shown target, but leaves before completion. [34]

2 | Study Objective

In summary, there is still a need for myoelectric prosthetic devices to fully close the neural loop by providing amputees with proprioceptive feedback to lower the need for visual attention. As presented in section 1.2 most studies have focused on providing exteroceptive feedback, while only very few studies have investigated how proprioceptive information could be conveyed to aid prosthetic control in cases where visual attention is less wanted. Using the modality of electrotactile stimulation as a mean of transferring information of position states offers multiple stimulation parameters which can be modulated through several channels enabling possibilities for intuitive and meaningful sensory feedback. However, even though several opportunities present themselves in modulating the stimulation amplitude, frequency and active channels, it would be of great interest to investigate which modulation would lead the sensory feedback to be perceived most intuitively. As stated in section 1.4 the frequency cannot be controlled individually for each pad in the electrode, thus a feedback scheme modulating frequency will not be investigated in this study.

Investigating whether spatially coded or amplitude coded information assists control the most when neglecting visual attention, will provide insight into which parameters future configurations should encapsulate. This leaves the following study objective:

Test and evaluate two novel stimulation schemes, one based on modulating amplitude and one based on spatial localization of activation, for conveying sensory feedback of the position state in a closed-loop prosthetic control system.

3 | Methods

Applying the knowledge acquired regarding myoelectric prosthetic control and feedback stimulation, the following section will document the implementation of the two novel feedback configurations, and the remaining requirements needed to test the usability of these in a closed-loop system. The methods chapter will contain sections documenting the implementation of study design, feedback configurations, a simulated virtual prosthesis, data acquisition, data processing, fitting of prosthetic control system, validation of subjects' control abilities, determination of sensory threshold levels, feedback configuration training and feedback configuration evaluation.

3.1 Study Design

In order to investigate whether amplitude or spatially-based electrotactile feedback aids prosthetic control the most when removing the visual dependency, an experiment was set up. A feedback coding scheme based on spatial activation and a feedback scheme based on amplitude modulation was developed and will be presented in section 3.2.

14 able-bodied subjects (13 right-handed, 12 males) were recruited, where the order of which feedback scheme the subjects would be trained/tested in was randomized. However, an equal number of subjects was assigned to each order. An overview of the subject population and demographics can be seen in table 3.1.

Table 3.1: Overview of subject population and demographics.

	Age, mean(std)	**Gender(n)**	
		Female	Male
Total (n = 14)	26.1(2.4)	2	12
Order 1 (n = 7)	25.7(2.3)	1	6
Order 2 (n = 7)	26.4(2.6)	1	6

Prior to enrollment, the subjects were assessed to meet the inclusion criteria stated in the experimental protocol, which can be found in section A.1. The subjects were handed a short experiment description prior to the experiment session (see section A.2), which gave an introduction to the background of the study and the different task the subjects would have to go through. Upon enrollment, the subjects were asked to sign an informed consent form, which stated that the subjects had received adequate information about the experiment and that they were always able to withdraw from the experiment. The experiment was ethically approved by the ethic committee of Region Nordjylland, Denmark (Approval number N-20150075).

The experiment was designed such that each subject was trained and tested in using both feedback schemes along with control during a single session experiment. A graphical illustration of the main stages that the subject went through can be seen in figure 3.1. For all subjects data used to build the prosthetic motor control system was acquired first. Secondly, the subjects were given time to familiarize with the control system and subsequently, the achieved control was evaluated through a target reaching test. Next, stimulation threshold levels used for feedback were determined for the subject. Subjects assigned to order 1 went through four steps of training and testing using the spatial scheme followed by the same four steps using the amplitude scheme. Subjects assigned to order 2 went through the schemes in opposite order. The next sections will further document the implementation and execution of the experiment.

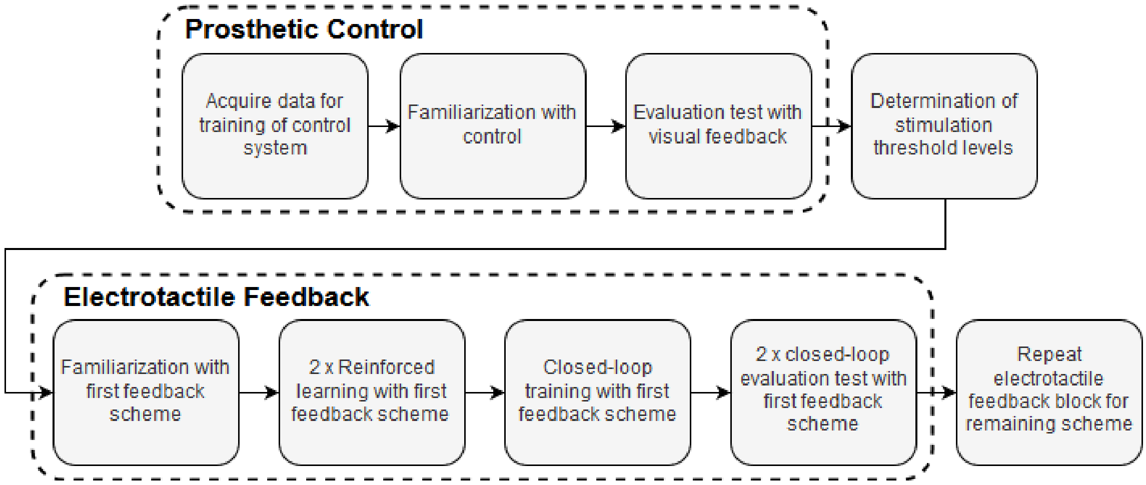


Figure 3.1: Pipeline showing the stages of the experiment. The stages in the first block focused on developing a prosthetic control system, and evaluating the subjects' ability to control the prosthesis. Then stimulation threshold levels were determined. The second block focused on training the understanding of the feedback schemes and evaluating their usability in combination with prosthetic control. The electrotactile feedback block was repeated for the remaining feedback scheme.

3.2 Feedback Configurations

The fundamental interest of this project was to develop two novel, intuitive and useful feedback schemes to convey proprioceptive information through electrotactile stimulation and evaluate which one would aid control the most. This was to be implemented in a two DoF virtual prosthesis using wrist rotation and hand aperture as motions, where four levels of sensory feedback would be provided for each DoF to communicate prosthetic position states.

The center electrode pads were placed most central on the dorsal side of arm, when using a pronated arm as reference. See illustration in figure 3.2. The electrode array was fixated on the non-dominant arm such that there was a maximum gap of three cm between the outer electrode pads volarly. It was chosen to place the electrode array on the non-dominant arm since the electrode pads used did not prohibit current leakage. Thus, placing the electrode on the same arm as the MYB could have resulted in interference, which might corrupt recorded EMG data and impair the control system. Providing feedback to non-dominant arm has, however, proven usable for providing meaningful artificial proprioceptive feedback [41].

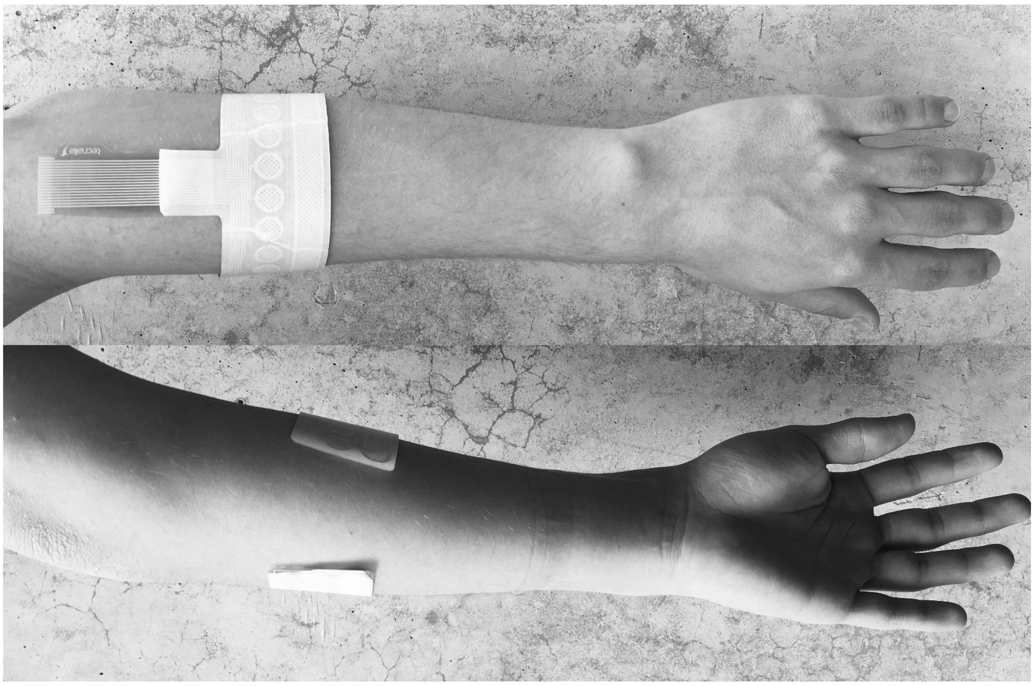


Figure 3.2: Illustration of the placement of the electrode array. There was a maximum gap of three cm between the outer electrode pads volarly.

The following section will present the two developed spatial and amplitude feedback schemes.

3.2.1 Spatial Configuration

The spatial feedback scheme was created with the interest of achieving an intuitive way to convey the feedback by focusing stimulation to localized regions on the skin. An illustration of the spatial feedback scheme can be seen in figure 3.3. The idea behind this configuration was to communicate wrist rotation movements by rotating the activated electrode pads and to convey the hand aperture by narrowing distance between active pads.

To achieve this, the electrode pads were broken into two groups: one upper and one lower. The upper eight pads (5-12) were used to convey information of the rotational DoF using four pads for either side. The four pads were divided into pairs of two, where the first from the center in e.g. pronation would be activated when the cursor entered the first level position state. Likewise, the second level pair would be activated when the cursor entered the second level. Hence, during a transition from neutral to level one and level one to level two, the subject should feel the stimulation moving either laterally or medially depending on the position state. For subjects with the electrode array fitted on the left arm, this meant that when the virtual prosthesis was in a supinated state the stimulation should be felt in the dorsal medial region of the arm, while when the virtual prosthesis was in a pronated state stimulation should be felt in the dorsal lateral region of the arm.

The lower eight pads (1-4 and 13-16) were used to convey information about the hand aperture. The pads were paired in an opposite manner for each of the four levels respectively: 4 and 13; 3 and 14; 2 and 15; 1 and 16. As the state would change to one hand aperture state out of four possible, a certain pad pair would activate. Transitioning from neutral to fully closed, the subject should sense the stimulation converging on the volar side of the arm. The virtual prosthesis was able to be in states, which was a combination of the two DoFs. In these cases the feedback would be a combination of any upper and lower pair, resulting in the activation of four pads simultaneously.

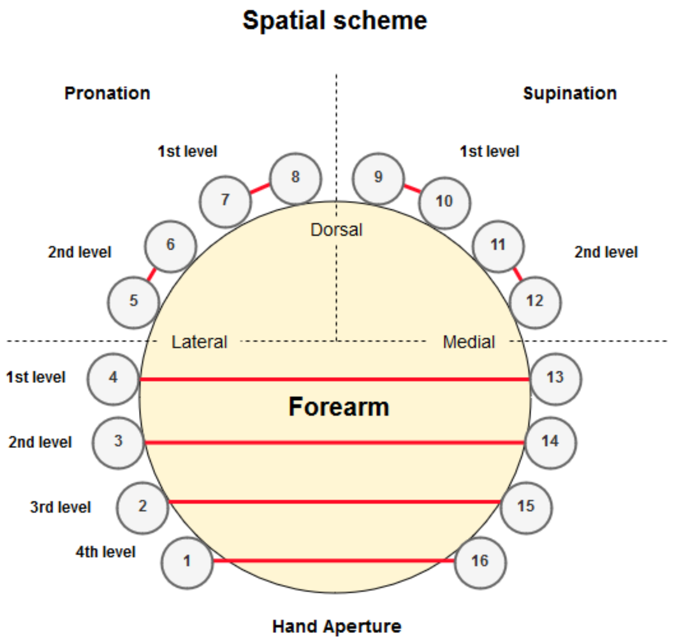


Figure 3.3: Transverse view of the developed spatial scheme, which was based on different pads being activated depending on the level of the position state. The level assigned to the various electrode pairs corresponded to levels of position states in figure 3.5. The highest number of possibly activated pads was four at a time. For subjects with the electrode array fitted on the right arm the rotational states were reversed.

3.2.2 Amplitude Configuration

In this scheme, attention to the recognition of stimulation localization should be less. Instead, the subject would have to discriminate between the intensity of stimulation in the regions which were active.

Compared to the spatial configuration where the feedback was given through dynamically changing the pads activated, the amplitude configuration instead conveyed feedback in three greater regions and solely modulated the amplitude of the stimulation. The upper eight pads were again used for the rotational DoF, illustrated in figure 3.4. Pads 5-8 were activated with different amplitude levels at pronated states 1 and 2, respectively. The same was applicable for supinated states using pads 9-12.

For conveying information about hand aperture, pads 1,2,15 and 16 were used. When in a combined DoF position state, eight pads would be active in amplitude levels relative to the level of the state. It was chosen to use groups of four electrode pads to exploit the largest number of pads in the electrode array, while still maintaining a symmetric distribution of possible active pads.

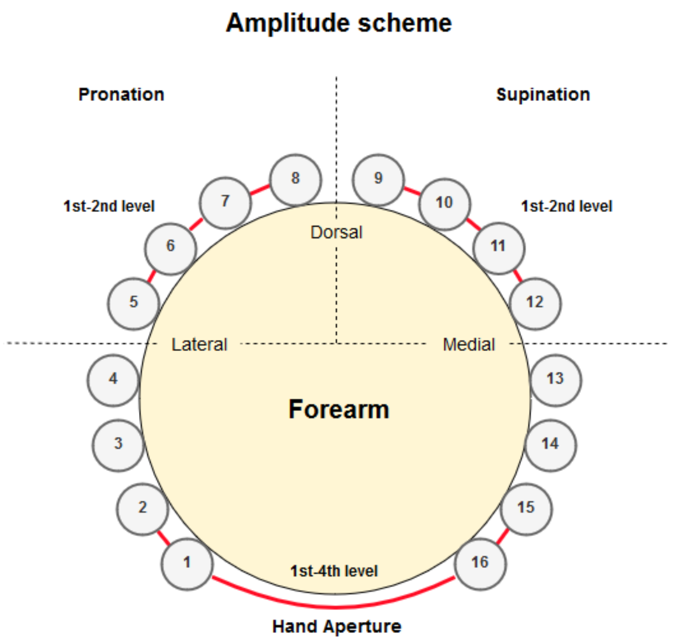


Figure 3.4: Transverse view of the developed amplitude scheme. Here, the amplitude of the active pads would increase with the increase of the position state; the higher the level the higher the current amplitude of the given pads. The level of amplitude strength assigned to the various pads corresponded to levels of position state in figure 3.5. The highest number of possibly activated pads was eight at a time. For subjects with the electrode array fitted on the right arm the rotational states were reversed.

3.3 The Virtual Closed-Loop Prosthesis

In order to test the usability of the two sensory feedback configurations in a closed-loop control system, a prosthesis which accommodated this was simulated. As no commercial or research prostheses were available in this project, a virtual system resembling prosthetic control was made. Using a virtual prosthesis also had the benefit of providing no sounds that might indicate the position state during evaluation tests.

The aim was to develop a system which could provide control and feedback of two degrees of freedom. In figure 3.5 is a depiction of a grid system and a black cursor symbolizing the different possible position states and the current state, respectively, where each square corresponded to a state. Performing supination would make the cursor move to the right into one of two possible states, while performing pronation would make the cursor move left into one of two states. Performing the closed hand movement would make the cursor move downwards into one of four possible hand aperture states and performing open hand would make the cursor move upwards. In total, the prosthesis could achieve a total of 25 different position states, which represented single DoF movements or combinations of two DoFs. However, as the control was sequential it was only possible to move the cursor in a single DoF at a time along an axis. In each of the squares, a unique electrotactile feedback was provided in each of the two feedback configurations, as explained in section 3.2.

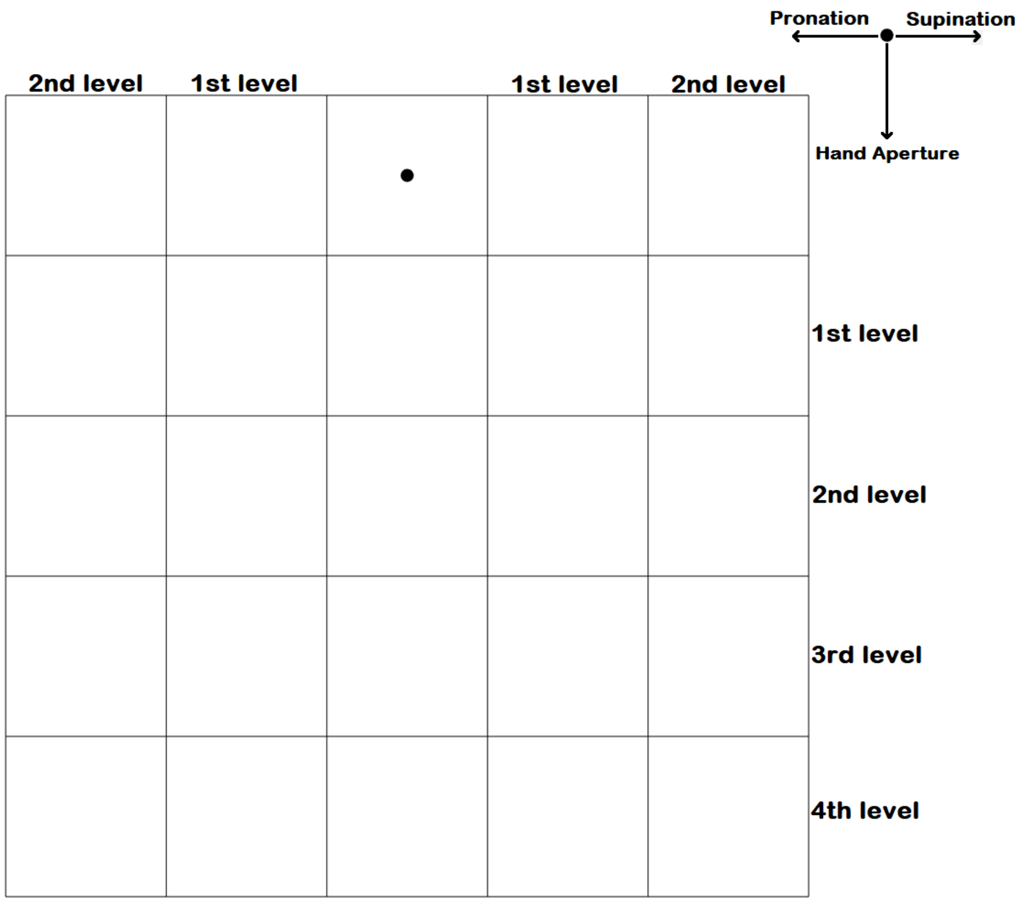


Figure 3.5: Image of the grid map and cursor used in the experiment. Performing supination moved the cursor to the right, pronation moved it to the left and closing the hand moved it downwards. For left handed subjects the rotational movements were reversed. Opening the hand moved the cursor upwards, and was used as a correction movement if needed.

3.4 Acquiring Control System Training Data

As presented in section 1.7, in order for a prosthetic control system to be able to differentiate between movements, a classifier could be trained with EMG data acquired while performing each movement. Therefore, individual subject EMG training data had to be acquired. Training data was acquired using the MYB placed around the thickest part of the dominant forearm while the subject performed wrist pronation, wrist supination, opened hand, closed hand and rest. The subsequent section will document how the data used for training the classifier was acquired.

First, a baseline recording was made, where the subject was instructed in keeping the hand perfectly still. The baseline consisted of a 15 second recording and was subtracted from each of the other recordings to reduce baseline noise. If the signal was below the baseline amplitude it was set to zero.

During a muscle contraction two main states can be recognized: a transient state, described by inconsistent myoelectric activity as the muscle length is changing, and steady state, where a constant muscle activity is reached. [42] Classification is often based solely on steady state data, however, including transient state might make for a more robust classifier as the delay until steady state is reached is eliminated [43, 44].

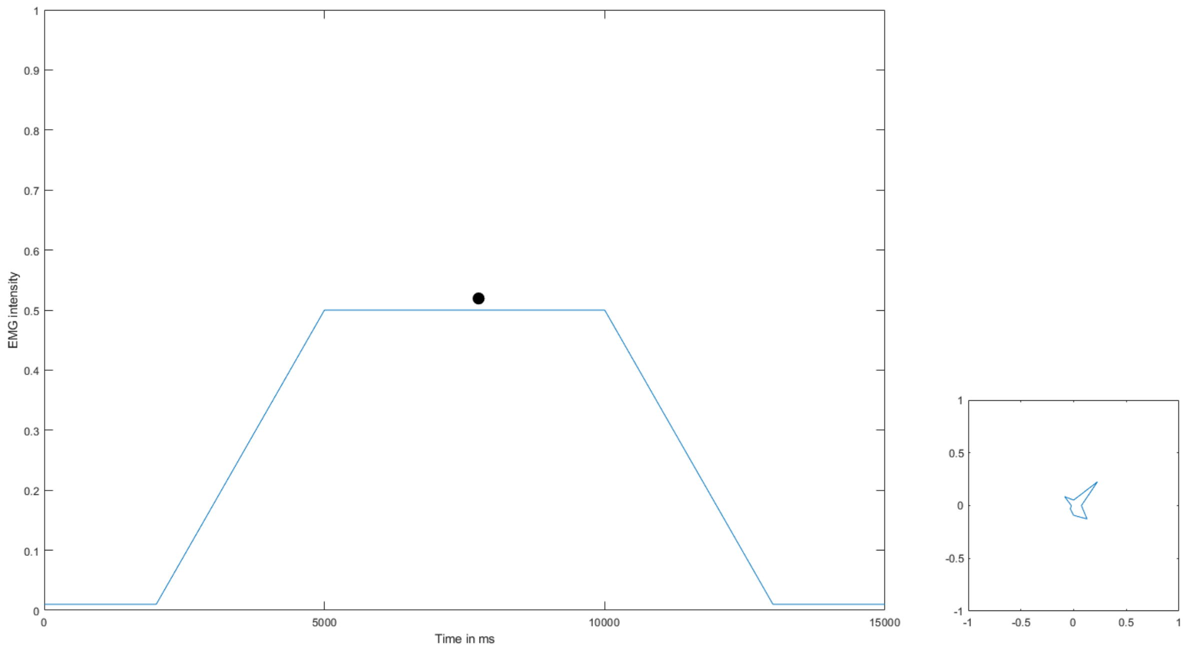


Figure 3.6: The trapezoidal plot (left) and contraction validation plot (right) used during acquisition of the training data. The trapezoidal plot represented the contraction amplitude requested. The black cursor moved continuous horizontally with time, and the height of the cursor position indicated the currently elicited contraction intensity. The validation plot was used by the investigators to assess the homogeneity of the performed movement. The mean of a segment in each electrode channel was plotted in different directions to get an overview of the activation recorded from the individual channels. The shape of the validation plot should be similar during a recording for it to be homogeneous.

To feed the classifier with training data representing muscle contractions with varying force, different fractions of maximum contraction force were recorded. In the process of obtaining training data for each movement, the same four contraction were carried out: a prolonged maximum voluntary contraction (pMVC) recording and 40, 50 and 70 % of the pMVC recordings. The pMVC was recorded for 15 seconds where the subject was instructed to elicit the contraction with a maximum contraction force which could be held steady, over the course of the 15 seconds. This resulted in an pMVC for each channel in the MYB, which was calculated as the mean of the absolute values of the EMG signal for each channel. The mean for each channel was used as a maximum reference when acquiring the subsequent fraction recordings.

Acquisition of the 40, 50 and 70 % fractions of pMVC were done using a graphical user interface (GUI) made in MATLAB 2018b, which can be seen in figure 3.6. The image shows the trapezoidal trajectory the subject were instructed to follow using the black cursor, where the height of the cursor was calculated as the mean absolute intensity across all channels of the elicited muscle contraction. The data was extracted over a 200 ms window. The cursor would automatically move positively along the x-axis in relation to time. The high plateau of the trapezoid represented either the 40, 50 and 70 % fractions of the pMVC. Data were recorded during 2.5 seconds rest periods in the beginning and end, a 2.5 seconds incline transition, 5 seconds steady state and 2.5 seconds decline transition, summing to a total time of 15 seconds. However, only data recorded during the steady state and the last and first second of the incline and decline of the transition phases, respectively, were used to train the classifier.

The additional plot, seen on the right in figure 3.6, plotted the amplitude of each of the eight channels in the MYB and was used by the investigators to assess whether the performed movements were done correctly. If the amplitude of the channels responsible for the performed movement shifted rapidly, or if channels not responsible for the performed movement were active, it would indicate that the subject did not perform a correct contraction and the recording would have to be redone.

3.5 Data Processing

The following sections will cover which filtering, segmentation and feature extraction solutions that were decided to implement, based on the background information presented in section 1.6.

3.5.1 Filtering

Due to the EMG bandwidth being 10-500 Hz and taking the MYB specifications into consideration the only interest was to remove low-frequency artefact noise. Hence, a 2^{nd} order Butterworth high-pass filter with a cut-off at 10 Hz was implemented. The order of the filter was chosen, as fast update time was highly desired in the online prosthetic control, and a higher order might have slowed the update due to a longer computation time. The choice of implementing a Butterworth filter was due to the desire of minimizing phase shift inside the EMG bandwidth, as this could further distort the fidelity of some of the extracted features.

3.5.2 Segmentation

In online myoelectric prosthetic control, quick update time is important to maintain naturalness in the prosthesis motion, while still ensuring robust classification. A windowing of 200 ms with 50 % overlap was therefore chosen. This would update the prosthetic motion output every 100 ms and segment 40 samples per window to feed the classifier. In initial tests, this proved adequate to yield smooth and reliable prosthesis motions, when using the MYB for EMG acquisition.

3.5.3 Feature Extraction

For this project it was decided to extract the space domain features recommended by Donovan et al. [31], due to the increased classification accuracy obtained compared to using Hudgins features when applying the MYB for data acquisition. The features formulated in [31] were MAV, Mean MAV (MMAV), Scaled MAV (SMAV), Correlation Coefficient (CC), Mean Absolute Difference Normalized (MADN), MAD Raw (MADR) and Scaled MADR (SMADR). Additionally, it was decided to extract the Hudgins feature, WL, to exploit frequency related information of the signal in the classification. All these features will be explained in the following text.

MAV is a commonly used feature to represent information on muscle contraction intensity and how much force a subject needs to produce to perform a movement at a given intensity. Its changes are linearly proportional with contraction intensity; the more intense the contraction is the higher the feature value will be and vice versa. For one window in the i^{th} channel, MAV is calculated as:

$$MAV_i = \frac{\sum\limits_{n=1}^{ws} |x_i[n]|}{ws} \tag{3.1}$$

where $x_i[n]$ denotes the n^{th} raw sample from channel i and ws denotes window size or number of samples in one window.
Scaling MAV with the mean of MAV across all channels will remove the dependency of specific movement intensity - some movements produce higher mean intensities than others at the same fraction of the pMVC. The average of MAV across all channels is denoted MMAV and is calculated as:

$$MMAV = \frac{\sum\limits_{i=1}^{8} MAV_i}{8} \tag{3.2}$$

MAV scaled by MMAV is denoted SMAV and is calculated as follows for each window in the i^{th} channel:

$$SMAV_i = \frac{MAV_i}{MMAV} \tag{3.3}$$

Each EMG channel in the MYB records a mixture of sources. Some individual sources can affect multiple channels, which will increase the correlation between channels, while other more local sources might only affect a single channel, which decreases the correlation. To represent the correlation between channel i and the neighbouring channel $i+1$, Donovan et al. proposed the calculation of a correlation coefficient (CC), which is expressed as:

$$CC_i = \frac{\sum_{n=1}^{ws} X_i[n]X_{i+1}[n]}{ws} \tag{3.4}$$

where $X_i[n]$ is the n^{th} sample from channel i in one window after the sample has been normalized. The normalization is done by subtracting the mean of raw samples from each sample followed by dividing the resulting values with their standard deviation.

In an effort to further represent the relationship between channels, the mean of the absolute value of the difference between normalized channel values was calculated. This is referred to as mean absolute difference normalized (MADN), and is expressed as:

$$MADN_i = \frac{\sum_{n=1}^{ws} |X_i[n] - X_{i+1}[n]|}{ws} \tag{3.5}$$

To decrease the computational denseness of first calculating the normalized values as done with CC and MADN, MAD was calculated using just the raw samples. This is referred to as MADR and is expressed as:

$$MADR_i = \frac{\sum_{n=1}^{ws} |x_i[n] - x_{i+1}[n]|}{ws} \tag{3.6}$$

Similar to MAV, MAD is affected by movement intensity and is therefore scaled by MMAV, which results in the final space domain feature SMADR:

$$SMADR_i = \frac{MADR_i}{MMAV} \tag{3.7}$$

Finally, to increase the amount information the classifier based its decisions upon, the Hudgins feature WL was included. WL represents both amplitude and frequency content of the signal by measuring the summed absolute difference between neighbouring samples in the signal in channel i in one window:

$$WL_i = \sum_{n=1}^{ws-1} |x_i[n+1] - x_i[n]| \tag{3.8}$$

To avoid redundancy in signal representation only SMAV, CC, MADN SMADR and WL were used to train the classifier and for online control.

3.6 The Prosthetic Control System

Having extracted features from the three EMG datasets of one movement for each of the four movements, the control system could be build in order to achieve online recognition of movements. The implementation of the control system was divided into two parts. To achieve recognition of performed movements a classifier was trained, however, this only produced a recognition of a movement and did not reflect the intensity of which the movement was performed with. Therefore, following the recognition of the performed movements multiple linear regression models were implemented to achieve proportional control.

3.6.1 Movement Classification

Online classification of movements was accomplished by implementing an LDA classifier. As presented in section 1.7 the classifier needed to be trained using data from each movement. Hence, the five features extracted for each of the 40 %, 50 % and 70 % fraction of the pMVC for one movement were assembled into one labeled matrix. The same was done for the three remaining movements. A fifth class was labeled rest and its matrix only contained the features from a single rest acquisition. These matrices were made for the data acquired from each of the eight channels in the MYB. All matrices were assembled into one training matrix with labels for each movement. Using the *fitcdicsr*-function in MATLAB the LDA classifier was trained by feeding it the training matrix. Hereby, the classifier was trained in separating the classes of pronation, supination, open hand, closed hand and rest, using linear decision boundaries. During online use, the *predict*-function was used to evaluate features from new input data in the classifier and decide which movement there was being performed.

3.6.2 Proportional Control

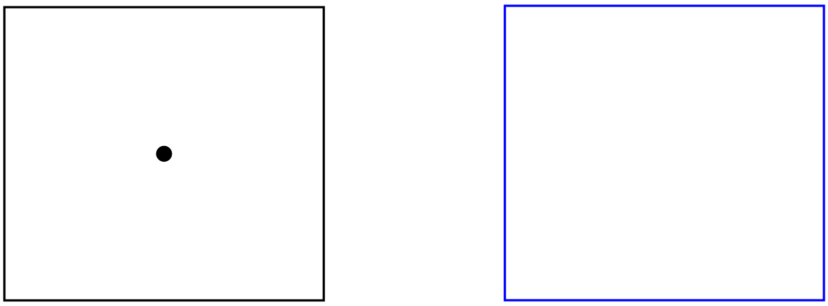
When a movement was decided upon by the classifier, the proportional control provided the control system with an actuation velocity which was proportional to the contraction intensity. For this purpose a multiple linear regression model was created for each of the four movements, through the MATLAB function *fitlm*. Each model were fitted with the MAV features extracted from the three recorded fractions of pMVC. These were set as the independent variable when training the regressor. The dependent variable was a vector of MAV features from the three fractions which had been normalized to the recorded pMVC. The data was scaled such that the pMVC data was set to 1 and the remaining data was scaled in relation to that. In the online control, the output of the decided regression models was written such that it would move in the direction described in section 3.3. The output from the regression models was limited to a maximum of 1, meaning that maximum level of activation detecting was the pMVC level. This was equivalent to moving the cursor 1 cm on the computer screen per update (100 ms). Thus, the cursor had a maximum speed of 1 cm per 100 ms. As the grid system was quadratic with 20 cm in length, each DoF could be actuated fully from one extremity to another in 2 seconds at maximum contraction intensity. Thereby, the virtual prosthesis achieved an actuation speed similar to the commercially available Bebionic prosthesis [45]. Another threshold implemented was a minimum activation of at least 15 % for a movement to count, otherwise no output would be provided. This idea behind this implementation was to provide a more stable resting state in addition to the classifier.

3.7 Online Control Training and Test

After the acquisition of training data and the training of the classifier, two stages where the subject could familiarize themselves with the control and test how well they were able to use the control system, were implemented. It was highly critical that the subject was able to achieve sufficient control abilities such that it would not be due to poor control that a subject was not able to perform well when combined with sensory feedback in the final evaluation tests. However, as the classifier only had five classes, representing five separable movements to distinguish between, a robust online control was achieved in an evaluation test during pilot tests after short training trials. Therefore, the need for subject training could be kept to a minimum.

3.7.1 Familiarization with Control

At first, the subject was presented with an image of the grid, which can be seen in figure 3.5, in section 3.3. The subject was able to control a cursor and navigate around inside the grid by performing supination to go right, pronation to go left, open and closed hand to go up and down, and rest to stand still. The familiarization was separated into two stages. In the first stage, the user had three minutes to get acquainted the functionality of the control by moving the cursor shown in figure 3.7 (a). The cursor acted as a direct output of the control. During the three minute familiarization, the subject was instructed in training unflawed performance of each movement and the transition from a movement to rest, such that the prosthesis acted according to the subject's intend. In the second stage, the visual feedback in the form of the cursor was made more discrete. This was done by making the cursor invisible and instead highlighting the outlines of the target that contained the cursor. This discretized cursor representation was included to make the visual feedback identical in resolution to the sensory feedback. The discrete visual feedback can be seen in figure 3.7 (b). Again the subject had three minutes to familiarize with the control.



(a) Illustration of the cursor used during the first familiarization stage.

(b) Illustration of the cursor used during the second familiarization stage.

Figure 3.7: Illustration of the cursor used in the two stage familiarization with control. Using the cursor in (a) the subject was informed the exact location of cursor in a square. Using the cursor in (b) the subject was provided with the information of which square the cursor was in, by highlighting it in blue, but not the exact location of the cursor inside the square.

3.7.2 Evaluation Test

After completion of the two stages of familiarization, a target reaching test was carried out. This evaluation test was carried out in a virtual environment through a Fitts' Law-based target reaching test. In this test, a square was highlighted with red and the subject would have to move the discretized cursor to the desired target and dwell inside it for 1.5 seconds in order for it to be deemed reached. The subject had 30 seconds to reach a target. The test was designed such that each of the 24 squares in the grid was to be reached. When a target was either reached or the time to reach the target ran out, the cursor would be reset to the neutral position (first row, third column in figure 3.5).

The target reaching test was made such that a measure of how well the subjects was able to use the control system could be obtained. Hereby it also acted as a reference for the later comparisons with control in combination with the two feedback schemes. Furthermore, if the investigators deemed the achieved subject control insufficient, the investigators could choose to exclude the subject. This was assessed empirically from observing the subject's performance during the control training and quantitatively by evaluating the results of the target reaching test. The subject had to reach 90 % of the targets while maximally use a mean time of 10 seconds per target. From the target reaching test, performance measures of completion rate, time to reach a target and path efficiency were extracted for performance evaluation.

3.8 Determination of Stimulation Levels

Having completed the prosthetic control part of the experiment, the next step was to determine the subject's sensory threshold levels, which would be used to convey feedback information.

In order to provide meaningful tactile feedback to the subject, a range of distinguishable sensory threshold levels had to be determined for the subject. As presented in section 3.3 the virtual prosthesis had a range of one to four states. Hence, four thresholds based on amplitude values were determined to accommodate four levels of feedback in the amplitude scheme. Furthermore, since the sensory sensitivity varies across different locations of the circumference of the arm, the sensory threshold levels had to be determined for each individual pad in the electrode armband. Sensory threshold levels were found by slowly increasing the amplitude while fixating the pulse width and frequency at 500 μs and 50 Hz, respectively.

In the first round, the lowest level was determined, which will be referred to as the perception threshold. For each pad, the amplitude was set to start at 0 μA and then increase in steps of 100 μA per second. The subject was instructed in reporting when electrical stimulation could be sensed and that the subject was sure the activated pad was the origin of the perceived stimulation. The pad was deactivated and reactivated once more with the determined amplitude value for a second verification. This process was carried out for each pad starting from pad 1 to 16. Subsequently, the subject was presented with the determined amplitude values in each pad, such that the sensation in the current pad was compared to the neighboring pad. This was carried out such that the determined amplitude values could be readjusted to achieve more homogeneous sensation intensities across all pads.

In the second round, the fourth level thresholds, referred to as tolerance threshold, were determined using the same procedure as in round one. The tolerance threshold was defined as the highest amplitude the subject felt pleasant. The starting amplitude was in this round, however, the perception threshold. The amplitude was set to increase in steps of 200 μA per second. The amplitude was increased until the subject reported that the threshold was reached, the stimulation was causing functional muscle activation or a maximum of 10000 μA was reached. Again the amplitude values were readjusted to achieve homogeneous sensation intensities. Throughout the process of determining sensory threshold levels, the subject was facing away from the computer screen to avoid bias from observing the visual increase of amplitude values.

Intermediate threshold levels 2 *lvl2* and 3 *lvl3* were calculated for the i^{th} pad based on the perception p and tolerance t threshold levels as:

$$lvl2_i = p_i + \frac{1}{3} \cdot (t_i - p_i) \tag{3.9}$$

$$lvl3_i = t_i - \frac{1}{3} \cdot (t_i - p_i) \tag{3.10}$$

3.9 Feedback Training

After determining the amplitude thresholds, the subject was trained in understanding the sensory feedback. Depending on which order the subject would test the configurations, the subject was either trained in understanding the spatial or amplitude scheme first. The structure of the training was, however, the same. The feedback training was divided into two phases: familiarization and reinforced learning. These phases will be presented in the following sections.

3.9.1 Familiarization

In the familiarization phase, the subject was presented with the sensation of 12 different position states and 12 position states indirectly, while observing which grid location corresponded to which sensation. This was carried out by the investigators by moving the cursor seen in figure 3.8 with the arrow keys on the keyboard. One press with an arrow key would move the cursor in a different grid square in the direction relative to the arrow key pressed. Pressing return would place the cursor in the staring point (the third grid square in the first row). The order of which grid square the cursor would be moved to can be seen in figure 3.8. After reaching a designated square, the cursor would be reset to the starting point. When moving the cursor to a grid square not adjacent to the staring point, the feedback from the transition grid squares would be felt. This transition is transferable to practical proportional prosthetic control/feedback, where the transition from rest to an outer prosthetic position is apparent. When moving the cursor to the grid squares 9, 10, 11 and 12, representing combined DoF positions, the direct route (moving fully in one direction and then the other) was used. In the familiarization phase, the cursor would be moved fully horizontally and then vertically. This enabled stimulations relative to all grid square to be included in the familiarization, without setting all grid squares to be designated targets. This design was chosen due to the single DoF direction being assessed to be most important to get familiar with, and to save time while still exposing the subject to all possible stimulations. Time spend in designated squares was approximately four seconds and time spend in transition squares was approximately two seconds.

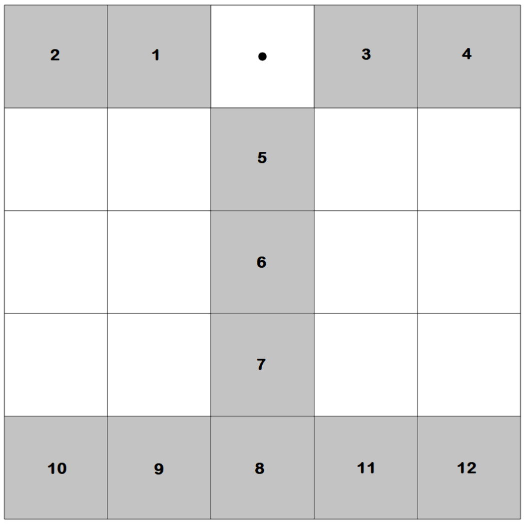


Figure 3.8: Illustration of the order the cursor would be moved to which grid squares in. The numbered grey squares were designated squares. After reaching a designated square, the cursor would be reset to the starting position (the grid square the cursor is located in).

3.9.2 Reinforced Learning

The reinforced learning phase consisted of two runs, in which all grid squares were designated squares and presented in a predetermined order. When a designated square was reached the investigator asked the subject about the location of the cursor. If the subject answered incorrectly, the investigator would reveal the actual location of the cursor. The stimulation related to the designated would be active until the subject answered. Afterwards, the cursor would be reset to the starting point.

The difference between the two runs was the order and path to the designated squares. The runs were, however, identical for all subjects. The path to a designated square was the direct route. However, which direction that would be moved in first was predetermined by the investigators. Thus, the transition stimulations would be felt by the subject before the designated was reached. This design was implemented to avoid bias in being accustomed to always receiving stimulation related to the same DoF first before the other. Time spend in transition squares was approximately two seconds.

3.10 Combining Control and Sensory Feedback

After the subject was trained in understanding one of the feedback schemes, the sensory feedback was combined with prosthetic control. Similar to the control block of the study, see section 3.7, the subject would go through a familiarization phase before undergoing evaluation tests. These stages will be explained in the following sections. An illustration of the full experiment setup used in this trial can be seen in figure 3.9.

3.10.1 Familiarization

This stage was similar to the second stage control training, see section 3.7.1, with the addition of receiving sensory feedback. The subject was instructed in getting reacquainted with the prosthetic control, while adapting further to the feedback related to the various position states as well the transitions felt when changing position state. These focus point were assessed most beneficial to train in order to perform well in the final evaluation test. The duration of the familiarization phase was three minutes.

3.10.2 Final Evaluation Test

This evaluation test was similar to the evaluation test from the control step, see section 3.7.2, with the addition of receiving sensory feedback. In this test, the position state would, however, not be visualized. Thus, the subject had to use the sensory feedback to determine the position state and reach the highlighted targets. The target reaching test was performed two times consecutively. Again the completion rate, time to reach a target and path efficiency were extracted for performance evaluation.

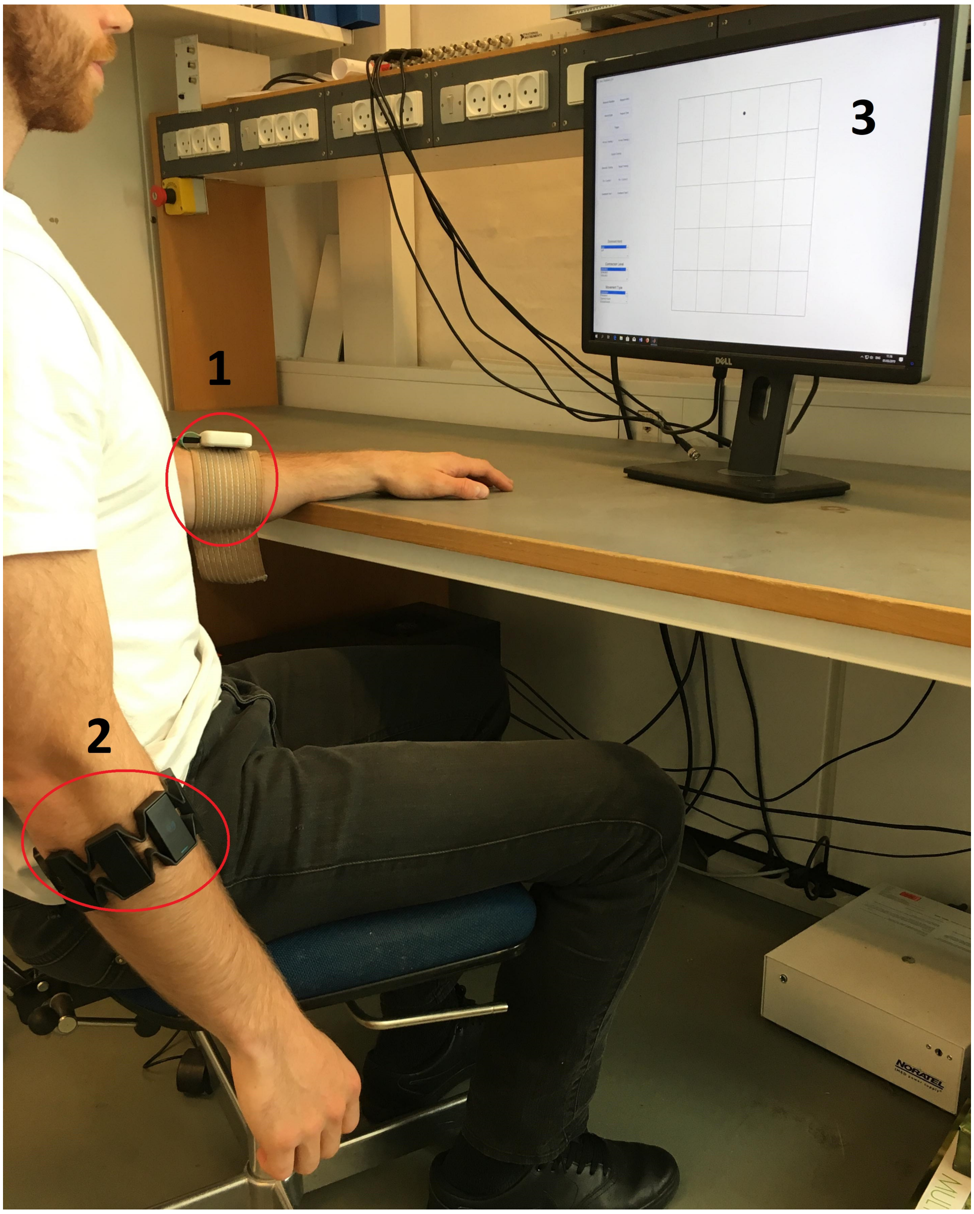


Figure 3.9: Image of the experimental setup. 1) is the stimulation device with the stimulation electrode placed under the brown armband, 2) is the electrode armband used to record EMG signals and 3) is the computer screen used to guide the subject and display tasks.

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A | Appendices

A.1 Experiment Protocol

Project Title
Evaluation of Electrotactile Feedback Schemes in a Closed-Loop Myoelectric Prosthesis.

Information on Investigators
The investigators are Biomedical Engineering Master students at Aalborg University.

Background
Losing an upper limb can be hugely debilitating and can result in lowered quality of life due to restrictions in function, appearance and sensation. As a mean to regain the functionality, transradial amputees can receive a functional prosthesis, where the majority are controlled by muscles signals, or electromyographic (EMG) signals. However, still 25 % of myoelectric prosthesis users reject their device, where a major reason for the low satisfaction is due to lack of sensory feedback. Many advancements have been made in the academic community to improve function accuracy. However, combining function with sensory feedback, thus closing the motor/sensory loop, is still a scarcely investigated area. Therefore, this experiment will combine the control of a prosthesis with sensory feedback delivered via electrotactile stimulation electrodes placed on the forearm. During the experiment the subjects will test two different feedback configurations while controlling a virtual prosthesis, represented as a cursor on a computer screen. The subject can move the cursor in a two-dimensional coordinate system, where the axes represents a degree of freedom (DoF) each (wrist rotation and opened/closed hand).

Purpose
The purpose of the experiment is to compare how subjects' perform in an evaluation test when receiving feedback from two different electrotactile stimulation configurations, respectively, in a closed-loop virtual prosthesis. This might provide information on which feedback that seems more intuitive to use in practice in a prosthesis.

Research Aim
Test and evaluate two novel stimulation schemes, one based on modulating amplitude and one based on spatial localization of activation, for conveying sensory feedback of the prosthesis state in a closed-loop prosthetic control system.

Experiment Duration
Approximately 2 hours and 30 minutes.

Inclusion Criteria
The subject must be:

- able bodied.

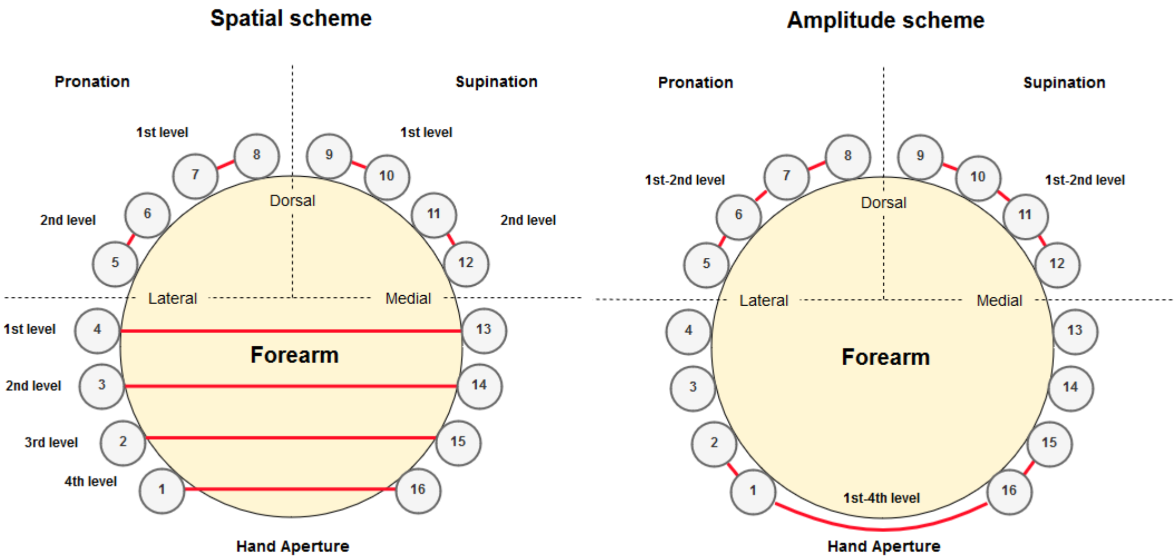
- at least 18 years of age.
- able to understand, read and speak English and/or Danish.
- assessed by the investigators to comply with the instructions given during the experiment.

Exclusion Criteria
The subject must:

- not have any diseases/conditions that may influence sensory perception.
- be willing to receive low amplitude current stimulation.
- be assessed by the investigators to have robust prosthetic control during the experiment.
- be willing to give informed consent.

Experiment Description

The main aim of the experiment is for the subject to be able to correctly interpret the two sensory feedback schemes when combined with myoelectric prosthetic control. The grid illustrated in figure A.2 is the map the subject will be able to navigate inside. Each square in the map will deliver a different stimulus corresponding to the motion state of the virtual prosthesis, represented as the black cursor. The square with center in the origin (square with cursor inside in figure A.2) corresponds to resting state and will provide no sensory feedback. The remaining squares in the first row will deliver stimuli corresponding to only the wrist rotation degree of freedom, and the remaining squares in the third column will deliver stimuli only corresponding to the closed hand DoF. The remaining squares will deliver a stimulation based on a combination of the two DoF's. The further away from resting state a square is, corresponds to a higher angular degree of the prosthetic state in relation to the performed movement (see figure A.1).



(a) Illustration of the spatial scheme.

(b) Illustration of the amplitude scheme.

Figure A.1: Figure (a) shows the spatial scheme, which is based on different pads being activated depending on the level of the grid square the cursor is located in. The highest number of possibly activated pads is four at a time. Figure (b) shows the amplitude scheme. Here, the amplitude of the active pads will increase with the increase of the level of the target location. The highest number of possibly activated pads is eight at a time.

The arrows in the upper right corner of figure A.2 represent the hand movements needed to be performed to move the cursor in the corresponding direction. The control system will only respond to single DoF movements. Thus, the cursor is only able to move along one axis at a time and not diagonally. The subject will control the cursor with the dominant arm through an EMG electrode armband. The subject will receive stimulation from an electrode array consisting of 16 electrode pads placed around the non-dominant forearm (see illustration in figure A.1).

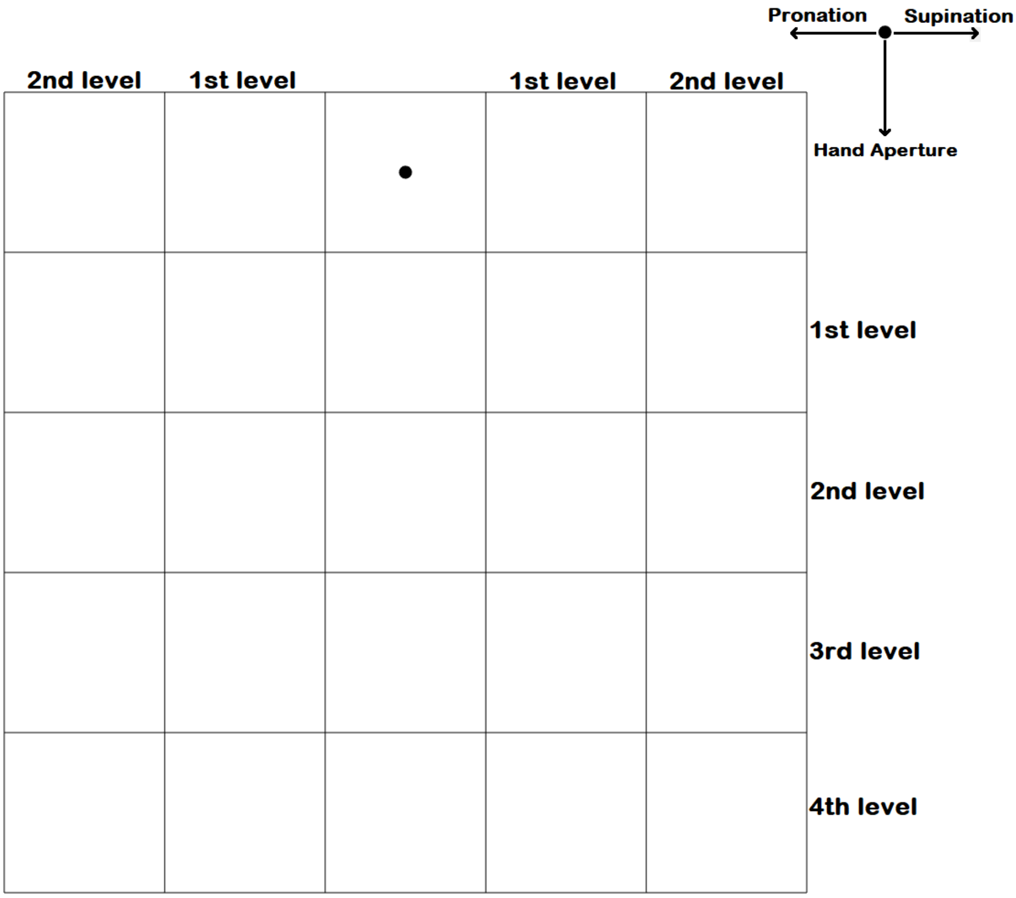


Figure A.2: Image of the grid map and cursor used in the experiment. Performing supination moves the cursor the right, pronation moves it to the left and closing the hand moves it down. Opening the hand moves the cursor up, and is used as a correction movement if a wrong movement has been made.

Hand Movements Used for Prosthetic Control

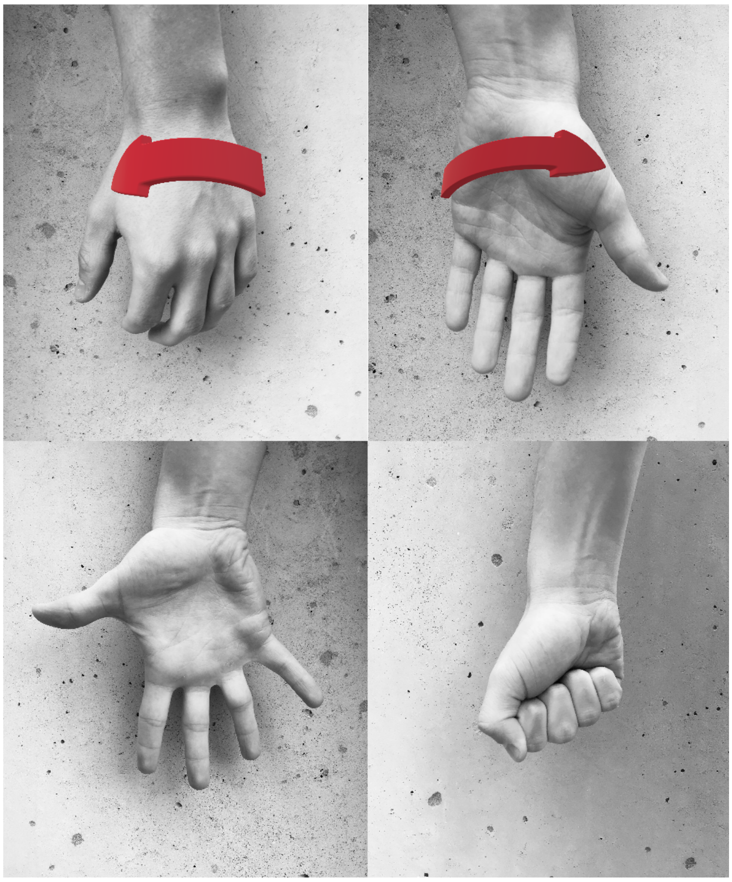


Figure A.3: Image of the hand movements used in the experiment for myoelectric prosthetic control. From top left corner: Wrist pronation, wrist supination, opened hand and closed hand.

Experiment Procedure

Before the final evaluation test is carried out the subject will be trained in controlling the cursor via EMG signals, trained in interpreting the sensory feedback and trained in interpreting the sensory feedback while controlling the cursor. The evaluation test is a target reaching test, where the subject needs to move the cursor to a highlighted target consisting of one of the grid squares. The cursor will not be visible, thus, the subject will have to only rely on the information received from the sensory feedback.
During the experiment the subject must let the dominant arm hang relaxed down the side of the torso and the non-dominant arm placed on a table without putting pressure on the stimulation electrode, as seen in figure A.5. The subject must be seated during all procedures. The following order represents the chronology of the procedures the subject needs to undergo; the steps will be divided in solely control, solely sensory feedback and feedback with control.
Control

1. Record EMG signals needed to build the prosthetic control system. To do this the subject must first perform five movements used as reference signals: 15 seconds rest, 15 seconds prolonged maximum voluntary contraction (pMVC) of wrist supination, 15 seconds pMVC of wrist pronation, 15 seconds pMVC of opened hand and 15 seconds pMVC of closed hand. Between each contraction the subject will get a 15 seconds break to avoid fatigue. Secondly, the subject must perform movements from which the recorded signals are used to build the control system. Here, the subject controls a cursor as seen in figure A.4, and must match the cursor with trapezoidal trajectory. The cursor moves horizontally with time and the subject control the contraction intensity vertically. The subject must perform three contractions per movement: 40, 50 and 70 % of the pMVC. The plateau of the trapezoidal trajectory corresponds to the designated fraction. Between each performed movement, the subject gets a 15 seconds break to avoid fatigue. Lastly, a 15 seconds rest is recorded.

2. Train the subject's ability to control the cursor via letting the subject move freely around inside the grid map for three minutes.

3. Train the subject's ability to control the cursor via letting the subject move freely around inside the grid map for three minutes. In this training, the cursor will not be visible, but the square the cursor is inside will be highlighted in blue. This cursor representation will be used in the remaining trainings and tests with visual feedback.

4. Perform target reaching test to evaluate the subject's ability to control the cursor. The designated target will be one of the squares in the grid highlighted in red. To reach a target the blue cursor square must match the target and dwell inside it for 1.5 seconds. Then a bell sound will occur and a new target appears. The time limit for reaching a target is 30 seconds. The starting point is always the resting state square (first square in third column), and the cursor will, thus, return to starting point when a target is reached or when the time limit is reached. A total of 24 targets will appear before this test is through.

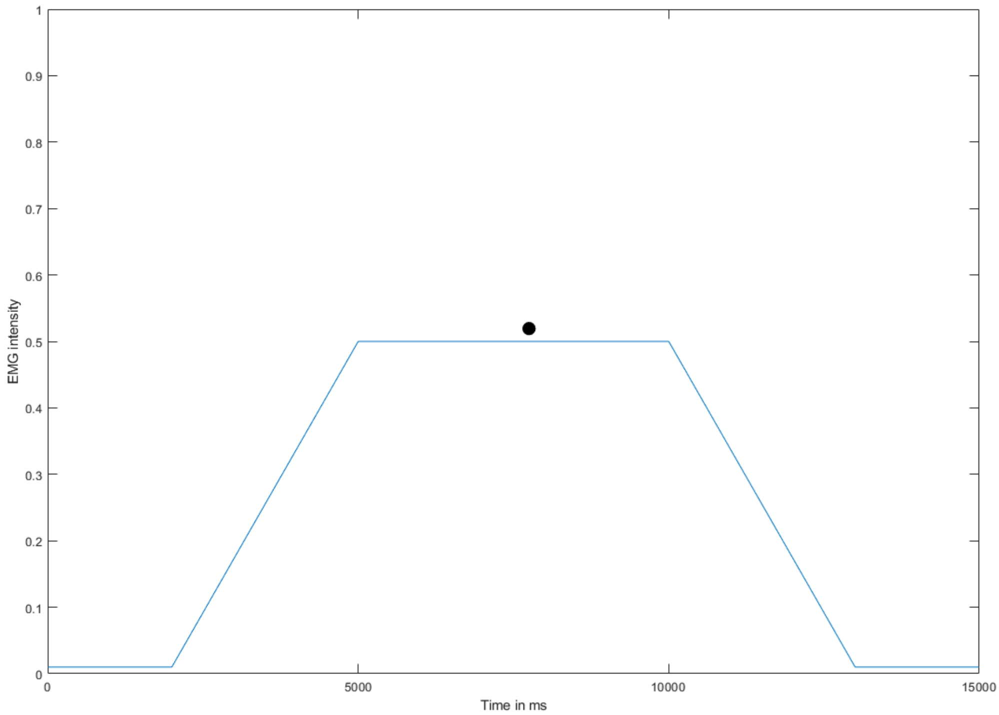


Figure A.4: Image of the trapezoidal trajectory used when recording EMG signals used to build the control system. The black cursor moves horizontally in time, and the subject controls the height of it by increasing contraction intensity.

Sensory Feedback

1. Record current amplitude thresholds needed to build the sensory feedback schemes. For each electrode the subject must first note when the stimulus is felt clearly. When all thresholds are set, the sensation of neighboring pads are compared to ensure homogeneity in the sensation. Afterwards the same procedure is performed for the subject's tolerance threshold.

2. Train the subject's ability to interpret sensory feedback for one of the schemes. This is done by exposing the subject to feedback from 12 grid squares. The subject will experience the transitions from square to square until the designated square is reached. The path taken to reach the designated square is the direct route (full length in one direction and then the other), where the rotational DoF will be moved in first.

3. Perform reinforcement learning on all grid squares. The path taken to reach the designated square is the direct route, but which direction that will be travelled first is predetermined by the investigators. During this step the subject must look away from the computer screen. When a designated square is reached, the subject will be asked where the cursor is located. After answering the subject will be informed on whether is was correct, and told the correct location, if the answer was incorrect.

4. Repeat reinforcement learning from step 3. The order of the squares and the route to each square will vary from step 3.

Sensory Feedback with Control

1. Train the subject's ability to control the cursor while receiving sensory feedback via letting the subject move freely around inside the grid map for three minutes.

2. Perform target reaching test where the cursor is invisible to evaluate how well the subject can utilize the sensory feedback regarding the cursor location. This test has the same format as the target reaching test from the control procedure step 3.

3. Repeat target reaching test from step 2.

4. Redo sensory feedback steps 2-4 and sensory feedback with control steps 1-3 with sensory feedback from the remaining scheme.

Experiment Setup

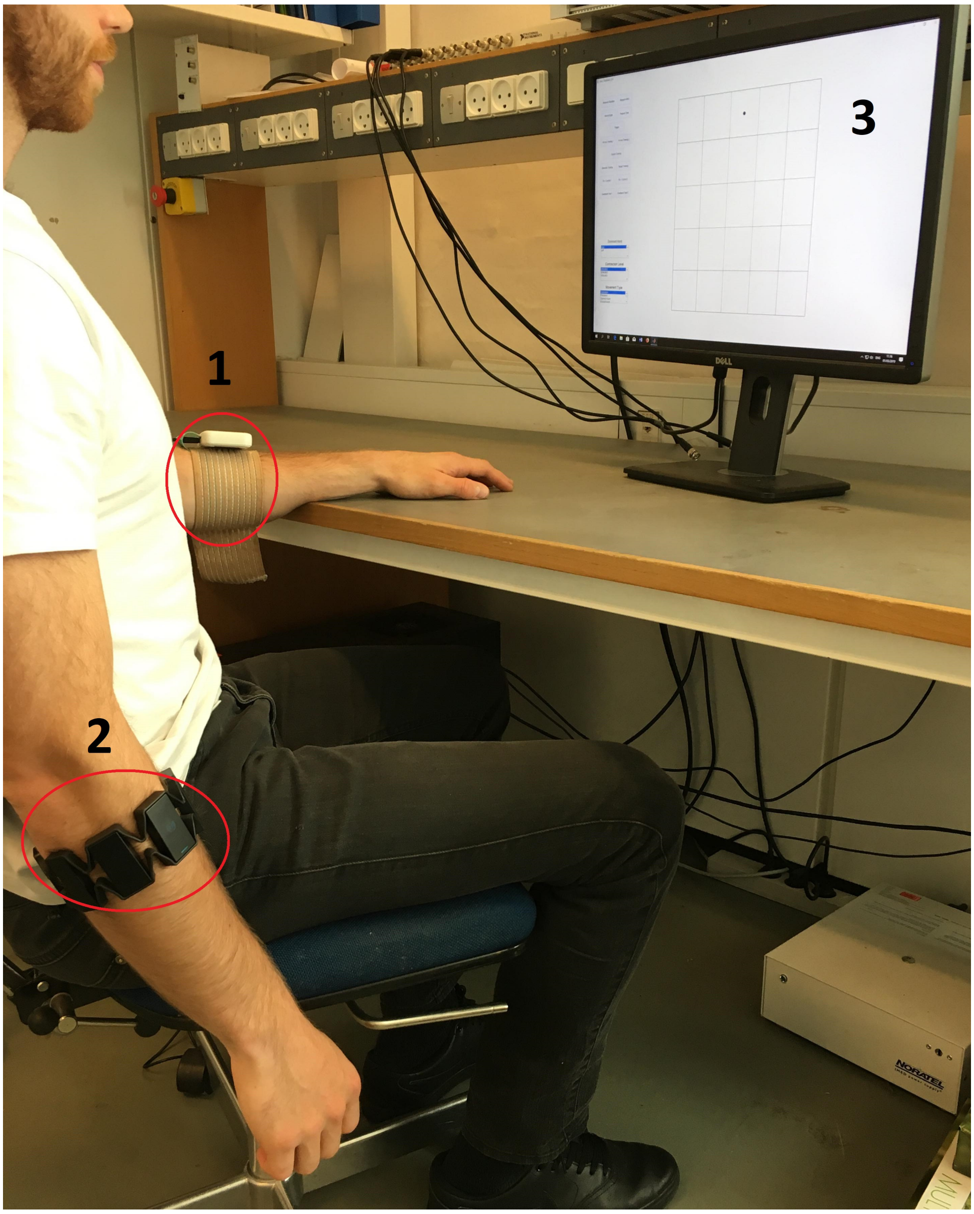


Figure A.5: Image of the experimental setup. 1) is the stimulation device with the stimulation electrode placed under the brown armband, 2) is the electrode armband used to record EMG signals and 3) is the computer screen used to guide the subject and display tasks.

A.2 Short Experiment Description

Project Title
Evaluation of Electrotactile Feedback Schemes in a Closed-Loop Myoelectric Prosthesis.

Experiment Purpose
When a person gets amputated on the lower arm, he/she can receive a functional prosthesis. This is controlled by muscle signals from the user, where the muscle signals are translated into a prosthesis movement. However, many functional prostheses do not provide sensory feedback, which results in some users to abandon their prosthesis. The purpose of the experiment is to compare how subjects perform in an evaluation test when receiving feedback from two different electrical stimulation configurations, while controlling a virtual prosthesis. The results might provide information on which feedback that seems more intuitive to use in a real prosthesis.

Experiment Overview
The experiment will take place in the laboratory D3-107 at Aalborg University. The duration of the experiment is estimated to be 2 hours and 30 minutes.

During the experiment a myoelectric armband will be placed on the dominant forearm and used to record muscle activity while the subject performs four different hand gestures. Subsequently, an evaluation of the ability to reproduce the gestures will be made. Afterwards, an electrode armband capable of delivering electrical stimulation at 16 different locations will be placed on the non-dominant arm. The subject will determine the level of sensory perception and tolerance level. The subject will then be made familiar with and trained in understanding two different feedback configurations that represents the possible states the virtual prosthesis can be in. At the end, an evaluation of the subject's ability to understand the feedback while making the trained hand gestures will be made.

At the day of the experiment, please refrain from using any types of sensory deprivation drugs (painkillers and alike). The test subject will not receive monetary compensation after the experiment.