Evaluation of Electrotactile Feedback Schemes in Combination with Electromyographic Control

Christian Korfitz Mortensen and Martin Alexander Garenfeld

***Abstract*—**
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***Index Terms*—Closed-Loop, Myoelectric Prosthesis, Electrotactile Feedback, Plumbus**

I. Introduction

The loss of an upper limb can be an incredibly traumatic and life-changing event with the consequence of a significantly reduced quality of life due to restrictions in function, sensation and appearance [1], [2]. In an effort to restore pre-trauma functionality, prosthetics of various functionality and complexity have been introduced to replace the missing limb [3]. However, despite advancements in prosthetic technologies 25% of users choose to abandon their myoelectric prosthetic device [4]. A major reason for the low user satisfaction is found in the lack of exteroceptive and proprioceptive feedback provided by commercially available devices [1], [5]. Presently, merely one commercially available device (VINCENT evolution 2, Vincent Systems Gmbh, DE), provides the user with feedback information of grasping force through a feedback interface [6].

The missing sensory feedback can cause the prosthetic hand to feel more unnatural and awkward [7]. Furthermore, the user mainly relies on visual feedback [7], [8], which is a need prosthetic users have shown a strong desire to decrease in order to enhance easiness and naturalness of use [9]. In a survey by Peerdeman et al. [5], it was found that secondly to receiving proportional grasp force feedback, prosthetic positional state feedback was of the highest priority. Visual independence can be achieved by providing the user with proprioceptive information through somatosensory feedback. This might facilitate the prosthetic device to be adopted by the user as an integrated part of their body, enhancing the feeling of embodiment and restoring the once physiologically closed loop [8], [10]–[12].

Various means of recreating the sensory feedback has been sought through either invasive and non-invasive approaches that translate information from sensors in the prosthesis to new sensory sites. Invasive methods, termed somatotopical feedback, aim to recreate the localization of the prior sensory experience by directly stimulating the nerves, which conveyed that particular sensory modality in the lost limb. This is, however, a complicated solution and multiple aspects, like long term effect, have yet to be investigated. [1], [8]. Substitution feedback utilizes various tactors (pressure, vibrational, temperature, electrotactile, etc.) and their use can either be modality matched using e.g. pressure as a substitute for grasp force [13] or non-modality matched via e.g. vibration for grasp force [14], [15]. Electrotactile feedback uses small electrical currents to activate skin afferents eliciting sensory sensations, which can be modulated in multiple parameters such as pulse width, amplitude, and frequency to convey feedback information along with the possibility of using multiple feedback channels [12]. As commercially available upper-limb prosthetics have multiple degrees of freedom (DoF's) [16] the need for multiple feedback channels is present to accommodate the amount of information which needs to be provided in a meaningful way.

In cases where two information variables are being conveyed e.g. grasping force and hand aperture using frequency and amplitude modulation in electrotactile stimulation [17] or pulse interval and stimulation frequency in vibrotactile stimulation [18], results have shown that one stimulator is not sufficient for users to distinguish between two modalities. In 2014, Witteveen et al. [19] provided sensory feedback of grasping force and hand aperture through a single vibrator and an array of vibrotactile actuators, respectively. Results showed that identification of stiffness for four virtual objects was around 60 %. Although the percentage was rather low, the feedback configuration proved better compared to no feedback showing that multichannel feedback helps distinguishability when conveying feedback of more than one information variable. [19] However, the use of multiple vibrotactile actuators might be less feasible and practical to implement in prosthetics, due to their size and greater power consumption compared to electrotactile stimulation.

The flexibility of electrotactile stimulation makes is desirable and its use has earlier been proven useful in cases of conveying force feedback from pressure sensors on a prosthetic hand or from sensors in artificial skin [20], [21]. However, the possibilities in electrotactile feedback have also been investigated with regards to communication information

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on states of a multi DoF prosthesis. Strbac et al. [11] presented a novel electrotactile feedback stimulation interface, which could be used to convey information about the current state of a multi-DoF prosthesis. The system was comprised of four different dynamic stimulation patterns communicating the states of four different DoF's through a 16 multi-pad array electrode. The state of three different DoF's were communicated by altering the electrodes activated in a specific pattern. The fourth pattern communicated grasp force by modulating the stimulation frequency. Tests of the stimulation design showed that six amputees were able to recognize the stimulation pattern of the four DoF's with an average accuracy of 86 %. [11] However, it was not tested how well these stimulation patterns was aiding the user when combined with prosthetic control.

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

Info on the structure of the following chapters/sections.

II. Methods

A. Study Design

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

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

B. Feedback Configurations

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

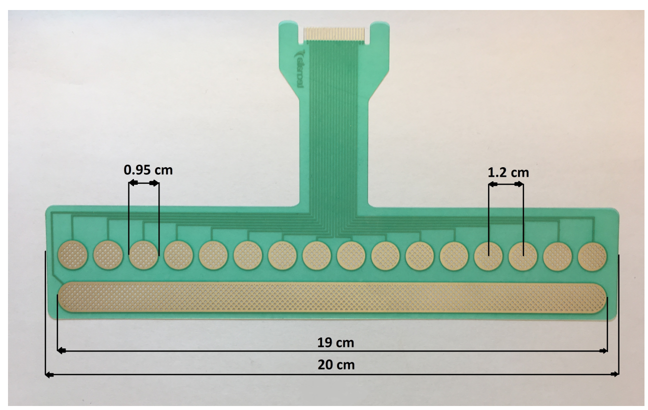

Fig. 2. Image of the 16 multi-pad electrode array used for stimulation. It consisted of 16 circular cathode pads, which each shared a common anode.

1) Spatial configuration: The motivation behind the spatial configuration was to communicate wrist rotation by spatially rotate anteriorly placed active electrode pads and to communicate closed hand by narrowing the distance between posteriorly 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 two groups each responsible for conveying information about a single DoF. The anteriorly placed pads were allocated for wrist rotation and the posteriorly placed for closed hand. The pads were furthermore paired such that each pair would represent one of four motion states in one DoF. For wrist rotation the pads were connected in

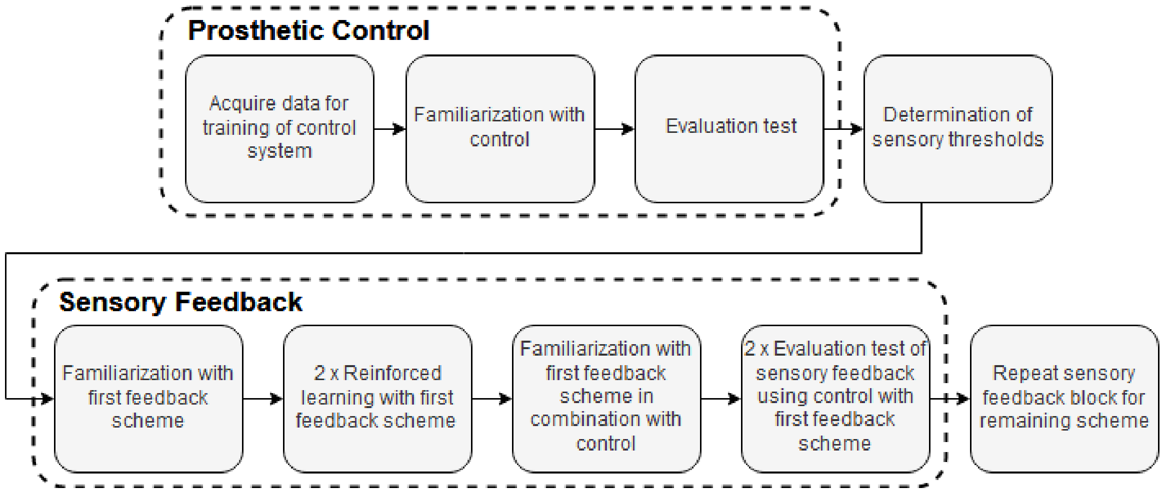

Fig. 1. Pipeline showing the stages of the experiment. The stages in the first block focused on developing and evaluating a subject specific simulated prosthetic control system. Then electrotactile sensory thresholds were determined. The second block focused on training the understanding of the feedback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

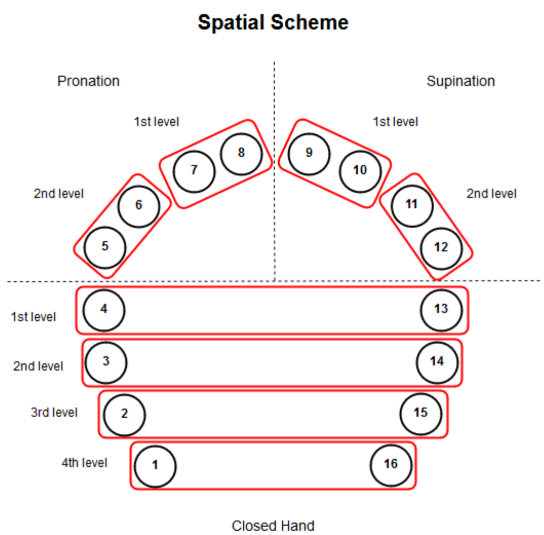

Fig. 3. Illustration of the developed spatial configuration. The levels written next to the pads pairs corresponded to the level of the prosthetic state; the higher the level, the higher the prosthetic state of the given movement was. For left-handed subjects supination and pronation were reversed.

side by side pairs. For right-handed subjects the activation of pads pairs would rotate laterally when increasing motion states during supination and rotate medially during pronation. The reversed activation was apparent for left-handed subjects. For the closed hand DoF the pairs consisted of oppositely located pads on the medial and lateral sides. When increasing motion states the active pairs would move posteriorly and the distance between active pads would become shorter.

When the prosthesis was in a combined DoF state, the pads pairs corresponding to the level of the prosthetic state of each DoF would be active. Thus, a maximum of four pads could be active simultaneously.

2) Amplitude configuration: The incentive behind the amplitude configuration was to convey information about the increase of prosthetic states by gaining the amplitude in electrode pad groups of four. 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.

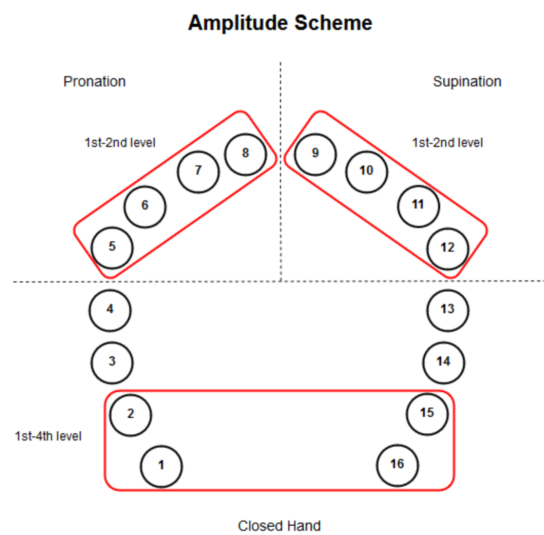

Fig. 4. Illustration of the developed amplitude scheme. Different groups of four electrode pads were active during supination, pronation and closed hand, respectively. The amplitude of the active pads would increase with the increase of the prosthetic state; the higher the prosthetic state level the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

The eight most anteriorly placed pads were used for wrist rotation and the four most posteriorly placed pads for closed hand. The eight pads used during wrist rotation were split such that the four most laterally placed were used during supination and four most medially placed were used during pronation for right-handed subjects. The pad activation was reversed for left-handed subjects. As the prosthetic state of a given movement would increase the the current amplitude in the pads corresponding to that movement would increase. When in combined DoF motion state, the pads corresponding to the level of the prosthetic state of each DoF would be active in the relative amplitude level. Thus, a maximum of eight pads could be active concurrently.

The choice of groups of four electrode pads was decided upon to exploit the highest number of pads in the electrode array, while maintaining a symmetric distribution of possible active pads.

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 open/closed hand DoF's. However, using an actual prosthesis might result in auditory feedback being provided to the subject through prosthetic actuation sounds, eliminating the interest of solely exploring the impact of sensory feedback. Hence, it was chosen to simulate a virtual prosthesis which enabled evaluation of the developed feedback schemes. In figure 5 is a depiction of a grid system and a black cursor symbolizing the different possible prosthetic states and the current prosthetic state, respectively.

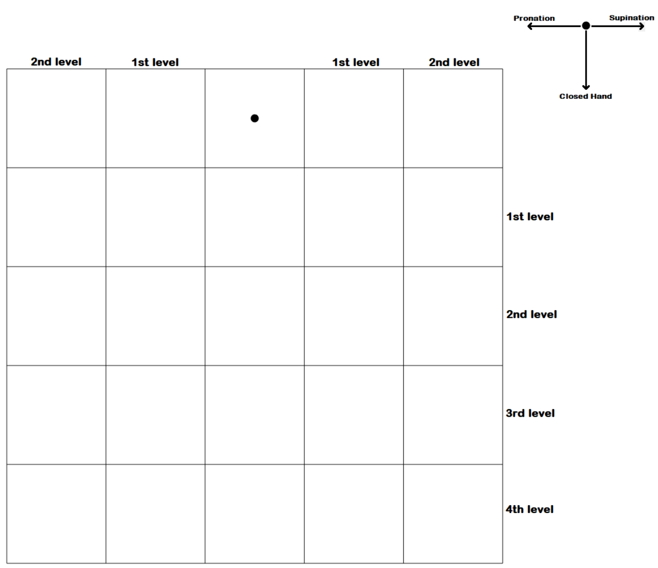

Fig. 5. Image of the grid map and cursor used in the experiment. Wrist supination moved the cursor to the right, pronation moved it to the left and closing the hand moved it downwards. For left-handed subjects, the rotational movements were reversed. Opening the hand moved the cursor upwards, and was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

Each square corresponded to a prosthetic state of either a single DoF or combinations of two DoF's. Performing supination would make the cursor move to the right and to the left when performing pronation. Performing closed hand would make the cursor move downwards and upwards when performing open hand. Finally, performing rest (relaxing the arm), would make the cursor stand still. The control was sequential which only enabled the cursor to move in one DoF at a time. When the cursor entered a square a specific electrotactile stimulation would be provided corresponding to the stimulation pattern for each scheme. In the neutral position (current location of cursor in figure 5), no sensory feedback was provided.

D. Data Acquisition

In order for a subject to be able to control the virtual prosthesis online, the prosthetic control system needed to be trained with previously acquired EMG signals. For EMG data acquisition the Myo Armband (MYB) from Thalmic labs was used, which contained eight dry stainless steel electrode pairs 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, thus, making the EMG signals prone to aliasing. A study by Mendez et al. [22] showed, however, a similar mean classification accuracy of nine hand gestures in a LDA classifier, when comparing data acquired with electrodes that covered the entire EMG spectrum and 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 [23]. 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 confused with rest. The trajectory and cursor position was scaled relative to an initially recorded prolonged maximum voluntary contraction (pMVC) of 15 seconds, which was set to 1. Data was acquired from three recordings per movement, where the plateau was 40 %, 50 % and 70 $\%t$ of the pMVC's, respectively. A last recording of 15 seconds rest was also performed.

E. Feature Extraction

Features were extracted from the acquired EMG signals to expand the amount of information used to train the classifier in the prosthetic control system. Due to the risk of the EMG signals being aliased, features representing frequency content might lose fidelity. In a study by Donovan et al. [24], the classification accuracy of space-domain features exploiting the relationship between EMG signals from neighbouring electrode pairs in the MYB were compared with the commonly used Hudgins features in a LDA classifier. Here, the use of space-domain features yielded a 5 % higher accuracy than the Hudgins features with EMG data acquired from the MYB. It was therefore chosen to use the five non-redundant features derived by Donovan et al., along with the Hudgins feature Waveform Length to represent frequency content indirectly [25], resulting in a total of six features. Both offline and online features were extracted in windows of 200 ms with a 50 % overlap to obtain quick update time, while preserving robust classification accuracy [26].

F. Prosthetic Control System

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 following section will address the fitting of the control system.

1) Classification model: A feature set was calculated for each of the eight electrode pairs and subsequently concatenated resulting in a 48-dimensional feature matrix that was provided to the classifier. It was chosen to implement a LDA classifier due to it being quick to train, while still yielding robust control [27]. The LDA classifier determined decision boundaries by maximizing the distance between centroids of the movement class feature values. Such decision boundaries were defined as a linear combination of feature values, where the output was posterior probabilities for each movement class. The decision rule was that the movement class with the highest probability would decide the determined motor function. The classifier was trained in distinguishing between five classes: wrist supination, wrist pronation, closed hand, opened hand and rest.

2) Proportional control: 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 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 pairs 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 value of 1; corresponding to the intensity of the pMVC. The distance of 1 corresponded to 1 cm on the computer screen, thus, the maximum speed 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 [28]. 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.

G. 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 prosthesis representation in each training. In the first training, the prosthesis was represented as a black cursor as seen in figure 5. Here, the cursor position would move continuously with each control system output. In the second training, the cursor was invisible, and the prosthesis representation was instead the square containing the cursor being highlighted. This discretized prosthesis representation was implemented to equalize the visual and sensory feedback. This prosthesis representation 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.

H. Determination of Electrotactile Sensory Thresholds

Providing meaningful sensory feedback required determination of four distinguishable subject specific electrotactile thresholds. Thresholds 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 to report when stimulation could be perceived confidently. Subsequently, the intensities were readjusted by comparing the sensation intensity in neighboring pads to achieve homogeneous sensations across all pads.

4th level thresholds termed tolerance threshold, were set using the same approach, however, the amplitude level was initialized at the perception threshold and increased in steps 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. Intensities were again readjusted to achieve homogeneous sensations. Throughout the process of determining thresholds, the subject was faced away from the screen to avoid bias from observing the visual increase of amplitude levels. Intermediate threshold levels 2 and 3 were calculated for the i^{th} pad based on the perception and tolerance threshold as:

$$2\ lvl(i) = percep.(i) + (\frac{1}{3} \cdot (tol.(i) - percep.(i))) \tag{1}$$

$$3\ lvl(i) = tol.(i) - (\frac{1}{3} \cdot (tol.(i) - percep.(i))) \tag{2}$$

I. Sensory Feedback Training

Following the subject training of prosthetic control, 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 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 states and stimulation patterns for a designated state. States in the top and bottom row and the middle column were presented actively, while the remaining 12 states were presented indirectly as transition states when moving to combinational states of 4th level closed hand and either 1st or 2nd level of wrist pronation and supination 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 states was assessed to be most crucial for comprehension, hence, these were favored in the familiarization phase.

For 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 state was based solely on the sensory feedback. If the subject answered correctly, the cursor was reset to the neutral position and the cursor was moved to a new target. If the subject answered incorrectly, the correct state would be communicated for the subject to learn from, before continuing. Each 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 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.

J. Closed-Loop Evaluation

The subject had until this point trained the prosthetic control and sensory feedback separately. The motor function and sensory feedback was combined in a closed-loop prosthetic system. During this final evaluation test the visual feedback regarding the prosthetic state was eliminated. The subject then had to rely on the sensory feedback to assess the prosthetic 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 feedback scheme. The evaluation test was similar to the evaluation test presented in section II-G, besides that the virtual prosthesis was not visualized. Thus, the subject had to solely rely on sensory feedback, when reaching a highlighted state. The evaluation test was performed two times consecutively.

K. Statistical Analyses

The metrics extracted from the evaluation tests were number of reached targets, mean time spend per target and mean distance travelled per target. Paired comparisons were made between results from evaluation tests. Due to the low sample size, comparisons was 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 5 % was used.

III. Results

A. 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 test single result for the amplitude feedback.

Figure 6 shows box plots of the extracted metrics for the visual, spatial and amplitude feedback evaluation tests. Worth noting was that visual feedback still outperformed solely relying on electrotactile feedback both when spatially or amplitude modulated for the completion rate and time to reach a target metrics. When comparing the spatial and amplitude feedback tests, using amplitude feedback yielded a slightly higher completion rate ($p = 0.044$). This quantitative result was also supported by the subjective opinion of the subjects as 64 % of the subjects favored the amplitude feedback. However, all subjects struggled in choosing a favored feedback scheme as they found both intuitive to understand.

B. Target State Hit Distribution

When observing the completion rate of the specific targets in figure 7, it can be derived that targets generally had a higher hit rate when using amplitude feedback compared to spatial (Mean completion rate with spatial feedback was 87 % and amplitude was 93 %). However, common for both feedback scheme was that the centered targets were more troublesome to reach (Mean completion rate for centered targets was 76 % with spatial feedback and 88 % with amplitude feedback; mean completion rate for peripheral targets was 93 % with spatial feedback and 97 % 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. Furthermore, combined DoF targets generally had a lower completion rate for the spatial feedback scheme (Mean completion rate for single DoF targets was 90 % with spatial feedback and 93 % with amplitude feedback; mean completion rate for combined DoF targets was 85 % with spatial feedback and 93 % with amplitude feedback). This could indicate that the sensory feedback regarding combined prosthetic states in the spatial feedback scheme was harder to interpret than in the amplitude feedback scheme.

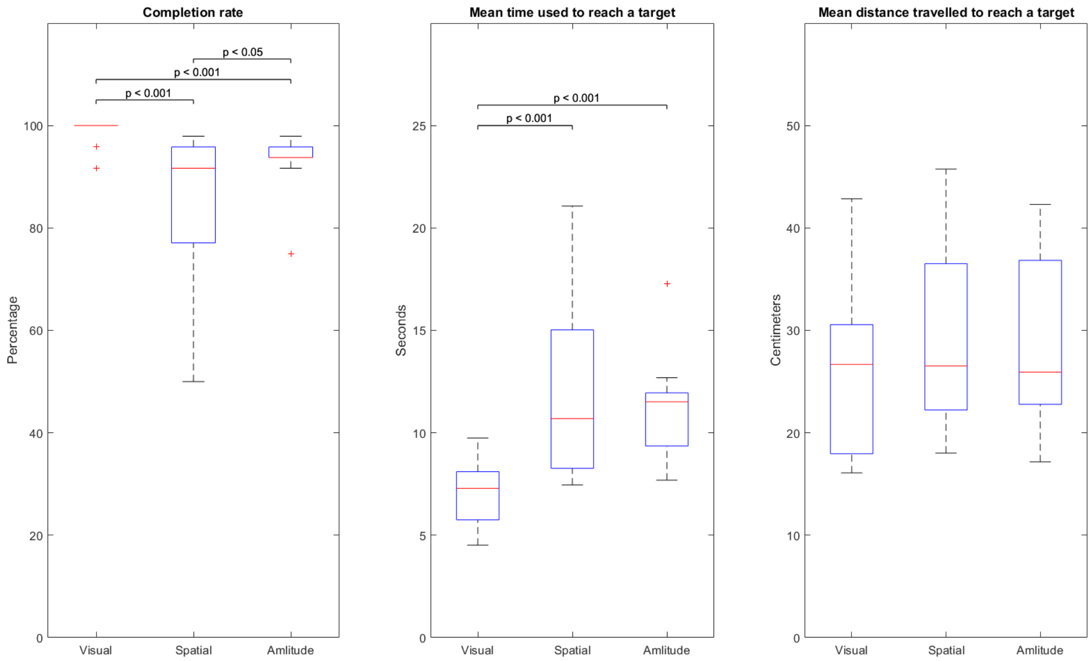

Fig. 6. Box plots of the metrics extracted from the visual, spatial and amplitude feedback evaluation tests. The two evaluation tests in the spatial and amplitude feedback block, respectively, were combined by calculating the mean between the two tests.

Fig. 7. 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.

IV. Discussion

V. Conclusion

Appendix

Acknowledgement

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