Evaluation of Electrotactile Feedback Schemes in Combination with Myoelectric Control

Christian Korfitz Mortensen* and Martin Alexander Garenfeld*

***Abstract*—The implementation of intuitive and meaningful proprioceptive feedback of myoelectric prosthetic states 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.

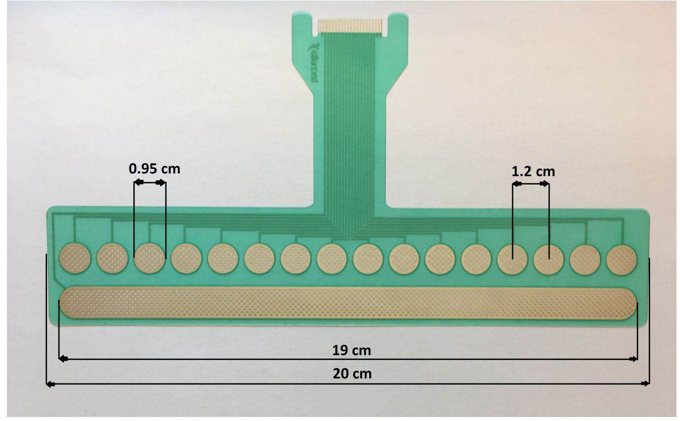

Fig. 1. Image of the 16 multi-pad electrode array used for stimulation. It consisted of 16 circular cathode pads, which each shared a common anode.

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].

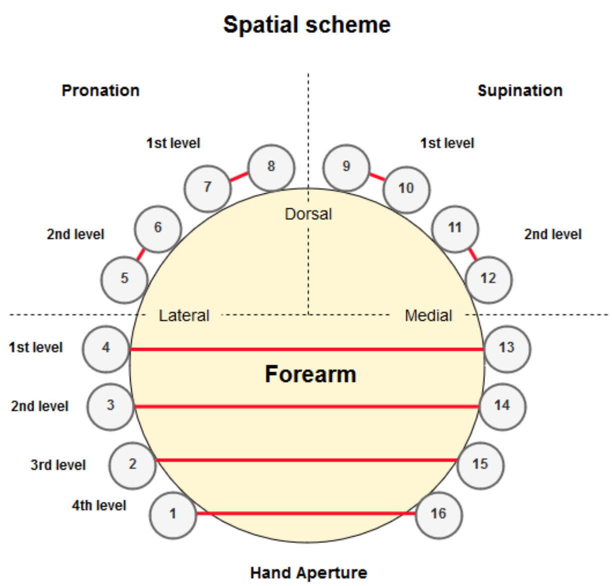

Fig. 3. Transverse view of the developed spatial scheme fitted on the left arm of a subject. The levels written next to the pads pairs corresponded to the level of the position state; the higher the level, the higher the position state of the given movement was. When fitted on the right arm medial and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

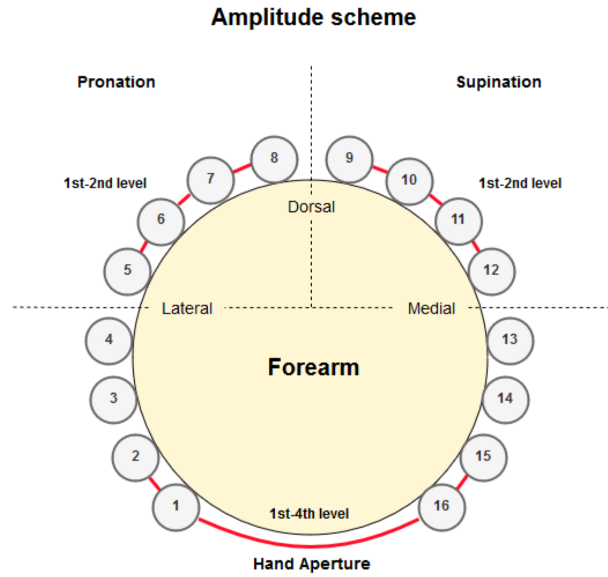

Fig. 4. Transverse view of the developed amplitude scheme fitted on the left arm of a subject. Different groups of four electrode pads were active during supination, pronation and hand aperture, respectively. The amplitude of the active pads would increase with the increase of the position state; the 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.

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].

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.

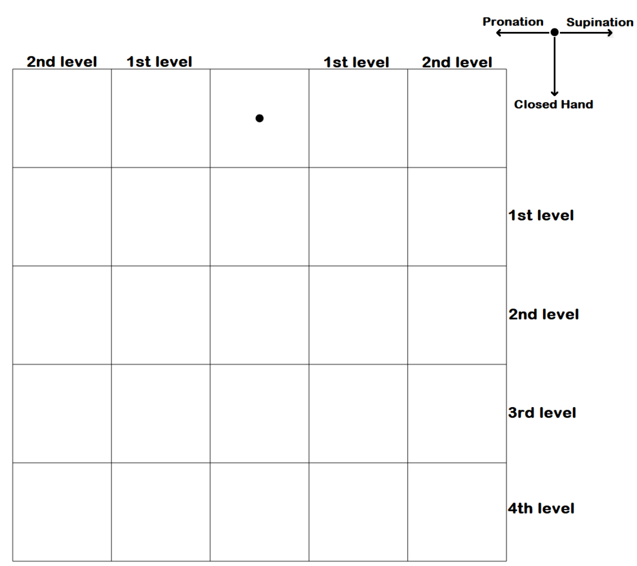

Fig. 5. Image of the grid map and cursor used in the experiment. Wrist supination moved the cursor to the right, pronation moved it to the left and closing the hand moved it downwards. For left-handed subjects, the rotational movements were reversed. Opening the hand moved the cursor upwards, and was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

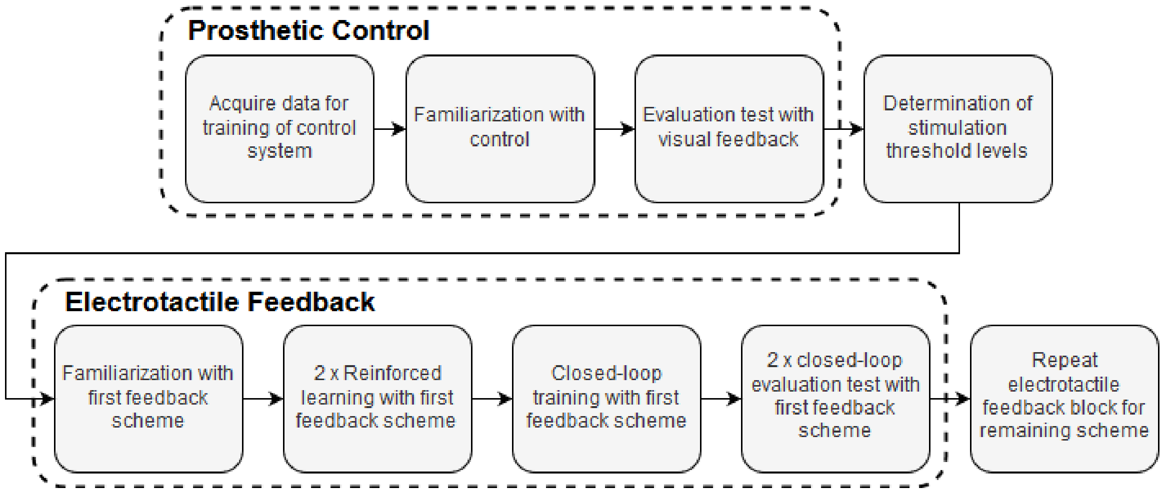

Fig. 6. Pipeline showing the stages of the experiment. The stages in the first block focused on developing a prosthetic control system, and evaluating the subjects' ability to control the prosthesis. Then stimulation threshold levels were determined. The second block focused on training the understanding 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 intensities 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 level 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 levels were again readjusted to achieve homogeneous sensation intensities. Throughout the process of determining thresholds, 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:

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

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

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.

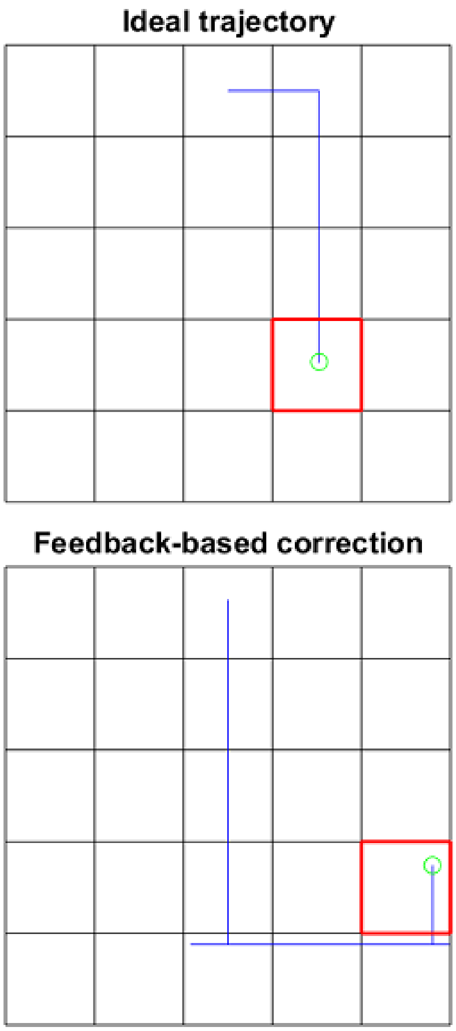

Fig. 7. Examples of two prosthesis trajectories when reaching a combined DoF target in the amplitude evaluation test. The top figure shows an ideal trajectory and the bottom figure illustrates a feedback-assisted path correction. The blue line is the prosthesis trajectory, the center of the green circle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

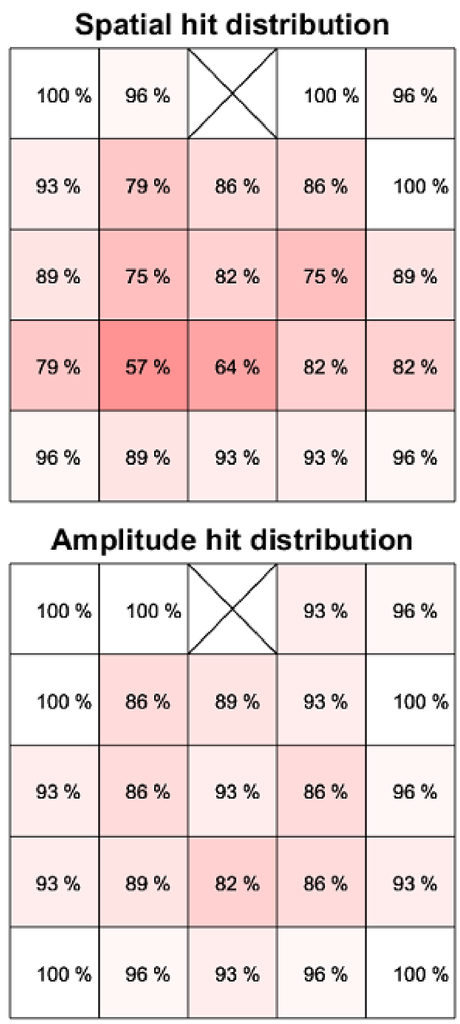

Fig. 9. Hit rate for each target in the spatial and amplitude evaluation test, respectively. The more transparent a target is, the higher the hit rate was. 100 % accounts for a total of 28 hits for each test.

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

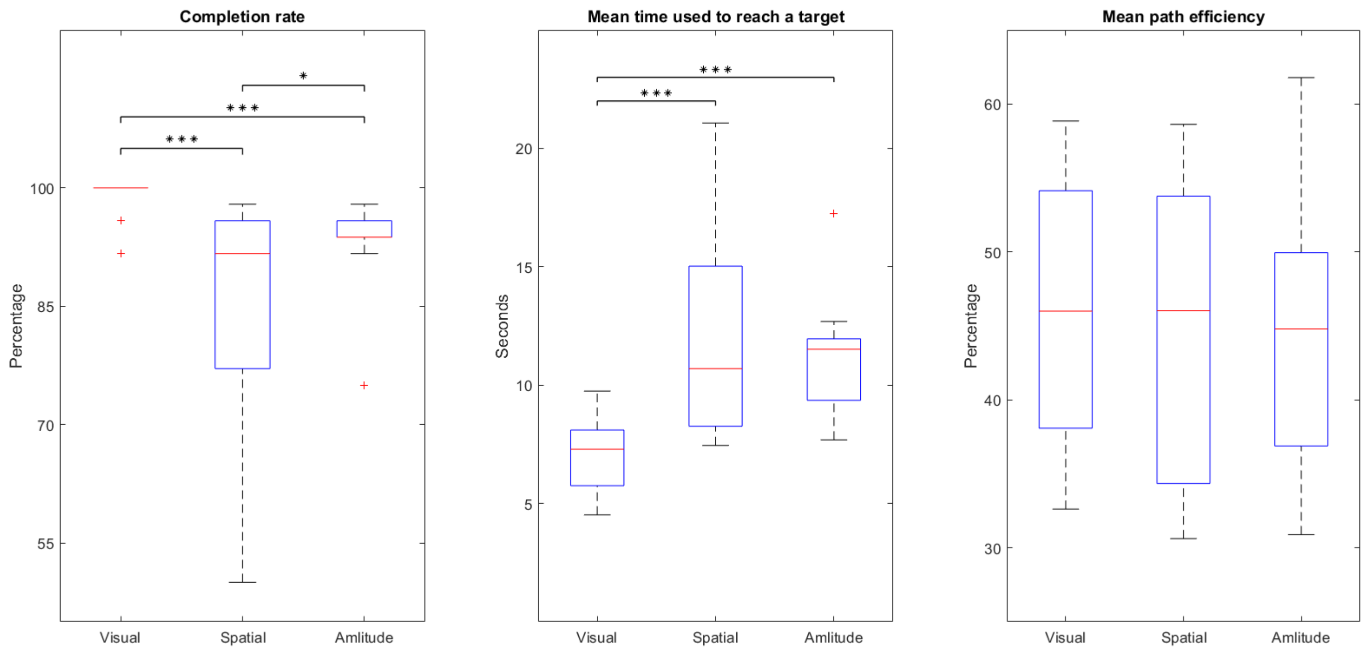

Fig. 8. Box plots of the metrics extracted from the visual, spatial and amplitude feedback evaluation tests. The two evaluation tests in the spatial and amplitude feedback block, respectively, were combined by calculating the mean between the two tests. One asterisk indicates p-value < 0.05 and three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

feedback; mean completion rate for peripheral targets was 93 % $\pm$ 6 % with spatial feedback and 97 % $\pm$ 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 % $\pm$ 12 % with spatial feedback and 93 % $\pm$ 6 % with amplitude feedback; mean completion rate for combined DoF targets was 85 % $\pm$ 11 % with spatial feedback and 93 % $\pm$ 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 % $\pm$ 2 % for rotational single DoF targets during spatial feedback and 97 % $\pm$ 3 % with amplitude feedback; 81 % $\pm$ 12 % for hand aperture single DoF targets during spatial feedback and 89 % $\pm$ 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 % $\pm$ 6 % and 87 % $\pm$ 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 % $\pm$ 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 % $\pm$ 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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References

[1] J. S. Schofield, K. R. Evans, J. P. Carey, and J. S. Hebert, "Applications of sensory feedback in motorized upper extremity prosthesis: A review," *Expert Review of Medical Devices*, vol. 11, no. 5, pp. 499–511, 2014.

[2] K. Østlie, P. Magnus, O. H. Skjeldal, B. Garfelt, and K. Tambs, "Mental health and satisfaction with life among upper limb amputees: A Norwegian population-based survey comparing adult acquired major upper limb amputees with a control group," *Disability and Rehabilitation*, vol. 33, no. 17-18, pp. 1594–1607, 2011.

[3] P. Geethanjali, "Myoelectric control of prosthetic hands : state-of-the-art review," *Medical Devices: Evidence and Research*, pp. 247–255, 2016.

[4] E. Biddiss and T. Chau, "Upper limb prosthesis use and abandonment: A survey of the last 25 years," *Prosthetics and Orthotics International*, vol. 31, no. 3, pp. 236–257, 2007.

[5] B. Peerdeman, H. Hermens, S. Stramigioli, H. Rietman, H. Witteveen, R. Huis in 't Veld, S. Misra, P. Veltink, and D. Boere, "Myoelectric forearm prostheses: State of the art from a user-centered perspective," *The Journal of Rehabilitation Research and Development*, vol. 48, no. 6, pp. 719–738, 2011.

[6] V. Systems, "VINCENT EVOLUTION 2," *https://vincentsystems.de/en/prosthetics/vincent-evolution-2/*, 2005.

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

[8] B. Stephens-Fripp, G. Alici, and R. Mutlu, "A review of non-invasive sensory feedback methods for transradial prosthetic hands," *IEEE Access*, vol. 6, pp. 6878–6899, 2018.

[9] D. J. Atkins, D. C. Heard, and W. H. Donovan, "Epidemiologic Overview of Individuals with Upper-Limb Loss and Their Reported Research Priorities," *Journal of Prosthetics and Orthotics*, vol. 8, pp. 1–11, 1996.

[10] H. Xu, D. Zhang, J. C. Huegel, W. Xu, and X. Zhu, "Effects of Different Tactile Feedback on Myoelectric Closed-Loop Control for Grasping Based on Electrotactile Stimulation," *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol. 24, no. 8, pp. 827–836, 2016.

[11] M. Štrbac, M. Belić, M. Isaković, V. Kojić, G. Bijelić, I. Popović, M. Radotić, S. Došen, M. Marković, D. Farina, and T. Keller, "Integrated and flexible multichannel interface for electrotactile stimulation," *Journal of Neural Engineering*, vol. 13, no. 4, pp. 1–16, 2016.

[12] B. Geng, K. Yoshida, L. Petrini, and W. Jensen, "Evaluation of sensation evoked by electrocutaneous stimulation on forearm in nondisabled subjects," *The Journal of Rehabilitation Research and Development*, vol. 49, no. 2, p. 297, 2012.

[13] S. B. Godfrey, M. Bianchi, A. Bicchi, and M. Santello, "Influence of Force Feedback on Grasp Force Modulation in Prosthetic Applications: a Preliminary Study," *Conf Proc IEEE Eng Med Biol Soc.*, pp. 1–8, 2016.

[14] A. Ninu, S. Dosen, S. Muceli, F. Rattay, H. Dietl, and D. Farina, "Closed-loop control of grasping with a myoelectric hand prosthesis: Which are the relevant feedback variables for force control?," *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol. 22, no. 5, pp. 1041–1052, 2014.

[15] M. Nabeel, K. Aqeel, M. N. Ashraf, M. I. Awan, and M. Khurram, "Vibrotactile stimulation for 3D printed prosthetic hand," *2016 2nd International Conference on Robotics and Artificial Intelligence, ICRAI 2016*, pp. 202–207, 2016.

[16] F. Cordella, A. L. Ciancio, R. Sacchetti, A. Davalli, A. G. Cutti, E. Guglielmelli, and L. Zollo, "Literature Review on Needs of Upper Limb Prosthesis Users," *Frontiers in Neuroscience*, vol. 10, no. May, pp. 1–14, 2016.

[17] R. E. Prior, J. Lyman, P. A. Case, and C. M. Scott, "Supplemental Sensory Feedback for the VA/NU Myoelctric Hand Background and Preliminary Designs," *Bulletin of Prosthetics Reasearch*, vol. 101, no. 134, 1976.

[18] A. Chatterjee, P. Chaubey, J. Martin, and N. V. Thakor, "Quantifying prosthesis control improvements using a vibrotactile representation of grip force," *2008 IEEE Region 5 Conference*, pp. 1–5, 2008.

[19] H. J. Witteveen, F. Luft, J. S. Rietman, and P. H. Veltink, "Stiffness feedback for myoelectric forearm prostheses using vibrotactile stimulation," *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol. 22, no. 1, pp. 53–61, 2014.

[20] C. Hartmann, J. Linde, S. Dosen, D. Farina, L. Seminara, L. Pinna, M. Valle, and M. Capurro, "Towards prosthetic systems providing comprehensive tactile feedback for utility and embodiment," *IEEE 2014 Biomedical Circuits and Systems Conference, BioCAS 2014 - Proceedings*, pp. 620–623, 2014.

[21] M. Franceschi, L. Seminara, L. Pinna, S. Dosen, D. Farina, and M. Valle, "Preliminary evaluation of the tactile feedback system based on artificial skin and electrotactile stimulation," *Proceedings of the Annual International Conference of the IEEE Engineering in Medicine and Biology Society, EMBS*, pp. 4554–4557, 2015.

[22] S. Dosen, M. Markovic, C. Hartmann, and D. Farina, "Sensory feedback in prosthetics: A standardized test bench for closed-loop control," *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol. 23, no. 2, pp. 267–276, 2015.

[23] I. Mendez, B. W. Hansen, C. M. Grabow, E. J. L. Smedegaard, N. B. Skogberg, X. J. Uth, A. Bruhn, B. Geng, and E. N. Kamavuako, "Evaluation of the Myo Armband for the Classification of hand motions," *International Conference on Rehabilitation Robotics*, pp. 1211–1214, 2017.

[24] A. Boschmann, B. Nofen, and M. Platzner, "Improving Transient State Myoelectric Signal Recognition in Hand Movement Classification using Gyroscopes," *2013 35th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*, pp. 6035–6038, 2013.

[25] I. M. Donovan, J. Puchin, K. Okada, and X. Zhang, "Simple space-domain features for low-resolution sEMG pattern recognition," *Proceedings of the Annual International Conference of the IEEE Engineering in Medicine and Biology Society, EMBS*, pp. 62–65, 2017.

[26] B. Hudgins, P. Parker, and R. Scott, "A new strategy for multifunction myoelectri control," *IEEE Transactions on Biomedical Engineering*, vol. 40, no. 1, pp. 82–94, 1993.

[27] R. Menon, H. Lakany, G. Di Caterina, B. A. Conway, L. Petropoulakis, and J. J. Soraghan, "Study on Interaction Between Temporal and Spatial Information in Classification of EMG Signals for Myoelectric Prostheses," *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol. 25, no. 10, pp. 1832–1842, 2017.

[28] K. Englehart and B. Hudgins, "A robust, real-time control scheme for multifunction myoelectric control.," *IEEE transactions on bio-medical engineering*, vol. 50, no. 7, pp. 848–854, 2003.

[29] J. T. Belter, J. L. Segil, A. M. Dollar, and R. F. Weir, "Mechanical design and performance specifications of anthropomorphic prosthetic hands: a review.," *Journal of rehabilitation research and development*, vol. 50, no. 5, pp. 599–618, 2013.

[30] M. Atzori and H. Müller, "Control Capabilities of Myoelectric Robotic Prostheses by Hand Amputees: A Scientific Research and Market Overview," *Frontiers in Systems Neuroscience*, vol. 9, no. November, pp. 1–7, 2015.

[31] J. A. Adams, D. Gopher, and G. Lintern, "Effects of visual and proprioceptive feedback on motor learning," *Journal of Motor Behavior*, vol. 9, pp. 11–22, 1977.

[32] S. Dosen, M. Markovic, M. Strbac, M. Belić, V. Kojić, G. Bijelić, D. Farina, and T. Keller, "Multichannel Electrotactile Feedback With Spatial and Mixed Coding for Closed-Loop Control of Grasping Force in Hand Prostheses," *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol. 25, no. 3, pp. 183–195, 2016.