The Influence of EMG Biofeedback on Robustness of Myoelectric Prosthesis Control

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***Abstract*—Most commercially available myoelectric prostheses only provide the users with incidental feedback. Sudden changes in the signal make the prosthesis users have limited information to react to these changes to make sure they perform the correct movement and apply the correct muscle contraction. This limited information indicates that the robustness of the system in commercial prostheses is poor. With EMG biofeedback it is possible to provide the subjects with predictive feedback to the control signal, meaning that they will have knowledge of a change in the signal. This study presents a system that is used to investigate the robustness of prosthesis control through the use of EMG biofeedback and Force feedback. The proposed system was tested with five able-bodied subjects in a virtual routine grasping task, using a Myo armband. The experimental task was performed with two different feedback configurations. The outcome measures were success rate, completion time, and trend of adaptability. The results demonstrated that EMG biofeedback generally performed better regarding quicker completion time compared to Force feedback. The results showed similar success rates for the two feedback configurations. These two results suggested that the EMG biofeedback would be providing the prosthesis with a functional benefit. The trend of adaptability was not noticeable for the results in this study. The present study showed that EMG biofeedback was providing the subjects with information which lead to a faster grasping during the routine grasping task, but it showed no considerable improvement in success rate, compared to Force feedback. This study provides insight into the robustness of myoelectric prosthesis control, and the relevance of somatosensory feedback in the subject's adaptability of myoelectric control.**

***Index Terms*—EMG biofeedback, force feedback, closed-loop prosthesis control, robustness, CLS toolbox, Myo armband, routine grasping.**

I. INTRODUCTION

THE human hand is versatile in its approach to grasping a variety of objects in the daily life. The hand is capable of producing stable and consistent force to guarantee an appropriate force exerted for the task. Besides this, the hand is able to quickly adapt to unpredictable changes in the object properties such as weight. The daily life tasks of grasping and manipulating objects are performed by the central nervous system, with help from the tactile receptors in the hand, which provide the brain with information about the environment, through a sensory feedback loop. The motor planning and performance of the hand depends on the sensory feedback [1, 2]. However, routine tasks can often be performed with feedforward control, meaning that both the feedforward and feedback loops are important in controlling the hand. Total loss of motor capabilities of the hand through an upper limb transradial amputation is greatly affecting the daily life activities. This makes the amputation a debilitating event for the amputee [3]. The capabilities of an upper limb transradial amputation can be somewhat artificially replaced by a body-powered prosthesis, or a myoelectric prosthesis.

The sensory feedback loop has to be closed to make sure the user has an almost complete overview of the environment, and thereby can manipulate the objects in the environment with an accuracy similar to that of healthy people. Several studies have stated a prosthesis rejection rate between 19-39 % for upper limb prosthesis users [4–6]. The reasons, frequently linked with abandonment of prosthesis, involved inferior durability, inadequate dexterity, and absence of conscious perceptual feedback [7, 8]. The sensory feedback provided by commercially available prostheses is typically limited to incidental feedback such as visual feedback. Healthy people use a lot of different sensory feedback to manipulate objects, and perform daily living tasks, whereas people with a transradial amputation are limited to the incidental feedback provided by the prosthesis and the environment. A body-powered prosthesis can provide the user with a direct haptic force feedback through the wire-pulling [9, 10]. Electrical activity of the remaining muscles in the arm of a transradial amputee can be captured and used to control and move a myoelectric prosthesis as intended by the user [11]. The user is shown to be able to reliably, precisely and robustly control a myoelectric prosthesis, by closing the control loop with artificial somatosensory feedback [12], but the adaptability of changes in EMG signal has not been studied with regards to comparing EMG biofeedback and Force feedback. The myoelectric prosthesis can be equipped with sensors to record relevant data such as grip force or hand posture. This can be provided to the amputee from the prosthesis as somatosensory feedback, by activating the tactile sensors which remain in the stump. This feedback can be provided to the amputee by using either invasive interfaces (e.g. direct nerve stimulation or brain stimulation) or non-invasive interfaces (e.g. mechanical stimulation or surface electrode stimulation) [10].

Although the disparity between amount of research and commercial prosthetic hands has increased in the past years, different progressive prosthetic hands have emerged in the market, equipped with greater range of motion and dexterity of fingers. These include the iLimb Hand, the LUKE arm, the Michelangelo® Hand, and the Vincent Hand, of which none are capable of providing sensory feedback to the user, highlighting one of the issues with current prostheses. Presently, only VINCENTevolution 2 provides grasping force feedback

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through vibrations [7].

The typical way of giving feedback in the field of research, is through force feedback, which is a corrective type of feedback, meaning that it is only obtained after the prosthesis has closed around the object. This feedback type is a feedback on how the prosthesis is behaving, and not on the signal to control the prosthesis itself. By providing a feedback on the EMG signal, the user will be provided with a predictive feedback to the signal which generates the prosthesis action. The concept of EMG biofeedback is based on the idea of delivering feedback on the myoelectric signals of the user. When receiving EMG biofeedback, the user can change their myoelectric signals while closing the prosthetic hand, hence permitting real-time control of muscle force and prosthesis force. This can be carried out due to the proportional relation between the prosthesis' grasping force and the user's myoelectric signals at the point of contact between the prosthesis and the desired object [13].

When the EMG biofeedback is implemented in the prosthesis system, it could lead to a greater understanding for the user, since they would have greater knowledge of the control signal, thereby increasing the robustness of the system. The robustness of myoelectric signal control (i.e. EMG control) can be influenced by internal and external factors. The internal factors mainly concern the user, involving unintentional movements and dynamic fluctuations of force. On the other hand, the external factors refer to changes associated with signal acquisition states, e.g. diverse limb positions and electrode shift [14]. When a sudden change in the EMG signal occurs, the user of the prosthesis will not know about this change before the prosthesis has closed around the object and then have either used too little or too excessive force to manipulate the specific object. With force feedback present at the setup, the prosthesis user will know what force was being produced, but will not inherently know why the prosthesis is producing a wrong amount of force. This problem of not knowing, can be solved by having feedback on the EMG control signal, meaning that the user will have knowledge about the EMG signal and the changes in this, before any contact with the object. The purpose of this study is to investigate whether EMG biofeedback improves robustness of prosthesis control. More specifically, the aim is to examine whether changes in the gain of the EMG can be deliberately compensated for by the subjects through the application of EMG biofeedback.

When performing a task and the EMG signal changes suddenly, it is expected that the users will be able to adapt more quickly with EMG biofeedback, as they can correct the muscle contraction to an appropriate level, before the prosthesis has closed.

In this experiment the robustness of closed-loop control when using EMG biofeedback and Force feedback is investigated. We hypothesise that EMG biofeedback will exhibit significantly higher robustness compared to Force feedback. This is because with EMG biofeedback the subjects are getting explicit feedback on the muscle activation (strength of EMG control signal), and therefore they will be able to use it to immediately understand that there is a change in gain. Based on this, it is expected that the subjects achieve a better performance[1] with EMG biofeedback compared to Force feedback.

II. MATERIALS AND METHODS

A. Subjects

Five able-bodied subjects (two males, three females, 35.6 ± 16.6 years) were recruited for the experiment. The subjects were informed about the aim and execution of the study preceding the experiment.

B. Experimental Setup

The setup, as seen in Figure 1, consisted of: 1) Myo Gesture Control Armband (Thalmic Labs/North), 2) Computer, 3) MATLAB, 4) Simulink, and 5) CLS toolbox [15].

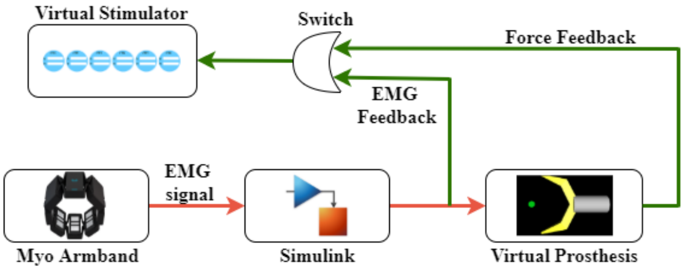

Fig. 1. Schematic diagram of the experimental setup, with the different components it comprises. The subjects were wearing a Myo Armband, which records the EMG signal in the forearm of the subjects. The EMG signal is converted into the control signal for the virtual prosthesis. There are two feedback signals sent to the virtual stimulator, one being the EMG biofeedback from Simulink and the other from the virtual prosthesis in the form of Force feedback. These two feedback are selected using a switch inside the program, so only one is presented to the subject at a particular time.

The Myo armband consists of eight EMG sensors [16], which were used during the experiment to record and acquire myoelectric activity for subsequent data processing. A computer, with MATLAB Simulink installed, was used to conduct the experiment. The entire experimental procedure was carried out through MATLAB Simulink models, which contained functionality necessary for execution of the experiment. A separate computer screen was used by the subject, with only the necessary information being displayed, as seen in Figure 2. The subject was introduced to the setup and equipment, along with the four different gain levels and four different target forces, presented in the training session. The four different gain levels are used to simulate the factors, which can affect the EMG signal. The four target forces are what the subject is reaching for, when doing the routine grasping task. The force produced by the prosthesis is divided into six force levels, correlated to the EMG signal. Six force levels could be reached, but level one and six were trivial and easy to produce, making them redundant in the experiment. Hence, they were used as indicators of producing insufficient or excessive amount of muscle contraction.

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[1] The performance is evaluated based on success rate and completion time.

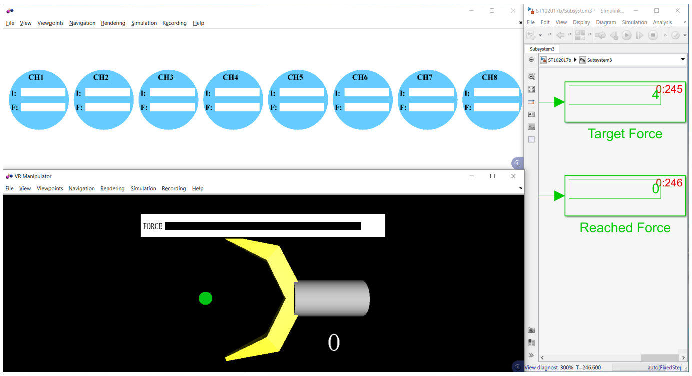

Fig. 2. The eight feedback display channels are shown on the upper left side. Of these, only the first six feedback channels are used. The virtual prosthesis is presented below the display of feedback channels. The target force and reached force are shown on the right side. The reached force is only visualised during training.

C. *Virtual Routine Grasping Task*

Able-bodied persons grasp objects in the daily life, by doing a smooth closing movement of hand around the object. The force needed to manipulate this object is reached immediately after contact with the object has been achieved. A prosthesis can do such a movement by closing with a certain speed, and then reaching the desired force. This movement is desired in prostheses, because it can be a tedious process to adjust the force produced in the grasp, and it is generally only possible to adjust the force to increase, making the grasp stronger. The prosthesis can obtain such a movement by having the user generate and hold a steady level of muscle contraction. The closing speed of the prosthesis is proportional to the muscle activity, meaning that with a stronger muscle contraction, you can achieve faster closing of the prosthesis, and thereby producing a larger grasping force. In several studies, the users only receive the feedback of the force being produced after the contact, making the feedback a corrective feedback [17–19]. The users are therefore unaware whether the muscle contraction they are doing is the correct control signal to get the desired force being produced. To get the predictive feedback, the prosthesis users can be provided with the EMG biofeedback of their muscle contraction. This makes the user able to modulate the muscle activity to match the desired force level. The routine grasping in this study will consist of a virtual prosthesis in a Simulink program, working as an ideal prosthesis without delay and other problems a real life prosthesis may encounter.

D. *Experimental Protocol*

1) Preparation: Firstly, the subject saw their EMG signal via a scope, displaying their rectified EMG signal, to get an idea of how muscle contractions affected the EMG signal. After the subject recognised the effect of the muscle contractions on the EMG signal, the baseline and maximum voluntary contraction (MVC) calculation were performed. The subject was asked to relax the muscles in the arm for five seconds, in order to calibrate the baseline of the EMG signal. The subject was then asked to do three trials of MVC with the flexor muscles of the wrist for a duration of five seconds each. This was done to identify the maximum of the signal, but also to determine the most active channel of the Myo Armband. More specifically, the MVC was used to linearise the velocity commands sent to the prosthesis, since the maximum force produced by the prosthesis corresponds to the maximum closing speed of the prosthesis, which in turn is proportionally related to 50 % of the subject's MVC. The subject's EMG was normalised to 50 % of the MVC to ensure that the subject was not experiencing fatigue during the experiment.

2) EMG Control Familiarisation: The subject went through a familiarisation process which showed them their EMG command signal, with the different EMG levels they had to be within to produce the required force level. The goal of this was to make sure that the subject was familiar with how the EMG command signal would behave, and how to maintain a certain muscle contraction to produce the desired force.

3) Main task: The first part of the task was to make the subject familiar with the task and feedback during the task. When the subject was familiar with the setup, they could proceed with the experiment. In order to get acquainted with the task procedure, the subject was asked to produce the random order of four target forces (force level two through five) in sets of five repetitions. The training comprised a total of 20 trials, and additional feedback was shown to the subject (reached force level). The reached force level was shown to the subject after the prosthesis had closed around the object, which they could then use to check if they were successful or they should correct their muscle contraction. This was done as a reinforced training for the subject, since this feedback was not presented to the subject in the real task. When the subject had finished the training task block, they were asked to perform two test blocks, each consisting of 40 trials for the virtual routine grasping task. The subject was asked to produce a force level corresponding to the target force shown on the screen. When the subject felt they had reached the correct force level, the virtual prosthesis was opened, and the next trial could be initiated. The experiment consisted of five trials for each gain level and target force combination. The sets of five trials were run sequentially to see how fast the subjects were to adapt to the changes in the signal (through the changes in the gain). The main task process was repeated in both feedback configurations. The subject was able to perceive the EMG biofeedback while the prosthesis was closing, meaning they used it as a predictive feedback. On the other hand, the subject was first able to perceive the force feedback only when the prosthesis was closed around the object, meaning that they could use this information only as a corrective feedback.

E. *Data Analysis*

For this study, success rate[2] and completion time[3] were chosen as outcome measures. The success rates were compared

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[2] The success rate was calculated by comparing the target force (set by the study holder) and reached force of the subjects for all trials. If the target force and reached force matched to each other, that specific trial would be counted as a success.

[3] The completion time was calculated by taking the time at which the subjects were starting to perform muscle contraction for the trial, and subtracting this from the time when the prosthesis was re-opened.

across different target force levels and gain settings between subjects, while the completion time was compared between subjects for an overview of their performance. Besides these outcome measures, the study also examined the subjects' adaptability to changes in gain, as they progressed from the first trial until the fifth trial in each set across both feedback configurations, in relation to the success rate.

III. RESULTS

In the following section, the results of the data analysis are presented.

Figure 3 presents the overall success rate of the individual subjects across both feedback configurations. It was observed that three out of the five subjects performed better with EMG biofeedback compared to Force feedback. Subject 3 performed with a success rate of 70.11 % with Force feedback, and improved the success rate to 76.25 % with EMG biofeedback. Subject 1 performed with a success rate of 69.14 % with Force feedback and 66.67 % with EMG biofeedback.

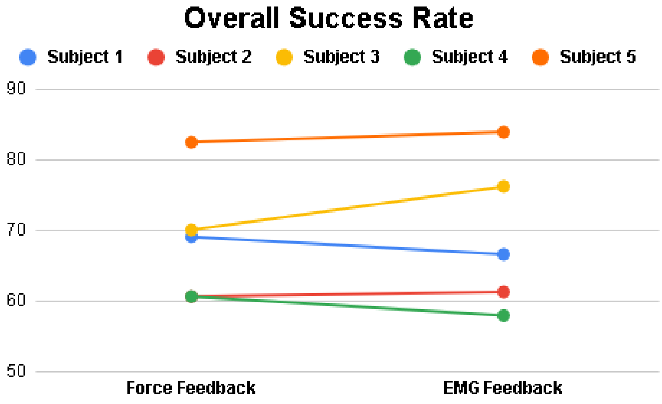

Fig. 3. The figure shows the overall success rate for each subject in the routine grasping task with the two feedback configurations.

Figure 4 depicts the variation of success rates for each target force. In general, the subjects performed quite differently for the target forces, as indicated by the first and third quartiles, especially for target force 2 (64.66 % and 83.13 %) and target force 5 (49.51 % and 74.87 %) in (a), and target force 4 (55 % and 77.5 %) and target force 5 (50 % and 79.3 %) in (b).

The variation of success rates for each gain setting can be seen in Figure 5. The subjects generally performed better with the lowest gain setting (0.5) compared to the highest gain setting (2), in both the feedback configurations. The first and third quartiles for the gain setting (0.5) are (70.54 % and 89.28 %), and likewise for gain setting (2) are (54.5 % and 70 %) for the EMG biofeedback configuration. The first and third quartiles for the gain setting (0.5) are (68.16 % and 88.03 %), and likewise for gain setting (2) are (45.46 % and 67.5 %) for the Force feedback configuration.

The completion time for each trial in both feedback configurations can be seen in Figure 6. The box plot shows that the subjects were generally performing the task with a shorter completion time in the EMG biofeedback configuration (lower quartile of 3.12 s and upper quartile of 4.85 s), compared to the Force feedback (lower quartile of 3.83 s and upper quartile of 6.23 s). It is also observed that there was a greater variation in completion time for Force feedback (minimum completion time of 3.23 s and maximum completion time of 8.96 s) than EMG biofeedback (minimum completion time of 2.63 s and maximum completion time of 5.40 s).

Based on the examination of the trials, the subjects did not show any trend of adaptation to the gain changes with respect to the trial being successful. The examination was done on the sets of trials, where the success rate was evaluated and checked on how quickly the subjects were able to get a successful trial in each set of trials (i.e. how efficiently the subjects were to adapt their EMG control to the changes in gain setting).

IV. DISCUSSION

The objective of this study was to investigate the robustness of prosthesis control through provision of EMG biofeedback and Force feedback. This is linked with the aim to examine the subject's adaptation to changes in the EMG signal. It was hypothesised that EMG biofeedback would express higher robustness compared to the Force feedback performing the experimental task. Our experiment has demonstrated that our initial hypothesis was partly confirmed. Indeed, EMG biofeedback allowed the subjects to reach the correct level of muscle activation quicker compared to Force feedback with respect to completion time, as seen in Figure 6.

The data gathered from the experiment showed that the subjects were performing at a similar success rate for both the feedback configurations, but with a quite considerable difference in completion time.

The overall success rate, which can be seen in Figure 3, does not suggest a clear trend for the data, although the completion time for EMG biofeedback was much shorter than for Force feedback, meaning they reached the correct target force level quicker. Three subjects (subject 2, subject 3 and subject 5) experienced a better success rate with EMG biofeedback compared to the Force feedback. However, the other two subjects (subject 1 and subject 4) experienced a better success rate with Force feedback compared to EMG biofeedback.

The subjects' success rate distribution across the target forces can be seen in Figure 4. The data show that there is no noticeable trend in the results regarding the success rate across the target forces, although it seems like there is a wider spread of data with target force 5 than the other target forces. Target force 5 is generally at a lower success rate than the others, even though the subjects were mainly performing force modulation instead of routine grasping (which they were instructed to do) during the tasks. This is a bit counter-intuitive, since with force modulation task, where the subjects are performing the lowest force, and then modulating slowly upwards, the subjects should hypothetically be performing better at the highest target force levels. The success rate in between the two feedback configurations was not distinctly different, which may indicate that the subjects were not performing routine grasping. The subjects' data had a wider range with regard to the whiskers in the box plot, in the EMG biofeedback configuration than

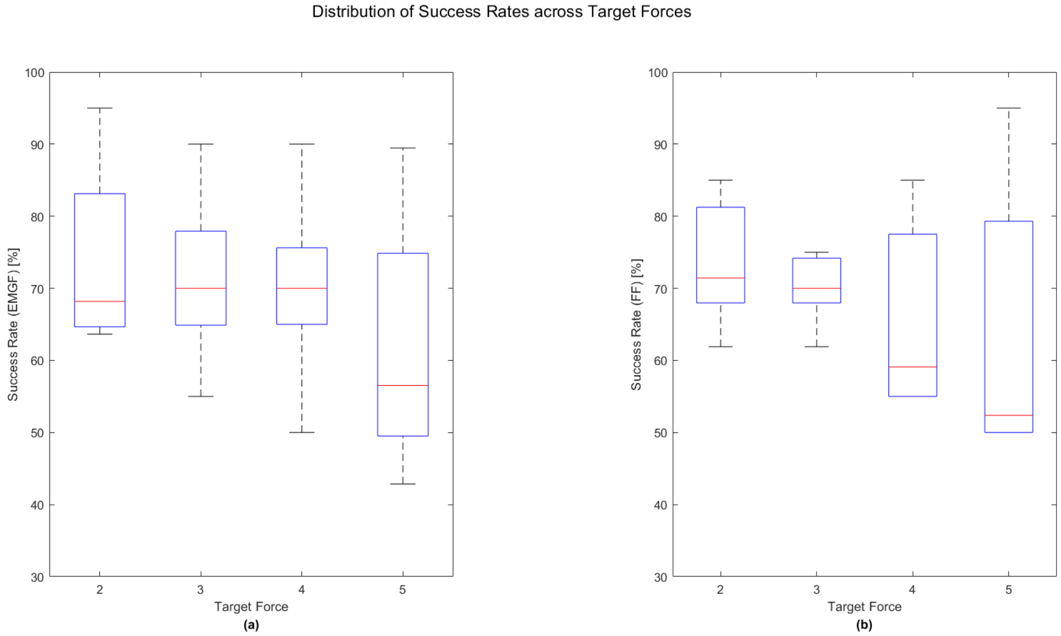

Fig. 4. The figure represents two box plots for the success rate across the target forces. (a) Box plot representing the difference of the success rates for all subjects with EMG biofeedback. (b) Box plot representing the disparity of the success rates for the subjects with Force feedback.

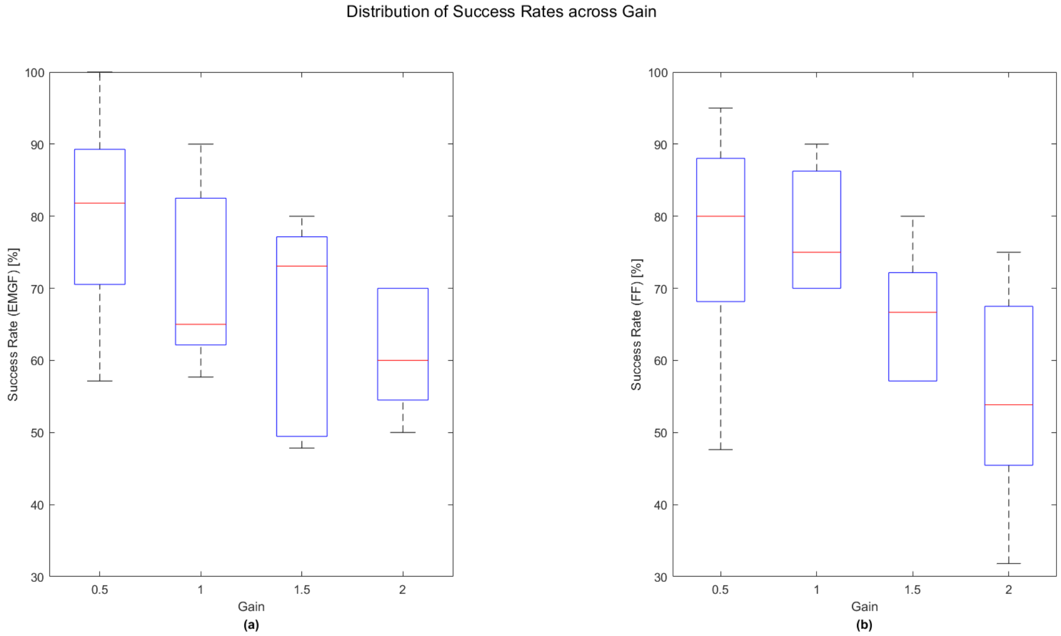

Fig. 5. The figure consists of two box plots, illustrating the dispersion of success rates across the gain settings. (a) Box plot showing a variation of success rates for all subjects across the different gain settings with EMG biofeedback. (b) Box plot visualising the range of success rates for all subjects across the gain settings with Force feedback.

the Force feedback configuration. We were expecting to see a steady similar success rate across all the target forces in both the feedback configurations, but with the EMG biofeedback to be performing with a higher success rate, due to the predictive feedback control. This means that there would be a smaller chance for the subjects to overshoot the target force, since they would know what force the prosthesis would be exerting before it was closed around the object. The majority of the subjects were experiencing more difficulty with achieving target force level 2 correctly compared to the other levels, since they were concerned about overshooting the target force level, when performing the muscle contraction. This is contradicting the results, since they generally perform better at target force level 2 than the other target force levels, but it indicates that

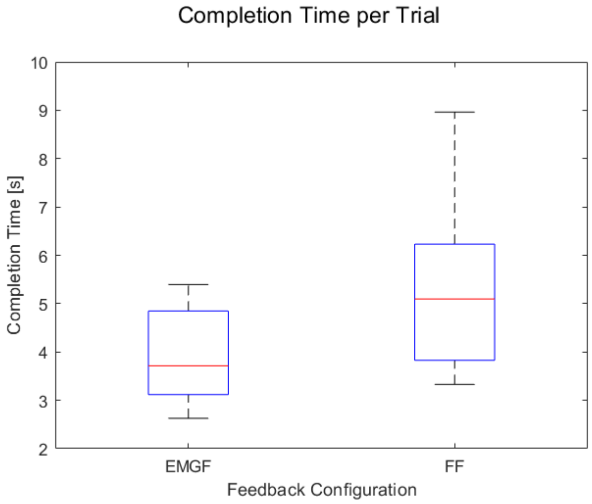

Fig. 6. The figure represents a box plot showing the distribution of completion time for each trial during both feedback configurations.

the subjects were performing the task as modulating the force upwards when the prosthesis was closed around the object.

Due to the system being virtual, the prosthesis was performing with no extra external factors (gearing problems and delay as in the real world). This means that the subjects were able to do force modulation correctly with EMG biofeedback, which would have been much more difficult in a real life setup, since the EMG biofeedback would not directly correspond to the force produced after the prosthesis had closed around the object (it would be shifted a bit, e.g. due to extra resistance).

The success rate regarding the different gain settings, as seen in Figure 5, shows the trend that the subjects' performance at the lowest gain setting (0.5) is generally better than with the other gain settings. This could be due to the EMG signal being less responsive to the muscle contraction with a low gain, because the subjects were required to produce a larger muscle contraction to achieve the desired target force, compared to a high gain. For this gain setting, the variation of success rate was the largest compared to the other gain settings in both feedback configurations. This could be caused by the fact that subjects had to estimate the exact amount of muscle contraction they had to produce to reach the intended target force, while simultaneously considering the risk of overshooting.

The completion time for both feedback configurations, which can be seen in Figure 6, shows that the completion time for the subjects during the EMG biofeedback configuration was quite a bit shorter than the completion time when doing the task with the Force feedback configuration. This indicates that the subjects were performing faster grasping with the EMG biofeedback than the Force feedback. This is due to the predictive behaviour of the EMG biofeedback, whereas the Force feedback is a corrective feedback only provided to the subjects after the prosthesis has closed around the object. With the EMG biofeedback, the subjects would know what force the prosthesis was going to produce while the prosthesis was closing, meaning that they could get to the proper target force even before the prosthesis was closed around the object. Contrary to the EMG biofeedback, the Force feedback did not provide the subjects with any knowledge of the force produced by the prosthesis before closing around the object. This was indicated by the subjects' careful approach when closing the prosthesis, in order to prevent overshooting the target force. The overshooting of force being produced is a problem with this setup, since the prosthesis is non-backdrivable, so the subject could only modulate the force to be greater, meaning progressing in target force levels when the prosthesis is closed. This could indicate that the subjects were performing the task more as a routine grasping task than a force modulation task with EMG biofeedback, compared to the Force feedback.

Adaptation to the different gain settings, with respect to success rate, was examined, and the results suggested that there was no obvious or consistent trend regarding the subjects' adaptation to achieving the desired target force within the sets of five trials. In other words, the subjects showed no trend with how many trials they needed, before they had adapted their signal to output the correct target force.

When asked about the feedback configurations after the experiment the majority of the subjects reported having a greater cognitive load with the EMG biofeedback. This may be due to the subjects trying to focus on both the EMG biofeedback on the virtual stimulator, but also on the virtual prosthesis while it was closing. With the Force feedback, the subjects were only focusing on the prosthesis while it was closing, since there was no information in the virtual stimulator until the prosthesis had closed around the object. When the prosthesis was closed around the object, the subjects were then focusing solely on the virtual stimulator.

Due to the current COVID-19 situation taking place globally, the university decided to close down until it was deemed safe to work at the university again. This also meant that the experiment could not be performed in the laboratory located at the university, and thereby the study was not able to use the laboratory equipment such as the vibrotactors and the Michelangelo® Hand. The experimental environment in which the subjects were performing the experimental task was therefore not ideal, since it took place at home with other people present (even though they were thoughtful and considerate, they could not avoid being there). This could influence the subjects in a way that they would feel pressure, and hinder them to perform to the best of their ability, through involuntary distractions. The study holders only recruited five able-bodied subjects to the experiment, due to the guidelines suggesting the use of subjects within one's household. This lead to the number of subjects being insufficient for a meaningful statistical analysis of the experimental results.

Schweisfurth et al. (2016) shows that subjects provided with EMG biofeedback compared to Force feedback performed significantly better in both precision of myoelectric commands and force control in intact bodied subjects [1]. Schweisfurth et al. (2016) used haptic feedback, while this study only had visual feedback. This could be a reason for the different results regarding the success rate. Dosen et al. (2015) shows a similar trend with EMG biofeedback providing the subjects with additional feedback to the already present Force feedback in their setup. This additional feedback made the subjects have a significantly more consistent and stable force level produced, since the subjects could predict the generated force before closing of the prosthesis [13]. Schweisfurth et al. (2016) demonstrated that the subjects performed faster routine grasping with EMG biofeedback compared to Force feedback [1]. This coincides with the results of this study emphasising that subjects achieved shorter completion times with EMG biofeedback compared to Force feedback.

To ensure that the subjects are all performing the same experimental task correctly, the experimental protocol could be fitted with specific constraints such as Schweisfurth et al. (2016). In the study, a constraint was set on the trial time (350 ms after touch onset) to make sure that the subjects were not performing force modulation task instead of the routine grasping they were asked to do [1].

V. CONCLUSION

The present study proposed an approach to investigate the robustness of a closed-loop control system, when using EMG biofeedback and Force feedback in a virtual environment. The experiment demonstrated that the EMG biofeedback did not facilitate the subjects with a notable improvement in success rate, but it was shown that the completion time for each trial was considerably shorter for EMG biofeedback than Force feedback.

VI. FUTURE PERSPECTIVE

For a future study, the main point of interest would be to examine the possibility of translating the current virtual setup into a setup using a real prosthesis and vibrotactile feedback. Besides inclusion of the physical setup, it would be interesting to investigate what the trend of the data would be with a larger sample size.

Another research point that would be worth investigating, could be to include completion times for the individual gain settings and target forces for EMG biofeedback and Force feedback, rather than only calculating the overall completion times. In this study, this was not possible to do since some of the subjects were not fully relaxed in between all of the trials. This would provide an overview of which parts of the two feedback configurations the subjects spent more time on during muscle contraction and reaching the target force.

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