Mechanisms of Sporadic Control Failure in Myoelectric Hand Prostheses

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ABSTRACT

This study is concerned with the control of hand prostheses based on electromyograms (EMG). As the arm is moved in space during activities, the socket and electrodes can shift on the residual limb, causing changes in the signals which can be misinterpreted by the electronic controller to open or close the hand inadvertently. To study these changes conventional prosthetic EMG amplifier/conditioners were augmented with force sensors so that an indication of the forces through the amplifier could be recorded. These multimodal myoelectric units (MMUs) were then used to control prosthetic hands by 15 users with losses below the elbow. The subjects performed four tasks resemblant of activities of daily living, including a user selected task, while the EMG signals, the forces onto the amplifiers and the performance of the hands (including video images) were recorded.

Eight subjects reported a total of 38 errors in the control of the hand during the four tasks. The paper shows examples of the EMG and force signals recorded during the control failures and discusses the possible causes of the failures. The types of failure include; failure to open or close when instructed, as well as accidental opening when not commanded to move. These were caused by changes in the contact forces between the electrodes and the skin. It was not possible to attribute clear causes for 27.5% of all failures. These were likely to be due to other factors. Knowledge of the common ways that the socket moves can guide improved design of sockets to reduce the errors.

KEYWORDS (TBD)

Hand prosthesis, electromyogram, control failure, contact force measurement

INTRODUCTION

Prostheses controlled via the surface electromyogram (SEMG) are known to occasionally fail to operate according to the user's intentions. Several factors may cause such sporadic malfunction events, including electrical interference and skin impedance changes due to perspiration. The main focus of this paper is concerned with another important class of disturbances, which are mechanical in nature; variations in skin-electrode contact forces or changes in relative positions between the residual limb and the electrodes, cause the SEMG to exhibit atypical behavior that is misinterpreted by the prosthesis control system.

These problems are known to most users and experts in the field, but little hard evidence has been published on the actual mechanisms at work inside a prosthesis socket during such malfunctions. The aim of this study was to provide some of this evidence, which may have implications for future socket and electrode designs, SEMG processing techniques, and user training.

BACKGROUND

In prostheses based on extra-skeletal suspension a certain amount of relative motion is inevitable between prosthesis and residual limb. All external forces are transferred through the prosthesis socket to the residual limb, causing the socket, and thus the electrodes, to locally be pressed harder against the residuum, or pulled away, displaced sideways, rotated, or any combination of these. Due to tissue compliance, changes in contact force will always be accompanied by some relative displacement, and vice versa. SEMG disturbances caused by such mechanical factors are thus collectively referred to as *motion artifacts*.

The properties of the observed SEMG may also be altered if the limb is operated in a new working position. This phenomenon, referred to as the *limb position effect*, has been observed both in healthy [1] and in transradial amputee subjects [2]. The result is the same as for motion artifacts, in that the prosthesis control system fails to correctly identify the user's intent. Recent studies indicate that this effect can be mitigated by appropriate system training strategies [2, 3] and/or by introducing new sensor modalities such as accelerometry [4]. Thus far, the limb position effect has been studied as a static phenomenon, and as such it cannot be regarded as a *motion* artifact. However, there is reason to believe that related effects occur during dynamic movements. The limb position effect in general also influences the performance of even the simplest commercial systems, since these are all (albeit implicitly) based on a form of pattern recognition. It is therefore considered to be of equal relevance for the present study as motion artifacts.

Artifact attenuation in SEMG signals has been researched extensively for numerous applications. In prosthetics, one example is the attenuation of electrocardiogram (ECG) artifacts, which is of particular importance when using SEMG sites on or near the torso [5]. When it comes to removing mechanically induced artifacts in prosthesis applications, the literature is considerably scarcer. Lovely et al. [6] pointed out the problem and suggested an implantable myoelectric sensor (IMES) as part of the solution. As of January 2012, a commercial IMES system has yet to been seen, in spite of significant research efforts; see e.g. [7]. In commercial prosthesis control systems, movement artifacts are usually attenuated by high-pass filtering the raw SEMG signal with a cut-off frequency of approximately 20 Hz. This filter is said to remove most of the transient noise induced by normal upper-limb movements, though the exact appropriate cutoff-frequency is still subject to debate [8]. Such filtering is not believed by the authors to have any relevance to the position effect.

Lovely [9] gives a concise record physical phenomena associated with movement artifacts. Most of these are unpredictable and may cause significant disturbance even at minute electrode displacements. Some disturbances are fundamentally nonlinear, e.g. changes in the effective signal gain, which cannot be removed through linear filtering. An extreme form of this occurs during electrode lift-off, in which case one or all of the electrode terminals completely lose contact with the skin (Figure 1). Electrode lift-off can be detected indirectly based on e.g. resistance measurements [10] or reflected near-infrared light [11]. Although lift off, as well as other phenomena related to movement artifacts, are well known and easily observable in laboratory settings, the research literature hardly reports any hard evidence as to what exactly causes the prosthesis to sporadically malfunction in practical use.

These phenomena might be illuminated by explicitly measuring the skin-electrode contact forces during operation of the prosthesis. In-socket force or pressure measurements have been demonstrated repeatedly, using mechanical, hydraulic and pneumatic devices, as well as ones based on Hall effect sensors; see [12] for a brief review. All these studies have aimed at using information related to force or muscle bulge explicitly for control purposes. For the purpose of this study, we have developed an augmented SEMG device with built-in contact force measurements, i.e. a *multimodal myoelectric unit* (MMU) [13], which has been applied to a group of experienced prosthesis users for maximally realistic measurements. To our best knowledge, this work represents the first attempt at measuring the actual contact force between SEMG electrodes and skin surface. Although the force information is still applicable as additional control information, the present study focusses on exploring the mechanisms related to sporadic myoelectric control failure. It is hypothesized that the force information will allow us to identify the causes of malfunction, at least qualitatively, and thus provide guidance in the quest for improved prosthesis function. A significant amount of space is therefore given to the description and discussion of the MMU device itself, in order to illuminate the possibilities and limitations of the additional information provided by the added sensors.

The study is limited to transradial amputations, one particular brand of SEMG electrodes and terminal devices, and Münster-type socket designs [14, 15], but the main results are believed to have validity beyond this category.

NOMENCLATURE

Abbreviations used in this paper are listed in Table 1.

MATERIALS AND METHODS

The experimental protocol was approved by the Regional Ethical Committee. All subjects signed a written informed consent before participation.

Subjects

A total of 15 subjects were included in the study. For one subject, only age, sex, terminal device type and amputation level was recorded. Thus, statistics related to other metrics are based on the remaining 14 subjects.

One subject was female and 14 were male. Ages ranged from 19 to 69 years (mean: 47 years; standard deviation: 16 years). The most recently amputated subject had been using a prosthesis for three years, while the most experienced subject had 62 years of experience (mean: 26 years; standard deviation: 17 years). All subjects had transradial amputations, with amputation levels distributed as follows; proximal forearm: seven; mid-forearm: four; distal forearm: three; and one not recorded. Four subjects were users of electric split-hooks, 10 used electric hands, and one used both types of terminal devices. For one subject the cause of amputation was not recorded; six subjects had a congenital absence and seven had lost their limb due to trauma.

The MMU

Each unit comprised a 13E200 electrode (Otto Bock HealthCare GmbH), which has a built-in preamplifier and produces an output which is roughly proportional to the amplitude of the SEMG. Four FS1500 force sensors (Honeywell Sensing and Control), each connected to a separate INA122UA instrumentation amplifier (Burr Brown Corp.), were employed for contact force measurements. The electrode was mechanically coupled to the force sensors with a layer of elastic foam rubber, sandwiched between two semi-rigid plastic sheets, and all parts were eventually stacked within a plastic housing (Figure 2).

The foam rubber acts as a spring that allows the electrode an excursion of up to 3 mm when exposed to contact forces, similar to that of the electrode when mounted the traditional way. The purpose of the plastic sheets is to distribute the spring force appropriately over the back surface of the SEMG electrode and the four force sensors. The electrode's suspension tabs, which can be seen as black cylindrical projections at each end of the electrode unit, protrude through slots in the MMU housing in order to allow the necessary 3mm of play. Each MMU was calibrated to yield a reading of 0% from all force sensors when no external force was present, and 100% when the SEMG electrode was maximally depressed. Table 2 summarizes the MMU's main characteristics.

While a single force sensor might enable detection of such states as total electrode lift-off (Figure 1, right) or excessive contact force, with separate sensors in each corner of the device we achieve a joy stick-effect through which we can detect both magnitude and direction of the contact force. Furthermore, this configuration facilitates the detection of partial lift-off (Figure 1, left), which may cause the electrode output to behave unpredictably and thus preclude any successful control of the prosthesis.

Experimental Protocol

The participants were first asked to do a series of three standardized activities named *Pigeon-hole*, *Tray* and *Hand behind back*, respectively.

The *Pigeon-hole* test is inspired by a procedure originally used for assessment of the Belgrade hand in the 1970's [16]. In the original setup, the user's ability to grasp and drop objects at 4 different height levels was tested, and several different objects were included. In the present study we used only 2 objects, namely a light cylinder and a small suitcase. During the experiment the user would stand in front of a rack with 3x3 compartments ("pigeon holes") with the task of lifting the object from one compartment at knee height to another compartment at shoulder height and then back. We only looked at diagonal movements, so as to provoke situations where the prosthesis was in an extreme position. The test was repeated 3 times for each side (starting at bottom right or left) and for each object. Each single grasp-move-release sequence was counted as one "run" in the following analysis (cf.

Table 3, rightmost column).

The *Tray* test was included to provide information about how the prosthesis behaves when the subject is moving. One problem reported by the users was unpredictable prosthesis behavior when carrying things like a tray from one place to another. Sudden stops and turns and walking in stairs were also reported to be problematic. In this test the participant was asked to carry a tray with an object (a wooden brick) on top with his/her prosthesis, while holding another object in the other hand to increase the cognitive load. The objects were carried fist up and then down a 6-step flight of stairs, with sudden turns on the upper and lower landing. This was repeated three times.

The purpose of the *Hand behind back* activity was to look at the performance of the prosthesis in an extreme position. The participant was asked to move the arm behind his/her back and then to the front three times while holding a light cylinder. At each end position the participant was asked to operate (i.e. open and close) the device. This was repeated three times.

Finally, the participants were asked to identify other situations where they had experienced sporadic control failure of the prosthesis and to move their prosthesis accordingly, in order to provoke a similar control failure. This was also repeated three times.

Every test took approximately 1.5 hours, including short breaks between tasks.

Experimental set-up

Two MMUs, a lateral one measuring muscle activity related to opening of the hand and a medial one for measuring activity related to closing, were mounted in the socket of a transradial prosthesis with the MMU housing flush with the inside of the socket (Figure 3). In order to copy the conditions in the user's ordinary prosthesis as closely as possible, the experimental prosthesis was built out of the test socket used for the manufacturing of each subject's ordinary prosthesis. Accordingly, the MMUs were mounted in the same positions as those of the electrodes in the user's ordinary prosthesis. No outer socket was used; the test socket was extended to the correct length by means of a PVC tube (Ø=40 mm), which was glued to the distal end of the socket (the proximal end of the tube can be seen in the upper right corner of Figure 3). A wrist adapter for the TD was mounted in the distal opening of the tube. All input signals were fed to an NI USB-6211 analogue input/output module (National Instruments Corp.), which was connected to a laptop computer via a 5 m USB cable extension. The input/output module was placed in a small textile bag that was attached to the user's clothes near the waist. The computer software was implemented in LabView (National Instruments Corp.), and was configured to sample all MMU signals at 100 Hz and display them on the computer screen in real time. In this study, the signals from the electrodes were relayed back to a pair of analog output channels that were connected to the terminal device's electrode input terminals, in order to have the prosthesis behave in its normal manner. The signal amplification was adjusted in software to yield similar sensitivity as that of the user's ordinary prosthesis. The computer was set up to log all input and output signals to a hard drive, along with video footage recorded during the signal acquisition. The video allowed us to thoroughly study significant events off-line, to establish exactly what happened in every situation.

Data analysis

Sporadic control failure events were categorized as *Failure to open* (FO), *Failure to close* (FC), *Involuntary open* (IO) or *Involuntary close* (IC). The first two of these event categories correspond to the prosthesis failing to open or close, respectively, at a time when the user solicited such action. The latter two represent movements of the prosthesis at a time when the user did not intend to trigger any movement. When a particular category of control failure was observed repeatedly within a time frame of a few seconds and within the same overall movement, this was counted as a single occurrence.

The force, SEMG and video data were scrutinized in order to establish the cause of each control failure event. Particular attention was paid to signal patterns that appeared to recur across different events within the same category. With this in mind, the each recorded scenario was labeled based on similarities in SEMG and force signal patterns immediately before or at the time of the control failure, and assigned to one of the categories *Total lift-off* (TLO), *Partial lift-off* (PLO), *High force* (HiF), *Low force* (LoF) or *Unidentified* (UI).

TLO occurs when all electrode terminals loose physical contact with the residual limb. Similarly, we define PLO as the lifting of at least one but not all electrode terminal(s) from the skin surface. These are well-known failure modes in myoelectric prostheses, although hardly documented. The immediate cause of electrode lift-off is that the tissue is moved away from the electrode site, or vice versa, in excess of what the elasticity of the electrode suspension, or that of the soft tissue, can compensate for. This situation usually is secondary to external forces displacing the socket with respect to the residual, or changes in residual geometry due to joint or muscle tissue movement. A TLO was expected to produce contact force signals identical to zero until electrodes and tissue reconnect. Correspondingly, during a PLO we expected to see two of the force measurements, corresponding to the one electrode terminal being lifted, to attain a constant value of or in the vicinity of zero.

During LoF situations, the contact forces become unusually low, as directly observable in the force measurement signals. This state can be thought of as a potential precursor to a lift-off event. In this perspective, LoF, PLO and TLO may be thought of as representing the same fundamental problem at different levels of severity.

Situations that were labeled UI represent instances of sporadic control failure in which the contact force data reveals no apparent mechanical reason for the failure.

It was detected that both MMUs had been significantly out of calibration during the experiment, most likely because non-ideal mounting surfaces caused deformations of the MMU housing. Therefore all force signals were offset-adjusted as follows before subsequent analysis:

- In recordings that exhibited at least one period of lift-off, the mode (i.e. the most frequently occurring sample value) of the signal during the lift-off period was subtracted from the raw signal.
- In signals without evidence of lift-off, the lowest sample value of the entire signal was subtracted from the raw data.

In the latter case it is unlikely that the adjusted signals attained the correct numerical values unless the offset-adjusted signal spanned the entire interval from 0% to 100% of force. Consequently these data cannot be considered to be quantitatively meaningful. They do, however, maintain their qualitative information.

RESULTS

General observations

It is interesting to observe the variable degree of correlation between SEMG amplitude and associated contact forces. Sometimes these signals are highly correlated, like during the first *Close* event at t=15 s, during which the medial SEMG and all eight force signals exhibit a synchronous peak. However, at other times these signals seem to be significantly less correlated, e.g. during the second *Close* event at t=18 s.

Sporadic control failure

Eight of the 15 subjects reported occurrences of sporadic control failure during the experiment. The *Tray* test induced no observable control failure; for the other three activities the occurrences are summarized in

Table 3.

All three subjects who reported control failure during the *Hand behind back* activity also reported control failure during *Pigeon hole*. One subject only reported control failures during the *Other* activity.

The number of recorded control failure events in each event category is summarized in the rightmost column of Table 4. We note that the IO category accounts for virtually half of all the recorded events, while no IC events occurred. FO and FC occurrence rates were comparable. The bottom row of the table summarizes the number of events assigned to each label, while the body of the table shows the number of recorded events for each combination of event category and label. TLO and PLO collectively accounted for 62.5% of the recorded failure events, while TLO, PLO and LoF together represented 72.5% of all events.

Involuntary Opening

The FO during the interval t=21 s to t=25 s is caused by total electrode lift-off on the lateral side, as indicated by the corresponding zero valued force signals.

- The IO at t=25 s is caused by spikes in the electrode output signals. In the force graphs one can see that these spikes coincide with the SEMG electrode's re-connection with the residual limb after the preceding period of lift-off

This implies that it is not the lift-off itself, but rather *the reconnection* of the electrode with the skin, that causes the involuntary movement. This particular chain of events was observed in conjunction with five of the nine IO events related to TLO or PLO. Another four cases of IO/TLO happened without any visible evidence of reconnection.

The single IO event classified as LoF was similar to the latter four, except for a minor disturbance in the force.

The last nine cases of IO were classified as UI. Four of these exhibited an increase in SEMG level coincident with rising contact force levels, while in the last five there was no apparent correspondence between force and SEMG levels.

Failure to Open

Of the 12 recorded FO events, nine were noted as being related to TLO. In some cases, as exemplified in Figure 5, the force levels stayed at zero for an extended period of time. In other cases the electrodes occasionally reconnected with the skin as shown for the lateral MMU in Figure 6. The video recording of this particular experiment contains evidence that at least once during the time frame $27\ s<t<32\ s$ the prosthesis motor was indeed activated, but without yielding the intended result. Thus, this might be an instance of *Involuntary Closing* which passed undetected because the hand was already closed.

Two FO events happened during LoF conditions, as illustrated in Figure 7. We see from the figure that the lateral MMU electrode is more or less in a TLO condition, but there is a finite, measurable contact force during the failing attempts to open the terminal device.

The last of the FO events, which is shown in Figure 8, was marked UI. Neither the LEMG graph nor the video footage from this experimental run suggests specific points in time where the user tried to issue an "open" command. Both electrodes appeared to have skin contact during most of the failure period, but as virtually no LEMG activity was recorded, the force variations cannot be correlated with any discrete opening attempts.

Failure to Close

Five instances of FC during TLO conditions were recorded. These were similar to the FO/TLO events, except that the lift-of occurred at the medial electrode site. Likewise, a single case of FC under LoF conditions was observed, qualitatively resembling FO/LoF but at the opposite site.

The two FC/PLO events, however, were qualitatively different from all other events. The MMU data from one of these is presented in Figure 9. Given that these are examples of *Failure to Close*, our attention is drawn to the graphs from the medial MMU since "close" commands are communicated via the medial electrode site. However, the forces on the medial side clearly exhibit nonzero values and the EMG level in fact saturates, which suggests that the TD should indeed receive a valid "close" command. Interestingly, the MMU on the opposite side experiences PLO during the entire FC event, while the associated EMG attains moderate to high levels.

Finally, a single instance of FC with unidentified cause was recorded. The signal recordings from this event are depicted in Figure 10. The force graphs suggest that there was no lift-off, but one notes that the "open" signal at t=53 s, which can be seen as a raised LEMG level, is kept at a significant level even during the attempted closing from t=54 s to t=56 s.

DISCUSSION

Limitations of this study

The present results should be interpreted with caution due to the inevitable limitations of the study. These limitations relate to the following factors:

- All experiments were based on users with transradial amputation and Münster-type sockets. Amputation level is believed to influence the severity of sporadic control failures, in that a short residual implies higher local contact force variations and thus increased likelihood of failure. Similarly, different socked design will influence the way in which the residual limb is displaced and deformed inside the socket during use. Radically different suspension techniques based on e.g. osseointegration [17] or soft roll-on liners [18] will obviously behave very differently with respect to these phenomena.
- Different SEMG electrode designs will respond differently both mechanically and electrically when exposed to mechanical perturbations. Furthermore, the motor consequences of SEMG artifacts are determined by the control system's algorithms, and as such one system may behave correctly in a situation where another fails.
- The activities performed by subjects during this experiment are resemblant of activities of daily living, but they were selected explicitly in order to create conditions under which some users experience sporadic control failure.

For these reasons the quantitative results in general are not applicable to normal prosthesis use or other prosthesis designs. The qualitative aspects, however, are believed to have great generality in that they exemplify

General issues

As expected, we observed a certain degree of correlation between SEMG amplitude and the electrode/skin contact forces. However, this correlation appeared to be highly variable, which suggests that the force sensors indeed capture additional information that is not contained in, or easily extractable from, the SEMG signals. Contact force measurements might provide information related to both user intent and other relevant phenomena like the position effect and movement artifacts. Future research therefore should assess the added modalities' applicability as general inputs to modern control schemes based on pattern recognition and sensor fusion.

The MMU

The present version of the MMU exhibited several weaknesses. As described in the Data analysis section, once the device was mounted in a prosthesis socket, it was essentially out of calibration. If this was actually caused by deformation of the housing, a more rigid housing material would reduce the problem. To the extent that this deformation was constant during each experiment, an in-socket re-calibration should be added to the protocol.

Two additional factors limit the device's fidelity. Firstly, minute force changes might be masked by friction between the SEMG electrode and the housing. The second factor is that the foam rubber spring has a limited dynamic response due to the air that needs to pass in or out of its pores during expansion or compression. This response can be seen in Figure 5 as a brief undershoot of the LDA and LDP signals at t=21 s. While the latter effect might in principle be eliminated by temporal inverse filtering, both these limitations should be addressed during future redesign.

Control failures

The recorded control failure events were unevenly distributed over the four categories. The most frequently recorded event, *involuntary opening* (IO), may be the most serious one, because unsolicited opening of the terminal device whilst handling an object may cause loss of grip and thus injury or material damage. This suggests that the IO failure mode should be given priority in the efforts to improve the reliability of the prosthesis control system.

IO events related to electrode lift-off seem to be equally often caused by the lift-off itself as by the subsequent reconnection. Some of these situations might include numerous rapid lift-off/reconnect events, akin to "contact bounce". This might not be observable in the MMU output force data due to the limitations discussed previously. Thus, when the force exhibits a sudden change, we cannot tell if the SEMG responds to a lift-off, a re-connection or both.

The scenario of Figure 8 was labeled UI. In this case there is no evidence of lift-off in any of the force signals. The true offsets of these graphs are therefore unknown, and the existence of this single FO/UI event is not given any emphasis in this study.

It should be mentioned that in one of the subjects, the extensor MMU indicated constant or barely changing contact forces at a medium level during the entire experiment. This may have been caused by a mechanical failure in the MMU itself, most likely that the SEMG electrode had fastened somewhat in the middle of its excursion range. The corresponding data should therefore not be regarded as quantitatively representative in any way. Qualitatively, however, we believe that the control failures observed in this subject represent the same typical scenarios as those found in the rest of the study group, because a partially depressed electrode with a barely flexible suspension in fact resembles the reality of some users' actual prostheses. These data have therefore been included in the analysis.

The study group size and prevalence of sporadic control failure in the present study do not allow for a stringent statistical analysis, but our observations seem to support the following statements about the mechanisms of failure and possible solutions.

As expected, electrode lift-off is associated with the loss of control and with involuntary prosthesis movements. However, it seemed to be the event of reconnection, rather than the loss of connection, that induced unsolicited movements. This failure mode may be alleviated by disabling electrode output during lift-of and only re-enabling it once proper reconnection has been established. Partial lift-off, which was only observed a few times during this study, is known to often cause saturated electrode outputs due to the heavily unbalanced input impedances it represents. The suggested temporary disabling of electrode outputs will prevent even this failure mode from causing involuntary movement (although acceptance by users of the trade off between a temporarily inactive system and one that opens inadvertently needs to be investigated).

As many as 27.5% of all the recorded failure events were categorized as unidentified (UI), most of which were involuntary openings (IO). In four of these cases we observed an increase in contact force coincident with increased SEMG output, which might be attributed to movement artifacts or a form of position effect, e.g. increased electrode sensitivity as the electrode terminals are pressed against and encompassed by soft tissue, thereby reducing resistance and increasing capacitive coupling between electrodes and muscle. A third hypothesis, which we believe is correct in at least some of the observed cases, is that the user inadvertently performs actual, centrally controlled muscle contractions. These contractions may also be seen as a form of position effect to the extent that they resemble the way the limb was controlled prior to amputation, when in certain limb positions they would produce desired effects like joint stabilization or gravity compensation. If the latter hypothesis is correct, it suggests that targeted user training with biofeedback from the detected SEMG might be appropriate. Also, it points to the value of introducing pattern recognition methods and additional sensor modalities even in dual-site, single-function contemporary myoelectric prostheses.

Not a single *involuntary closing* (IC) event was recorded. These events are inherently harder to observe – once the TD holds an object, further closing of the hand is virtually unperceivable except if the object is soft. Thus, no conclusions can be made with respect to the prevalence of IC events in our experiment, but as mentioned in conjunction with Figure 6, certain observations suggested that IC were in fact occurring.

Lift-off related events including the "lift-off precursor" state LoF accounted for a vast majority of the recorded control failures. This suggests that electrode lift-off should be given attention as a possible point of improvement. Such improvements might include redesigned electrode suspension that offers more compliance, so that the system can tolerate more tissue movement while still maintaining good electrode/skin contact. Snugger sockets contribute similarly, although a tradeoff must be made with respect to comfort. While such mechanical improvements may have an immediate effect, the authors believe that a more thorough understanding of the influence of tissue movement on SEMG signals may pave the way for more fundamental improvements in the future, especially in advanced multifunction systems. Achieving such understanding requires further research that should be based on multimodal sensors with hi-fidelity raw EMG and force signals, and perhaps even explicit measurements of sideways skin displacement using e.g. optical mouse technology, in order to allow examination of more subtle connections between these quantities.

CONCLUSION

The changes in normal and shear forces between EMG amplifiers/processor units was recorded as 15 prosthesis wearers used their hands to perform four everyday tasks identified prone to interference due to socket movements. Different causes of failure of the control of the hand were identified: Failure to open, failure to close, involuntary opening and unidentified causes. It could be seen that the changes in the position of the socket relative to the arm caused by shifting in the mass of the arm and the held objects caused increases and decreases in the signal strength as measured by the control amplifiers. Involuntary opening of the hand was identified as the most common failure, which is also the most undesirable failure. The failures seem to be associated with the electrode moving away from the skin or reconnecting with the skin. The force sensor allowed many of these events to be identified, and it is possible that the output of the electrode amplifier could be disabled when the controller identifies an interfering event.

While 27.5% of the events did not have an easily identified cause based on the electrode lifting off or pressing on to the arm, it did allow those contractions that might be centrally mediated and are part of the natural control of the unamputated arm. It may be possible to train out these compensations. Similarly, the information about the shifting of the socket during activities of daily living should help prosthetists to design sockets which are less prone to shifting during such activities.

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Figures

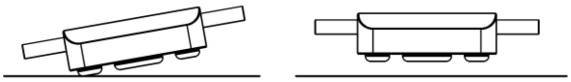

Figure 1 Illustration of partial (left) and full (right) electrode lift-off. The figure depicts a typical active SEMG electrode, similar to the one used in the MMU, as viewed parallel to the skin.

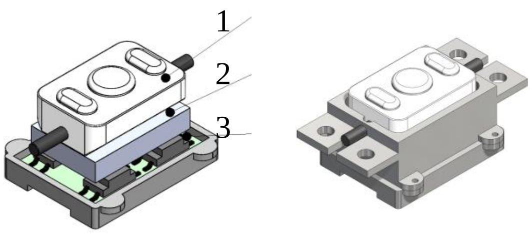

Figure 2 Left: The MMU's inner structure. 1: SEMG electrode; 2: Foam spring; 3: Force sensor board. Right: Fully assembled MMU. The illustration depicts and older electrode version than the one actually used.

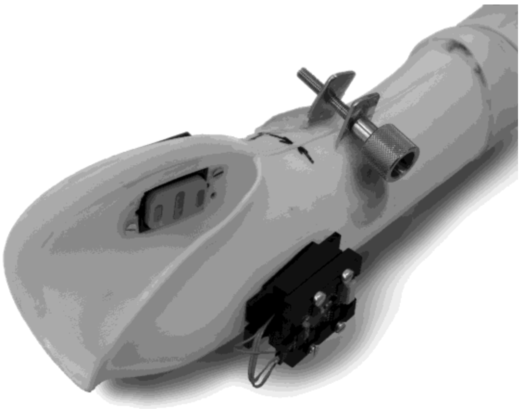

Figure 3 Test socket with both MMUs mounted. Countersunk screws were inserted from the inside of the socket to engage with threads in the MMU casing or external metal nuts.

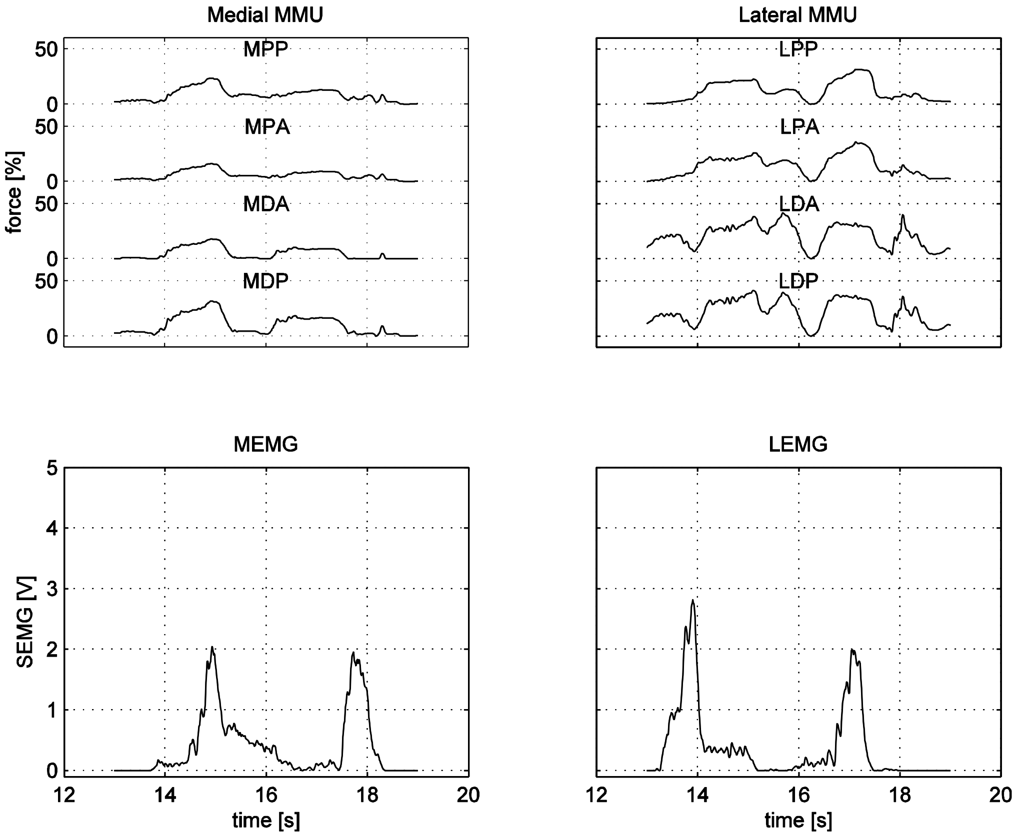

Figure 4 Typical sensor readings for a *Pigeon hole* activity without reported control failures. The two left panes show the four force sensor readings and the sensed SEMG signal, respectively, from the medial (flexor) MMU, while the panes to the right show the same information for the lateral (extensor) MMU. Recorded events include the following (time references are approximate): t=14 s: opening the TD; t=15 s: closing the TD around an object; 15 s<t<17 s: moving the object to another shelf; t=17 s: opening the TD to release the object; t=18 s: closing the TD.

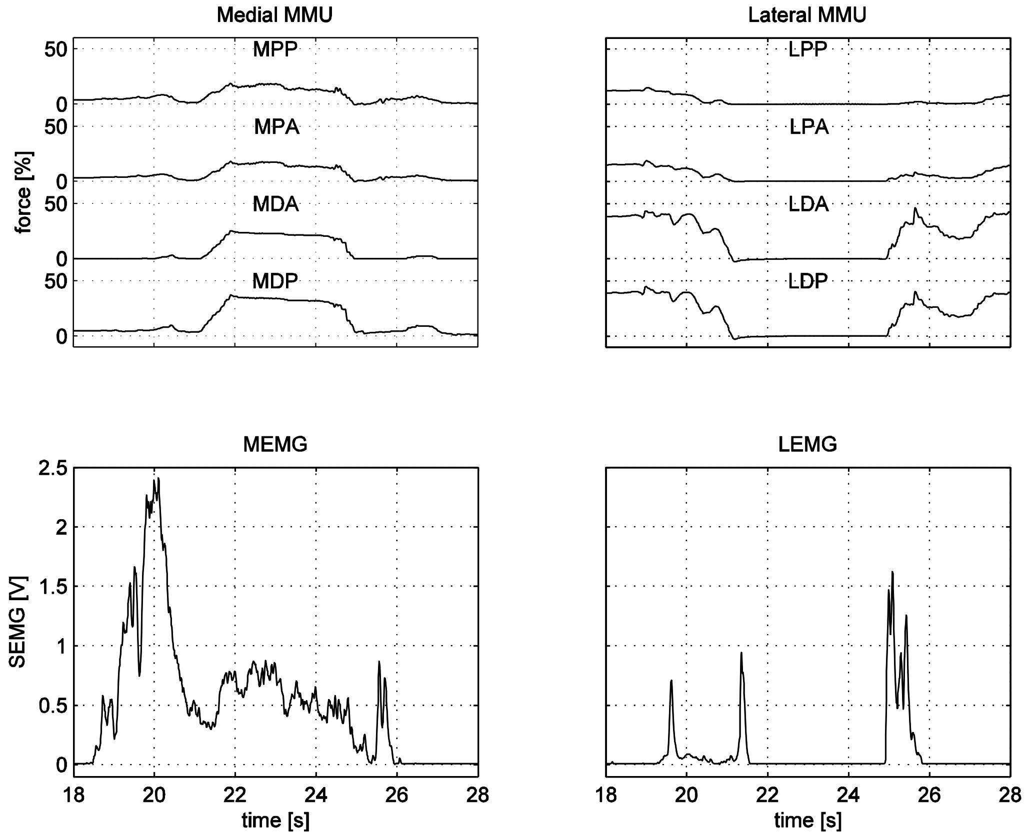

Figure 5 Example of a typical MMU read-out during total lift-off. The following observations were noted: t=20 s: successful closing; 21 s<t<25 s: hand behind back, failure to open (FO); t=25s: hand moved towards front, involuntary opening (IO).

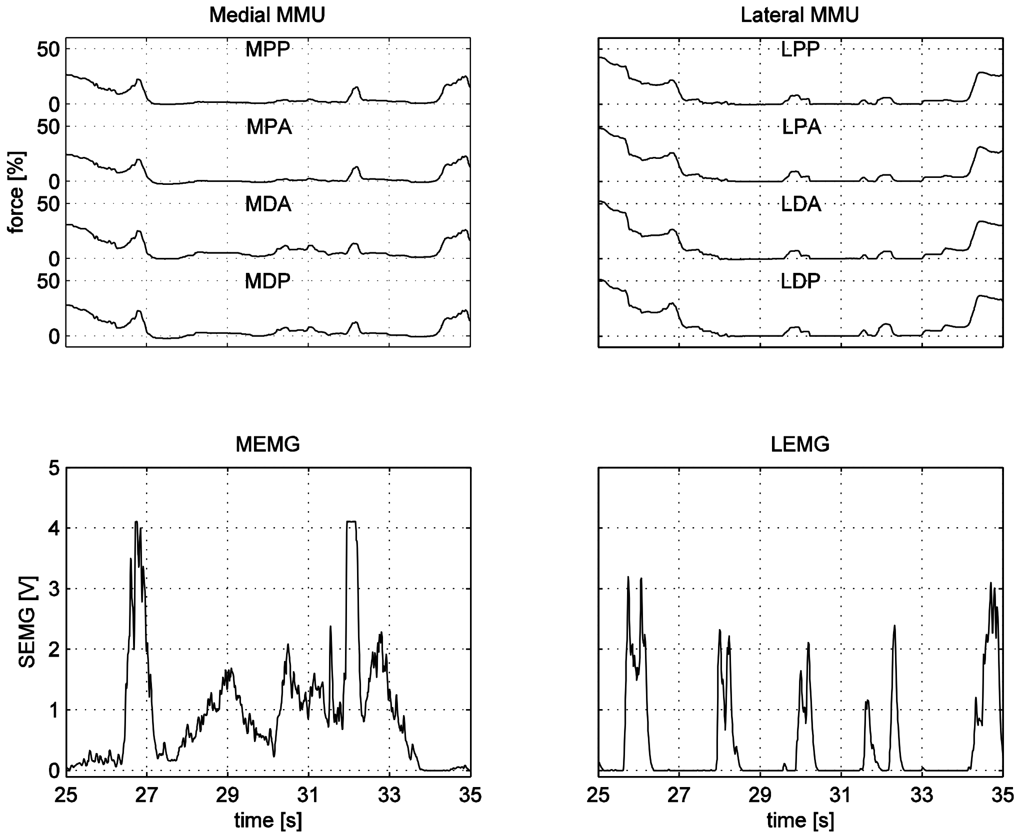

Figure 6 Failure to open (FO) with TLO and occasional reconnection at very low force levels. The following observations were noted: t=26 s: hand in front of body, successful opening; t=27 s: successful closing; t=28 s, t=30 s and t=32 s: hand behind back, failure to open (FO); t=34.5 s: hand in front of body, successful opening.

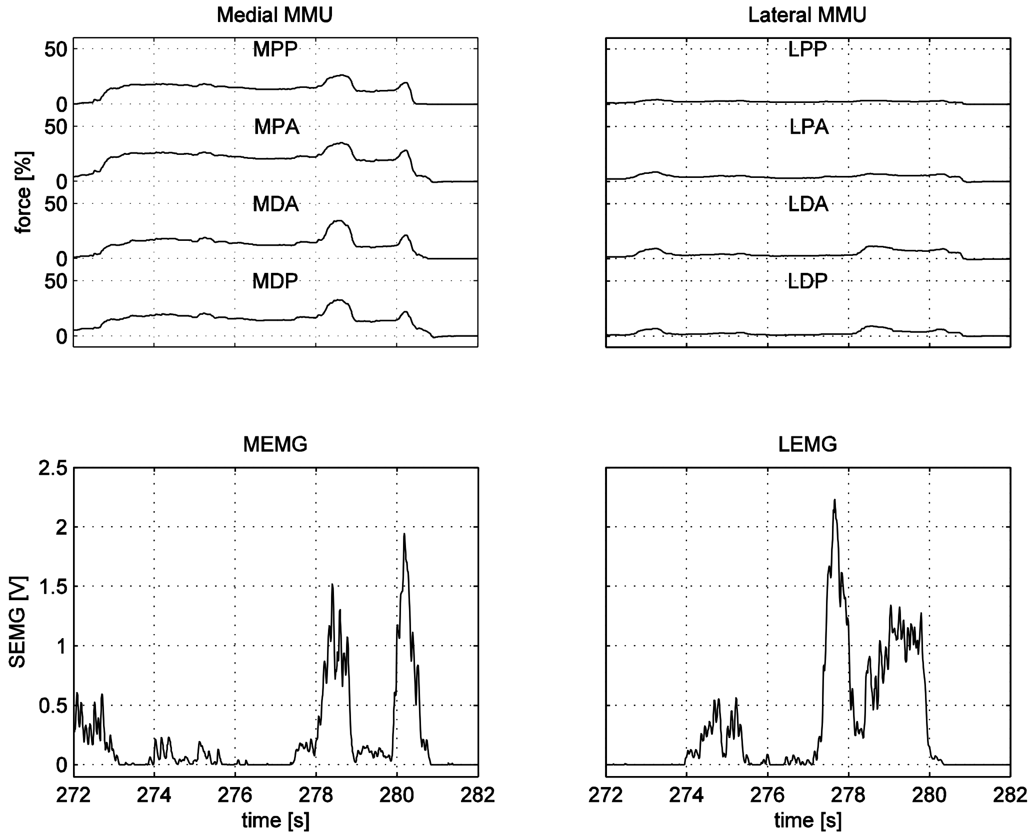

Figure 7 Failure to open (FO) under Low force conditions (LoF) during a *Pigeon hole* activity. The following observations were noted: The amputated arm was stretched forwards, upwards and laterally at t=272 s, and stayed in this posture until t=280 s; 274 s<t<277 s: failure to open (FO); t=277.5 s: successful opening; t=280 s: successful closing.

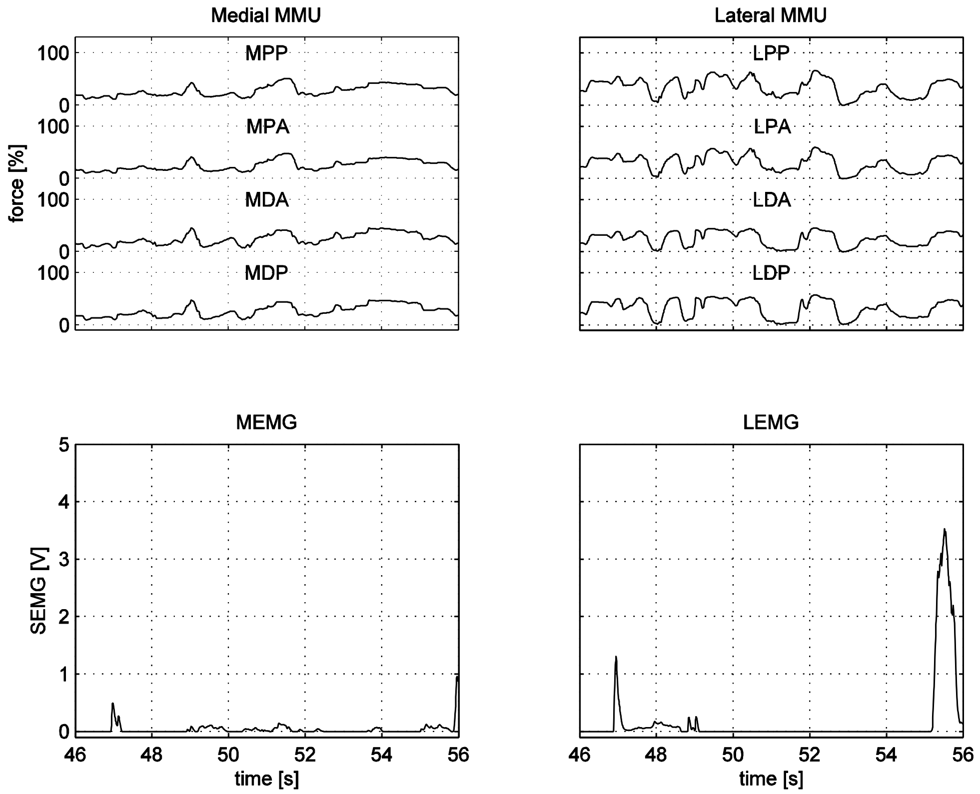

Figure 8 Failure to open (FO) with unidentified cause (UI) during a *Pigeon hole* activity. The user repeatedly but unsuccessfully tried to open the terminal device during the entire interval depicted in the figure, until eventually succeeding at t=55.5 s.

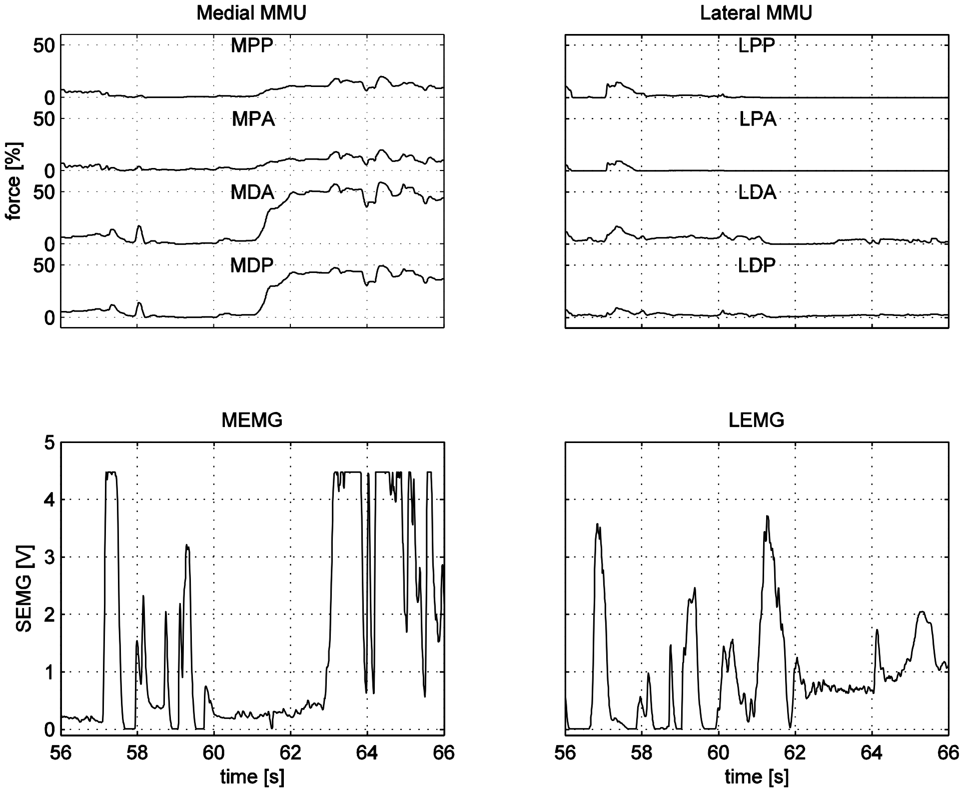

Figure 9 Failure to close (FC) accompanied by partial lift-off during a *Pigeon hole* activity. At t=57 s, the TD is quickly and successfully opened and then closed; t=59 s: successful opening; t=61 s: partial lift-off (PLO) occurs at the lateral electrode site (signals LPP and PLA); 62 s<t<66 s: the user repeatedly but unsuccessfully tries to close the terminal device.

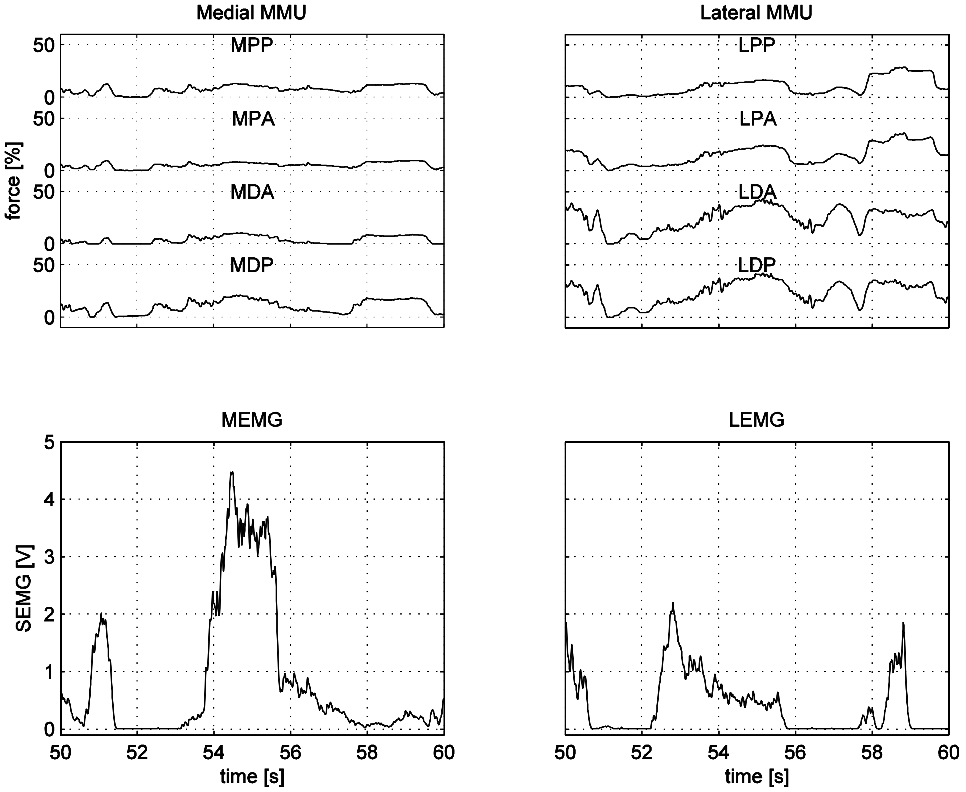

Figure 10 Failure to close (FC) with unidentified cause (UI) during a *Pigeon hole* activity. At t=53 s, the TD is successfully opened; 54 s<t< 56 s: failure to close, followed by successful closing at the end of this interval; t=59 s: successful opening.

Table 1 Abbreviations used in this paper.

General	
MMU	Multimodal Myoelectric Unit
EMG	Electromyogram
SEMG	Surface EMG. The term is also used interchangeably with "SEMG amplitude" to denote the output signal of the active EMG electrodes used, which is more appropriately referred to as estimated EMG amplitude.
TD	Terminal device (e.g. a prosthetic hand)
MMU myoelectric signals	
MEMG	SEMG from the Medial MMU
LEMG	SEMG from the Lateral MMU
MMU force signals	
MPA, MPP, MDA, MDP, LPP, LPA, LDP, LDA	The three letters indicate each sensor's position on the forearm: 1st Medial or Lateral MMU 2nd Proximal or Distal 3rd Anterior or Posterior
Failure event categories	
FO	Failure to open
FC	Failure to close
IO	Involuntary opening
IC	Involuntary close
Cause-of-failure labels	
TLO	Total lift-off
PLO	Partial lift-off
HiF	High force
LoF	Low force
UI	Unidentified

Table 2 MMU technical specifications.

Component or parameter	Specification
SEMG sensor	13E200 (Otto Bock)
Maximum excursion	3 mm
Contact force at maximum excursion	10 N (approx.)
Force sensors	FS1500 (Honeywell)
Number of force sensors	4
Output signal range (all outputs)	0-5 V
Approximate outer dimensions ex. flanges	25 x 30 x 32 mm^2

Table 3 Number of control failure observations during different activities. The columns indicate the count of control failure occurrences (mean number of occurrences per subject ± standard deviation), the number of subjects with control failures, and the percentage of runs during which control failures occurred. No control failure was observed during the Tray activity.

Activity	Occurrences of control failure	Users with control failures	Control failure frequency (by runs)
Pigeon hole	27 (1.8±2.4)	7	15%
Hand behind back	8 (0.5±1.1)	3	18%
Other	3 (0.2±0.5)	2	7%

Table 4 Number of sporadic control failures by event category and label.

		Label				
		TLO	PLO	LoF	UI	**Sum**
Event	FO	9	0	2	1	12
	FC	5	2	1	1	9
	IO	7	2	1	9	19
	IC	0	0	0	0	0
	Sum	21	4	4	11	**40**
	%	52,5 %	10,0 %	10,0 %	27,5 %	100 %