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A surface EMG test tool to measure proportional prosthetic control

Abstract: In upper limb amputees, prosthetic control training is recommended before and after fitting. During rehabilitation, the focus is on selective proportional control signals. For functional monitoring, many different tests are available. None can be used in the early phase of training. However, an early assessment is needed to judge if a patient has the potential to control a certain prosthetic set-up. This early analysis will determine if further training is needed or if other strategies would be more appropriate. Presented here is a tool that is capable of predicting achievable function in voluntary EMG control. This tool is applicable to individual muscle groups to support preparation of training and fitting. In four of five patients, the sEMG test tool accurately predicted the suitability for further myoelectric training based on SHAP outcome measures. (P1: "Poor" function in the sEMG test tool corresponded to 54/100 in the SHAP test; P2: Good: 85; P3: Good: 81; P4: Average: 78). One patient scored well during sEMG testing, but was unmotivated during SHAP testing. (Good: 50) Therefore, the surface EMG test tool may predict achievable control skills to a high extent, validated with the SHAP, but requires further clinical testing to validate this technique.

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Non-standard abbreviations: EMG, electromyography; IRT, item response theory; MLVC, maximum long-term voluntary contraction; sEMG, surface electromyography; SHAP, Southampton Hand Assessment Procedure; VR, virtual reality.

Introduction

Myoelectric prostheses are used to restore function and appearance in upper limb amputees. To improve the ability of controlling a prosthesis, training is recommended prior to and after prosthetic fitting. As myoelectric prostheses rely on electromyography (EMG) signals as control inputs, the main focus of investigation is on the ability to generate such signals, beginning prior to prosthetic fitting. This includes a selective activation of muscle groups as well as reliable voluntary control of specific EMG amplitudes, where the former are needed to perform intended movements (e.g., hand opening, hand closing), and the latter allows adjustment of speed of the prosthesis' movement.

In proportional control, the speed of movement is directly related to the strength of the muscular contraction [22]. In patients fitted with a pattern recognition prosthesis, where proportional control is also used, this is principally done in the same way as for conventional two-signal control. In conventional prosthetic control, selective activation of single muscles or single muscle groups, usually the flexors and extensors of the forearm, need to be learned. Prosthetic movement is sequentially selected with subsequent proportional control of single movements. Amputees control pattern recognition prostheses by generating combination patterns in varying groups of muscles, with the ability to access various prosthetic movements without switching. Tests have shown that on the basis of a specific training setup, highly reliable voluntary pattern activation can be achieved [7]. Reproducible activation of muscle group patterns, and also the gradual control of single muscle contractions, is subject to preparatory training for prosthetic fitting.

To assess the ability to control fitted prostheses in experienced users, many different tests are available, such as the Southampton Hand Assessment Procedure (SHAP) [2, 15], Action Research Arm Test (ARAT) [16, 18, 21], Assessment of Capacity for Myoelectric Control (ACMC) [13, 14, 17], and box and blocks test [4–6, 16]. The SHAP, the ARAT, and the box and blocks test rely on measuring the time needed to handle various objects in a standardized setting, the ACMC on a score-based assessment of 30 different grasping maneuvers in four different areas rated by trained observers. All these tests are suitable for validating achieved function in an advanced training state, but not for early or predictive assessment or monitoring of training. To the authors' knowledge, there are no complete tests available for the early phases of training that can be easily administered to monitor rehabilitation progress.

This is particularly important when deciding whether to fit an EMG-controlled prosthesis is the appropriate clinical choice. It includes determining whether there is any foreseeable functional benefit for the patient or if alternatives, like body-powered prosthesis, are a more promising option. A possible way of testing EMG signals is to use virtual reality (VR) systems; however, these are currently limited to laboratory settings [12, 24]. Some of these VR systems provide the clinician with a score for motor control, but can only be used with patients who already have good EMG control. They are neither suitable for the initial phase of rehabilitation, nor providing specific information for functions to be trained. There are also several other training systems available that rely on simpler feedback technology than VR, such as the "MyoBoy" from Otto Bock, based on visual feedback. However, none of these systems can support planning of skill training by specific single function-related data.

The authors aimed to develop a tool for pre-evaluation of trainable voluntary muscle-activation skills for decision support prior to prosthetic fitting. In addition, the tool supports planning of rehabilitation procedures as well as their further monitoring. Essential considerations for system development and the main features of the developed prototype are presented here. Additionally, a first application study on persons with an amputated hand, either using conventional EMG-controlled prostheses or pattern recognition prostheses, is described. The study outcome is compared by reference to an established clinical standard for assessment of prosthetic upper extremity function, the SHAP.

Materials and methods

Study population

Five individuals with transradial amputation gave informed consent to take part in this study at the Medical University of Vienna. Ethical approval was granted by the local Ethical Institutional Review Board [No. 1164/2013].

Measurement setup and procedure

For surface electromyography (sEMG) recording, eight commercially available double differential electrodes (13E200=50AC, Otto Bock Healthcare Products GmbH, Vienna, Austria) were used. They were placed circularly around the forearm of the subjects, approximately 6.5–7 cm distal to the olecranon of the elbow as shown in Figure 1. As an anatomical reference, the ulna was palpated, and electrodes 1 and 8 were placed bilaterally next to the bone. This allowed acquisition of sEMG signals from all superficial muscles of the forearm. The pre-amplified and band pass-filtered (30–450 Hz, -3 dB) and notch-filtered (50 Hz) EMG signals were sampled at 1 kHz by the AXON Master® (Otto Bock HealthCare Products GmbH, Vienna, Austria, 10bit A/D converter) and transferred via Bluetooth to a personal computer (Intel(R) Core i7-2600K, 3.4 GHz, 16 GB RAM, Microsoft Windows® 7–64 bit). Further signal processing was done using MATLAB R2009a (MathWorks Inc., US) and custom software, which is explained in detail elsewhere [11]. The custom software was written in C#, used for calculating the normalized root mean square error (NRSME) between the given profile line and the contraction feedback red line of the contraction summations from the EMG signals, for calculating the IRT score distribution, and for calculating the total IRT score classification as described later. This was used to monitor a continuous signal trace expressing the actual contraction intensity.

At the beginning of each recording session, the subject performed a maximum long-term voluntary contraction (MLVC) calibration for a specific movement task with maximum contractions

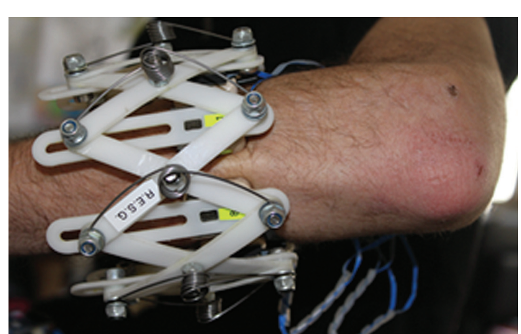

Figure 1: Alignment of the eight electrodes around the forearm using a scissor-fence electrode carrier.

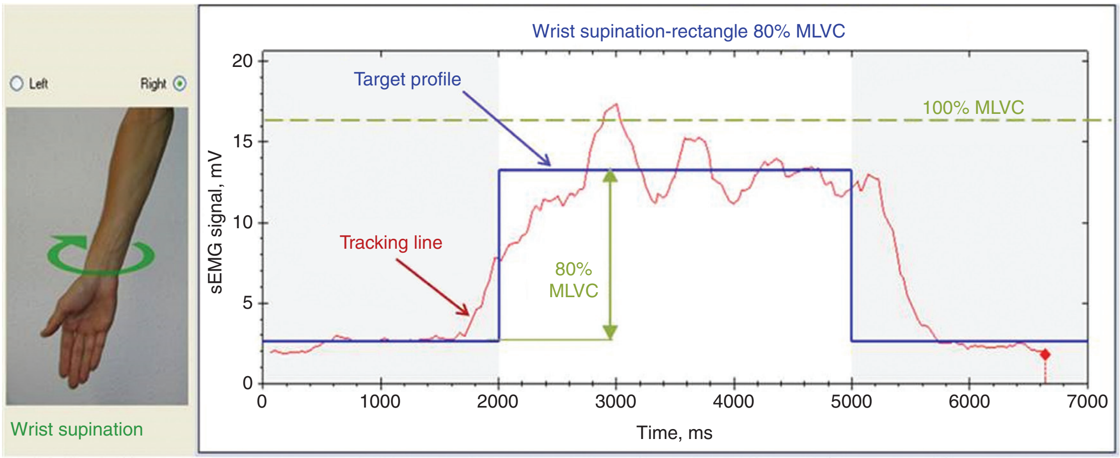

Figure 2: Screenshot of the sEMG test tool during wrist-supination with 80% of MLVC-showing the targeted profile (blue) and the amputee's actual tracking line (red).

of involved muscles at a level the subject was able to maintain for a minimum of 5 s. Calibration was necessary as the amplitude of EMG signals varied between different recordings, due to unavoidable variations in electrode position, contact resistance, and even the patient's current mood [10].

For data assessment, the subject is sitting upright, arm freely moveable, with a direct view of a computer monitor (resolution 1280×1024 pixels) providing a target trace (Figure 2: blue line, rectangular) and visual feedback trace (Figure 2: red line). The red feedback trace displays a simple (non-weighted) summation of all eight recorded EMG signals in real time. Each training or testing session consists of 16 runs including eight trials with 5 s/trial. The pause between sessions was, on average, 10 min; the pause between runs was 2 min. The training is always performed with visual feedback. The assessment can be done offline for each session. For quantification of the subject's ability to control EMG, the root mean square error (RMSE) between target trace and feedback trace was calculated and normalized to the MLVC, as NRMSE. This was done for each trial. A small NRMSE value corresponded to high-level EMG control skills. Higher values indicated erroneous and unstable EMG control. The calculated values are further processed using the item response theory (IRT), a standardized psychometric quantification technique for expressing a person's ability to perform tasks in comparison to a reference population.

Item response theory

IRT, also referred to as the latent trait theory [2], is a psychometric instrument for the design, the analysis, and the scoring of tests to measure abilities, attitudes, and other latent traits. IRT is based on the key assumption that the probability of a person giving a correct response to the presented item is a function of person parameters and item parameters [1, 3]. A response, herein, is the tracking error between the tracking line and the target profile, i.e., the NRMSE between subject's controlled sEMG-derived trace and a given target trace profile.

The basic form of IRT is the one-parameter logistic (1 PL) model. The persons' parameter is called "latent trait" or "ability θ_p of the person", e.g., the intelligence or the ability to follow a given intensity profile with the muscle contraction of a certain movement. In this function, the item parameter is the item difficulty β_i, i.e., the item's grading on the ability latent trait. The probabilities P_r of correct responses from a person with ability performing a certain task (i.e., an item) with difficulty β_i on the latent trait can be modeled by a logistic function. The logistic function's inflection point is located at the difficulty β_i. The function assesses a person's ability location θ_p on the latent trait as the difference to the difficulty of the item. Hence, using IRT, it is possible to compare a user's ability relative to the item difficulty that has been defined by a reference population as shown in Figure 3. Thereby, the IRT score is formed. In other words, a distribution of score differences on the latent trait gets transformed by the logistic regression function into a distribution of IRT score values. The histogram with five bins of this distribution forms the final IRT score of the method.

Classification in score classes

To establish a clinically useful classification scheme for primary assessment, decision support for prosthetic fitting and monitoring of skill training, the IRT score was split into five classes. For each class, a worded definition of clinical skill condition was stipulated, as shown in Table 1. The classification can be assessed for single muscle functions and movement patterns with multiple muscles involved. The principle ability of a subject to control EMG intensity of single muscles and muscle groups repeatedly, as reflected by this classification, can be one of the decisive criteria for investment and choice of a prosthetic solution.

Applying IRT to form a score for sEMG accuracy

Those considerations are applied in the sEMG test tool by forming sigmoid curves with the mean value of NRSME for each item from a reference population as the 50% mark, as shown in Figure 3. As described before, this is the item difficulty β_i. Therefore, this number

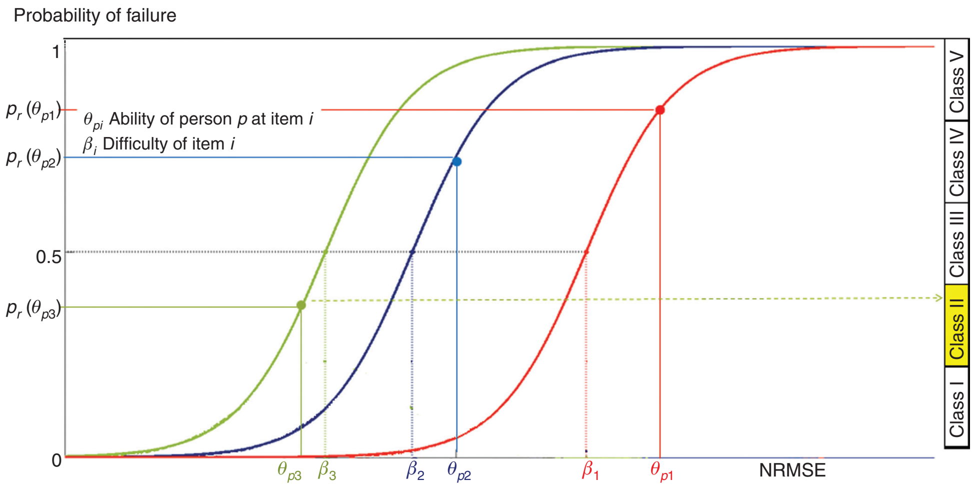

Figure 3: Calculating the participant's probability of failure P_r for one item can be visualized by drawing the subject's NRSME on the specific sigmoid curve for the item and reading the P_r value on the y-axis. This is shown here for three different items. The difficulty of the item β_i always defines the 50% value of the curves. For item 3 (green curve), also the connection between P_r and the final IRT score with five classes (here class II) is denoted.

always defines the value where the probability of failure P_r is 0.5. In a next step, the NRSME of the tested subjects that reflects their ability θ_p of performing the task is applied to this curve, and the subjects' probability of failure is calculated by using

$$P_r = \frac{e^{\theta p - \beta i}}{1 + e^{\theta p - \beta i}}$$

This probability of failure P_r refers to a certain ability class as demonstrated in Figure 3.

Reference population

The reference data pool is taken from measurements performed elsewhere [11] on 39 well-trained able-bodied subjects using 63 items (nine contraction profiles for seven movements). The assumption is that the response probability P_r (of a person performing a certain task, i.e., an item) follows a normal distribution on the latent trait θ where the item's difficulty β is the mean value. The location of an item's difficulty β_i needs to be configured by the samples from the defined population. The x-axis is the NRMSE value, ranging from 0 to 0.4, which is equivalent to an error range from 0 to 40%. NRMSE values >0.4 are, in fact, too large for controlling a prosthesis and are, therefore, not of interest to this study. Well-trained able-bodied subjects, who can perform exemplary predefined movement patterns, serve as reference population for item difficulties. The reference for the difficulty of an item is the mean value of NRMSE assessed from the well-trained healthy subjects. Data from reference subjects were only included, if their probability of failure was below 0.2. Placement of recording electrodes was according to the procedure for subjects with amputation as described above.

Test sessions in the frame of the study

In order to validate if our sEMG test tool is able to measure changes in proportional control, two of the five subjects with trans-radial

Table 1: The ability score.

Class	Descriptor	Value	Explanation
I	Excellent	1.0–1.5	No further training required
II	Good	1.5–2.5	Some refinements may be done, but are not yet mandatory
III	Average	2.5–3.5	Not able to control the prosthesis yet, but will most likely learn with some training
IV	Poor	3.5–4.5	A lot of training is required to achieve useful prosthetic function
V	Incapable	4.5–5.0	No muscular function at all

amputation were tested once a day for a week. The training duration was about 2 h, with two trainings sessions consisting of 16 runs, each including 18 trails with 5 s/trial as described above. The data recorded in the first session of trainings 1 and 3 were used to generate the IRT scores. In the fifth session, data was recorded in the second session to get a post-training score.

Additionally, the IRT scores of all five subjects with trans-radial amputation after the battery of five training sessions described above were compared to the results from an established standard assessment test for prosthetic function, the SHAP [2, 15]. The SHAP was performed after the five sessions of training. The SHAP protocol relies on eight light and eight heavy specific handling objects and 14 activities of daily living (ADL). The subjects were asked to do the specific tasks as fast as possible using their prosthesis with a custom socket. Each task was timed by the participant and recorded on an assessment sheet by the assessor. The SHAP was scored on the basis of the time needed to fulfill each task. One hundred points or more were regarded as normal hand function.

Results

The outcome measures in the study were the pre-rehabilitation assessment score determined using the IRT and the post-rehabilitation score recorded using both the IRT and the SHAP scores. These scores were used to determine whether a relationship exists between measurement of EMG activity and final prosthetic function. Owing to restrictions on patient availability, we were only able to record IRT scores over time for the first two patients; the results are reported in Table 2. A gradual improvement was observed in both patients. Notably, both these patients' early IRT scores reflected their final SHAP scores as shown in Table 3, where a low IRT score resulted in a low SHAP score, and the converse was also true.

Table 2: Changes of IRT scores during training.

Patient	1st training	3rd training	5th training
P1	3.81	–	3.55
P2	2.38	2.44	2.21

Table 3: IRT score compared with the index of function measured with the SHAP.

Patient	IRT score	IRT class	SHAP index of function
P1	3.55	IV (poor)	54
P2	2.21	II (good)	85
P3	3.10	III (average)	78
P4	1.98	II (good)	81
P5	2.25	II (good)	50

In the five patients who we were able to record post-rehabilitation measures there, was a consistent relationship between IRT and SHAP scores, except for patient 5. Patient 5 reported that he did not use his prosthesis for ADL. Table 3 shows the SHAP scores and the previously measured IRT scores for overall ability of five transradial patients.

Discussion

Not every patient with an upper limb amputation qualifies for the same fitting [8, 20]. While for some, a cosmetic prosthesis might be sufficient, others might benefit from mechanical prostheses, and for others, a myoelectric prosthesis is the best solution. The choice of the most appropriate prosthesis should be agreed by the medical team together with the patient. This decision is based on their goals, lifestyle, level of amputation, and general physical condition as well as on their physical and cognitive abilities to control a prosthesis [8, 9, 20]. Therefore, the patient's ability of generating EMG signals for prosthetic control should be assessed at an early stage, to decide if a myoelectric fitting is, indeed, the most effective choice. This can be done by the sEMG tool described in this paper. Furthermore, the tool also supports decision-making on the amount of training required to achieve adequate proportional control and shows the therapist which signals or muscles need to be trained. For instance, if a functional muscle group is identified with an IRT score of 3, while for another, an IRT score close to 1 can be achieved, the therapist should focus on training the muscle groups/functions with the higher scores. Thus, a higher score indicates a higher need for intensive training. If an IRT score of 5 or close to 5 is seen for a single muscle group, it should be discussed whether it is possible to use another muscle group to achieve the specific prosthetic function because the medical team cannot be sure if the patient will ever be able to use proportional control with this muscle group.

The sEMG tool also seems to be capable of showing changes through training as described by Sturma et al. [23] and as indicated by the data measured in this study. Here, an improvement in proportional control could be detected for P1 and P2 between the first and the fifth session of training. P2 was also assessed after the third session of training, were a minimal decrease was noticed. This could be explained by the day's form of the amputee.

It is important to keep in mind that the sEMG tool is only designed to measure the quality of proportional control for all signals, but not their selectivity. Therefore, additional measurements should be used, like the classification rate in pattern recognition patients. This parameter describes the patient's ability to perform the intended prosthetic movements with accuracy, i.e., using the exact pattern of muscular activation that had been used during training for control of the prosthesis [7]. Nevertheless, proportional control is crucial for achieving good prosthetic function. In order to explore a possible correlation between the ability for proportional control and actual prosthetic function, the scores of the sEMG test tool and the SHAP were compared. Owing to the small sample size, the explanatory power of this study is limited. Nevertheless, it could be shown that the three patients who did well at the SHAP testing also had a good to average IRT score. In addition to this, P1 who had an IRT score of 3.55 also encountered difficulties when performing the SHAP. While a correlation between the IRT scores and the SHAP scores seems to exist for P1–P4, P5 had the lowest SHAP score of all patients tested, but a good IRT score. This can be explained by low selectivity of the EMG signals, the patient's poor motivation to perform well on the SHAP testing and his little experience with using the prosthesis in daily life.

This study suggests that good proportional control (as measured with the sEMG tool) is necessary, but not the only condition for good prosthetic function (as measured by the SHAP test). This can be explained by the fact that there are many other factors apart from proportional control influencing the actual prosthetic function. They include the type of myoelectric prosthesis (type of hand or hook), the control algorithms [19], the fitting of the shaft, and the ability of separating the EMG signals as well as the user's experience with the fitting.

Conclusion

The sEMG tool was developed to measure proportional prosthetic control in upper limb amputees before prosthetic fitting. It allows forming a five point ranking scale for representing the amputee's EMG performance by applying the IRT. The use of this psychometric measure compares the amputee's ability of mastering a certain task to the ability of others. Hence, the score not only includes the amputee's actual performance but also the difficulty of the task.

In longitudinal testing, improvements during training were detected by the sEMG test tool. Also, when compared to the outcome of SHAP testing, a correlation between the IRT score and the SHAP score was seen. Nevertheless, there are many factors that contribute to good prosthetic function apart from proportional control.

In conclusion, the sEMG test tool allows measuring proportional prosthetic control and can, therefore, assist in decision-making in the rehabilitation after upper limb amputation.

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