Longitudinal high-density EMG classification: Case study in a glenohumeral TMR subject

Meike A. Schweisfurth*, Jennifer Ernst*, Ivan Vujaklija, *Student Member, IEEE*, Arndt F. Schilling,
Dario Farina, *Senior Member, IEEE*, Oskar C. Aszmann, Gunther Felmerer

Abstract—**Targeted muscle reinnervation (TMR) represents a breakthrough interface for prosthetic control in high-level upper-limb amputees. However, clinically, it is still limited to the direct motion-wise control restricted by the number of reinnervation sites. Pattern recognition may overcome this limitation. Previous studies on EMG classification in TMR patients experienced with myocontrol have shown greater accuracy when using high-density (HD) recordings compared to conventional single-channel derivations. This case study investigates the potential of HD-EMG classification longitudinally over a period of 17 months post-surgery in a glenohumeral amputee. Five experimental sessions, separated by approximately 3 months, were performed. They were timed during a standard rehabilitation protocol that included intensive physio- and occupational therapy, myosignal training, and routine use of the final myoprosthesis. The EMG signals recorded by HD-EMG grids were classified into 12 classes. The first sign of EMG activity was observed in the second experimental session. The classification accuracy over 12 classes was 76% in the third session and ~95% in the last two sessions. When using training and testing sets that were acquired with a 1-h time interval in between, a much lower accuracy (32%, Session 4) was obtained, which improved upon prosthesis usage (Session 5, 67%). The results document the improvement in EMG classification accuracy throughout the TMR-rehabilitation process.**

I. INTRODUCTION

Targeted muscle reinnervation (TMR) has been established as state-of-the-art surgery to allow for improved prosthetic control in high-level upper-limb amputees [1]. Following TMR, patients use direct control from the EMG signals at the reinnervation sites. In this approach, however, the number of control signals and motions is limited. Therefore, several studies explored the use of pattern-recognition approaches following TMR [2] to allow for the control of a greater number of degrees of freedom (DOFs). This achievement would improve the recovery of function in daily-life activities and reduce compensatory movements which are detrimental for the posture [3]. High-density EMG (HD EMG) has been shown to provide greater classification accuracy than simpler recording systems with few recording channels, at least in experienced users [4].

Here we present a longitudinal case study that documents the classification of EMG signals over a period of 17 months post-surgery in a TMR patient. The testing intervals have been chosen based on the progress in the rehabilitation process, consisting of physio- and occupational therapy, signal training, prosthetic fitting, and routine prosthetic use.

II. METHODS

A. Subject and surgical procedure

A 19 years-old male amputee (traumatic incident) underwent TMR surgery [5][6] after which he was recruited to participate in this study. The TMR treatment was performed at the University Medical Center of Göttingen.

The patient lost his left non-dominant arm in a car accident. Immediate management of the injury involved replantation of the left arm, several radical wound debridements and antibiotic therapy. These extensive reconstructive attempts failed and in order to control the fulminant septicaemia the arm was amputated at the glenohumeral level. Having in mind the alternative functional reconstructive possibilities, such as TMR, the nerve residuals located in the depth of the stump were kept as long as possible and were smoothly covered by the remaining deltoid muscle.

One year after the rehabilitation and the complete recovery (Table 1), TMR surgery was performed. Extensive psychological examination excluded personal instability or grave impacts of a remaining post-traumatic stress disorder. Sufficient endurance and motivation for the post-surgical rehabilitation necessary for reliable control of the prosthesis were determined.

The TMR surgery was performed in general anesthesia. According to the followed nerve transfer matrix [7] (Fig. 1), the nerve stumps of the residual brachial plexus were mobilized, cut back to healthy fascicles, and directly end-to-end sutured to the recipient nerves of the target muscles. The patient left the hospital one week after surgery and the wound was fully healed after three weeks.

---

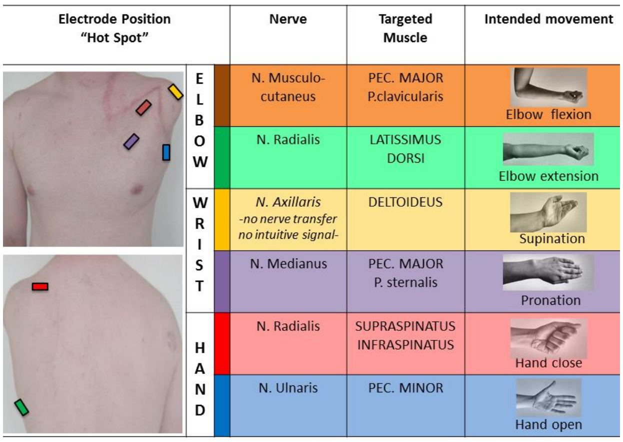
*These two authors contributed equally to this study

Research supported by the European Research Council Advanced Grant DEMOVE (contract no. 267888).

M. A. Schweisfurth, J. Ernst, I. Vujaklija, A. Schilling, and G. Felmerer are with the Department for Orthopaedic, Trauma-, and Plastic Surgery, University Medical Center of Göttingen (UMG).

D. Farina and I. Vujaklija are with the Department of Bioengineering, Imperial College London, London, UK.

O. C. Aszmann is with the Christian Doppler Laboratory for Restoration of Extremity Function, Division of Plastic and Reconstructive Surgery, Department of Surgery, Medical University of Vienna, Austria.



Electrode Position “Hot Spot”	Nerve	Targeted Muscle	Intended movement
ELBOW	N. Musculo-cutaneus	PEC. MAJOR P.clavicularis	Elbow flexion
	N. Radialis	LATISSIMUS DORSI	Elbow extension
WRIST	*N. Axillaris* *-no nerve transfer no intuitive signal-*	DELTOIDEUS	Supination
	N. Medianus	PEC. MAJOR P. sternalis	Pronation
HAND	N. Radialis	SUPRASPINATUS INFRASPINATUS	Hand close
	N. Ulnaris	PEC. MINOR	Hand open

Figure 1. TMR muscle/nerve/function matrix of the subject.

TABLE 1. TEMPORAL OVERVIEW. General rehabilitation time course and experimental sessions. *The timepoints of the experimental sessions are marked in bold. HD = high-density, PT = physiotherapy, OT = occupational therapy.*

Time (months*)	Occurrence/ conventional therapy	Motor activity	Experimental session
-13	Accident and traumatic amputation	-	-
0	TMR surgery	-	-
0-**3**	wound healing	no motor activity	Session 1
3-**5**	intermittent OT & PT	first marginal sign of motor activity	Session 2
5-**9**	continuous OT & PT	for first time distinguishable signals	Session 3: HD, 3 matrices on chest
9-**12**	continuous OT & PT, signal training, detailed prosthetic training	good signals	Session 4: HD, 6 matrices on chest and back
12-**17**	highly proficient with his prosthesis	good signals	Session 5: HD, 6 matrices on chest and back

B. *Postoperative therapy and prosthetic fitting*

Intensive physiotherapy (PT) and occupational therapy (OT) are recommended immediately after wound healing until measurable reinnervation of the target muscles and stabilization of the sites of EMG activity [8][9]. PT twice per week was applied to strengthen the trunk muscles (target muscle s) and to avoid asymmetry of the upper body as a result of the weight misbalance due to the amputation. The orthopedic technicians adapted a “plumb shaft” to assure an adequate counterweight. The occupational therapy, performed twice a week, aimed at maintaining the cortical representation of the missing arm through conventional mirror therapy and by motor imagery training.

Dependent on the distance between the nerve stump and the targeted muscles, the signal training was aimed to prepare for prosthetic training as soon as at least one surface EMG signal was detectable (recommendation by the TMR-Rehabilitation and Training Otto Bock HealthCare GmbH). As the reinnervation is estimated by an axon regrowth at a rate of 1.7 mm/day after suture [10] and the average gap to be bridged by each axon was approximately 10 cm, the first signs of EMG activity were expected approximately 60 days after surgery. The aim of the signal training is to get control over the coordination of the reinnervated targeted muscles, i.e. over generating isolated and appropriate, separated activation of the target muscles via the altered nerve control.

According to [9], final prosthetic fitting begins 12 to 24 months after TMR surgery, as the signals generally are stable at that time. Prosthetic fitting of this subject was done 11 to 13 months post TMR surgery. Since then, he has been routinely using his prosthesis at least six hours per day. The patient was able to sequentially control six movements: elbow flexion/extension, wrist supination/pronation and hand open/close. All of these motions were performed intuitively, except for wrist supination, which was mapped into deltoid muscle activity. 17 months after surgery, the subject performed the Southampton Hand Assessment Procedure (SHAP) [11], to allow for a functional quantification of the success of the reinnervation process and the prosthetic fitting.

C. *Experimental procedure and data analysis*

Prior to the experimental participation, the subject signed the informed written consent. The study was approved by the ethics committee of the Universitätsmedizin Göttingen (no. 11/10/14). The patient participated in a total of five experimental sessions throughout the whole rehabilitation process. The experimental EMG testing was performed in parallel to the conventional rehabilitation process described above. The sessions took place 3, 5, 9, 12, and 17 months post-surgery (Table 1).

At the beginning of each experimental session, the subject was asked to sequentially attempt hand opening and closing, wrist pronation/supination, and elbow flexion/extension. Through visual inspection and palpation of the targeted chest and back muscles, the current status of reinnervation was clinically assessed. In the first two sessions, a standard monopolar EMG derivation with reference and ground electrodes on the bony areas of C6 and C7 was used to test for the presence and location of the reinnervation sites. In the last three sessions, three (Session 3, chest only) and six (Sessions 4 and 5) HD-EMG grids of 8 x 8 surface electrodes each (10 mm inter-electrode distance) were mounted on the subject’s chest and back, on the identified reinnervation sites (Fig. 2). The HD-EMG signals were recorded in monopolar derivation with reference and ground electrodes on the bony areas of C6 and C7 (EMG-USB2 amplifier, OT Bioelettronica, Torino, Italy; gain 1000; bandwidth 3-900

Hz; sampling rate 2048 Hz; A/D conversion on 12 bits). These HD-EMG sessions lasted approximately three hours.

Across all sessions, the subject was seated comfortably in front of a computer screen. In that position, the following 12 movements were sequentially tested: humeral pronation and supination, elbow flexion and extension, wrist flexion and extension, wrist pronation and supination, radial and ulnar deviation, hand open, and hand close. All movements were performed at a self-chosen, comfortable force level. In Sessions 4 and 5, neutral and no-movements runs were also acquired. Using a custom MATLAB software, the patient was prompted to follow a trapezoidal movement cue (with 2-s rise and fall times and a 6-s plateau), but did not receive any feedback on his performance, such that the activation strength was not fully reproducible. The movement cue was further emphasized by an experimenter who verbally communicated the time course of the action and performed the movement with her own arm. For each movement, three runs were acquired. In Sessions 5 and 6 only, this initial measurement block of 13 x 3 runs was repeated with a delay of 1 h. To prevent fatigue, appropriate rest periods were inserted after consecutive runs.

For Session 1 and 2, the single-electrode data were only visually explored. For Sessions 3 to 5, the HD-EMG data were analyzed. Noisy channels were removed. For each remaining channel and each run, the signal was digitally filtered (5th order Butterworth, 10-250 Hz; 2nd order notch filter, 45-55 Hz). Further, the mean from all channels was removed (common average reference) prior to feature extraction. Following this preprocessing, for each channel and motion, the steady-state plateau-part of the signals was segmented into intervals of 100-ms duration (75-ms overlap), from which the following features were extracted: root-mean square (RMS), zero crossings, slope sign change, and wavelength [12]. Finally, the extracted features were fed to a linear-discriminant analysis (LDA) classifier with 13 (12 in Session 3) output classes. For Session 4 and 5, the classification was performed using the signals from either all six electrode grids or only the three grids located on the chest (for comparison with Session 3, therefore using also only the first three runs per session).

Figure 2. Matrix constellation for Session 4 *(Session 5 was as similar as possible), with four high-density 8 x 8 electrode matrices on the chest (left) and two on the back (right), covering the six reinnervated spots used for prosthesis control.*

The LDA performance was assessed within each block with a three-fold cross-validation procedure (two of the three repetitions of each movement were used as training and the remaining as test set). The overall classification accuracy was then obtained by averaging the results of the three combinations. For Sessions 4 and 5, this procedure was performed separately for the first and second block. The performance between blocks was also tested in the last two sessions, using the three runs of one block as training and the three runs of the other block as test data.

Wilcoxon signed-rank tests assessed whether the classification accuracies of the 12 (13 when comparing Session 4 to 5) motions differed between sessions.

To assess whether a performance benefit was obtained through HD-EMG compared to standard EMG, the average classification performance in Session 4 and 5 has been calculated for a reduced number of channels (equally distributing the used channels across the matrix and averaging across all possible starting channels).

III. RESULTS

The progress of the assessed signal quality is shown in Fig. 3 which, for all five sessions, depicts which rehabilitation training was performed and whether EMG activity was at all present. For the HD-EMG sessions, the within-block as well as across-blocks classification accuracies are shown. Significant differences between sessions are marked.

During the first session (3 months after TMR surgery), no motor activity could be observed by palpating the respective muscles or by targeted single-electrode EMG investigation. The first sign of motor activity could be detected through palpation as well as through EMG assessment after 5 months (Session 2). Upon these first signs of reinnervation, the subject started with intense physiotherapeutic training and occupational therapy (three times per week) to foster the reinnervation in preparation for a prosthetic fitting. At month 9 (Session 3), pronounced signals, distinguishable between motions, could be observed through palpation for the first time, allowing for the initial HD-EMG assessment. With continuous physiotherapy, the activation of the reinnervated muscles further improved. One week before the next HD EMG session at month 12 (Session 4), the subject received prosthetic training at the Ottobock Competence Center in Duderstadt, Germany, and was first fitted with an arm prosthesis (Dynamic Arm with VariPlus Speed Hand, Ottobock Healthcare GmbH, Germany). At the time of the final HD EMG assessment at month 17, the patient was already proficient with his prosthesis, as documented by an achieved SHAP score of 52.

In Session 3 only three electrode grids positioned on the subject's chest were used, as still no muscle activation was

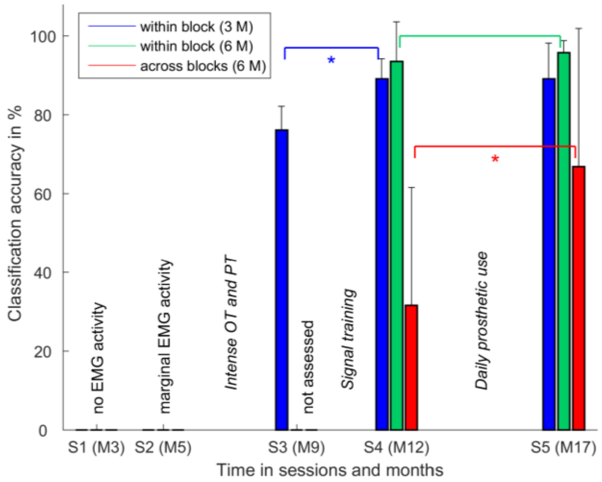


Figure 3. Performance over time. *The initial absence and first presence of EMG activity (Sessions 1 and 2) as well as the average classification accuracies (mean ± standard deviation) are given (Session 3 to 5). The within-block accuracies are shown in blue (3 matrices considered) and green (6 matrices considered), the across-blocks accuracies in red. Performed tests are indicated by squared brackets, significances marked by asterisks.*

TABLE 2. ACCURACY IN THE HD-EMG SESSIONS 4 AND 5.
The crossvalidated classification accuracies (mean ± standard deviation) are given for the last two sessions. The number of training and test runs is given in brackets behind the condition.

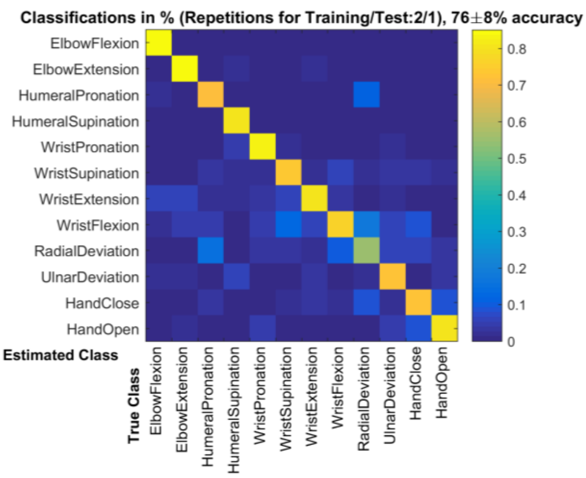
	Session 4, m 12			Session 5, m 17		
Within 1st block (2/1)	92	±	12	95	±	4
Within 2nd block (2/1)	95	±	6	97	±	2
Across blocks (3/3)	32	±	26	67	±	20

detected through palpation of the back muscles. For this session, the classification accuracy was 76% ± 8% (Fig. 4A).

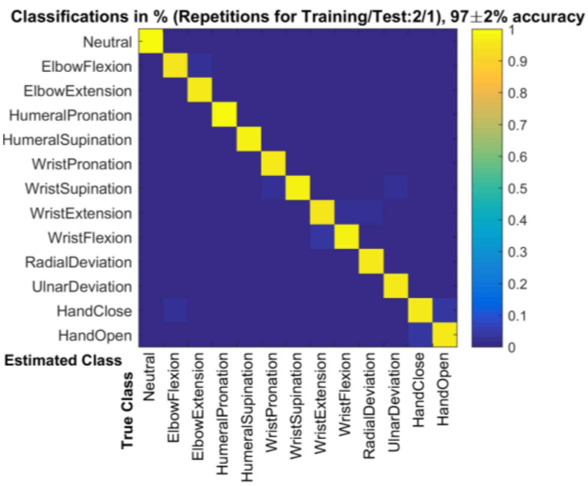
The average accuracy for the movements expected to be represented by the reinnervation sites on the chest (‘Elbow Flexion’, ‘Wrist Pronation’, and ‘Hand Close’) was 80% ± 7%. The two motions with expected reinnervation on the back (‘Hand Open’ and ‘Elbow Extension’) corresponded to an accuracy of 82% ± 3%.

When either the 6 or only the 3 grids were used, the accuracy achieved in Session 4 was significantly greater than in Session 3 (86% ± 7% and 94% ± 9%; $p < 0.01$, Table 2). In contrast, when the runs of the first block were used for training and the ones of the second block for testing or vice versa, the accuracy (approximately 32%) was rather bad, but better than chance level of 7.7%. The accuracy of the movements that were explicitly trained during the signal training (‘Elbow Flexion’, ‘Elbow Extension’, ‘Hand Open’, ‘Hand Close’, ‘Wrist Pronation’, and ‘Wrist Supination’) was higher than that for the other, non-trained motions (35% compared to 29%).

A: Session 3:



B: Session 5 (block 2):



C: Session 5 (across-blocks):

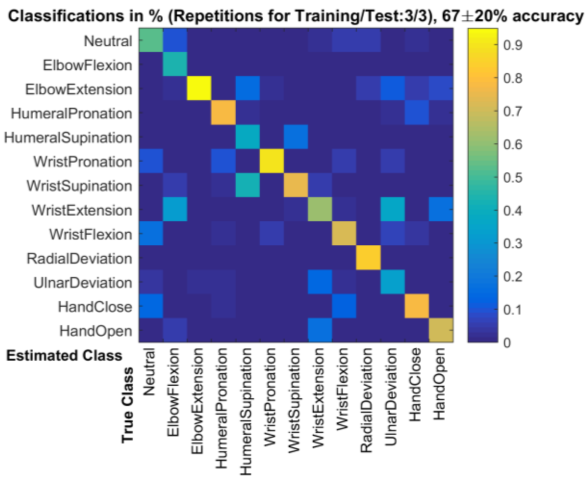


Figure 4. Confusion matrices. *The crossvalidated within-block confusion matrix is shown for A) Session 3 (month 9, first block) and B) Session 5 (month 17, second block). C) shows the crossvalidated across-blocks confusion matrix for Session 5. Accuracy is calculated as mean percentage of correct classifications across classes.*

Similar results as for Session 4 were obtained for Session 5 for the within-blocks analysis (3 grids, accuracy 85% ± 7%; 6 grids, 96 ± 3%) (Table 2 and Fig. 4B) (no statistically significant difference between Session 4 and Session 5, $p = 0.787$). Conversely, the average across-blocks accuracy (67% ± 20%, Fig. 4C) was significantly greater than in Session 4 ($p < 0.01$). As in Session 4, the accuracy was considerably greater on average for the movements that the patient used for the control of his prosthetics than for the other movements (75% versus 60%).

Comparing to (simulated) standard EMG, a clear benefit of HD-EMG was observed. While the average performance was still above 90% if only 32 or 16 channels were used per 64-channel matrix (i.e., every 2nd or every 4th channel), it strongly reduced to below 70% for two or one electrode(s) per matrix spots.

IV. DISCUSSION

We report longitudinal data on the reinnervation and rehabilitation process as well as on HD-EMG pattern recognition for a patient following TMR.

Although we expected the first signs of reinnervation after 60 days (see Methods), there was still no muscle contraction palpable at Session 1, three months post-surgery. This is in contrast to previous reports [6] which at that time post-surgery reported either muscle twitching or palpable muscle contraction and clear EMG activity in glenohumeral TMR patients. The observed delay in this subject most likely resulted from poor compliance to recommended and prescribed PT and OT in the first months due to a temporary lack of motivation. An augmentation of phantom-limb and deafferentiation pain in Session 1 was also reported. After re-entering PT and OT after Session 1, the first sign of motor activity could be detected through palpating at month 5 (Session 2), with a low amplitude EMG activity. Upon these first signs of reinnervation, PT and OT were even further intensified, such that the subject established a good neuromuscular control. Additionally, the phantom-limb pain decreased, most likely due to the extensive motor imagery training and mirror therapy. After 12 months (Session 4), only 5 days of signal training were sufficient to learn to generate five isolated signals, allowing the intuitive control of five motions. Hence, this case study appears to corroborate the finding that early PT and OT as well as visual feedback are crucial for a fast and successful reinnervation and signal generation after TMR [8][13]. After four weeks of intensive signal training, the subject was fitted with the final prosthesis. The SHAP score (52) in Session 5 shows his proficiency in prosthesis usage, which is comparable to the average performance observed in less impaired transradial amputees ([14], no data available for higher-level amputees). Hence, the initial delay in muscular activity did not prevent a successful prosthetic outcome.

However, with direct control, as currently implemented in TMR subjects, the intuitive motions are limited by the number of reinnervation sites. Therefore, pattern recognition methods have been combined with HD EMG measurements to differentiate between more than double as many movement classes, to potentially allow for the intuitive control of a prosthesis with many more degrees of freedom. In previous studies, using 115 monopolar electrodes, 16-motion classification rates of over 90% have been reported [4]. Even without the use of HD EMG, the feasibility of online control of a prosthesis with pattern-recognition algorithms was shown for 11 movement classes [15]. This advanced control was shown to considerably outperform direct control in real-life tests with a prosthesis [2]. This result is explained by the observation that muscle portions active in different motions can have strongly overlapping surface representations [16], limiting the applicability for direct control. In the current study, a clear superiority of HD-EMG versus (simulated) standard EMG was corroborated, because only HD-EMG allowed for reliable decoding of the 12 motions. The performance with standard EMG might have been better than presented here, if the electrode positions had been optimally chosen according to the current neuromuscular hotspots. However, that procedure would have been very time demanding and would have had to be repeated in every session, because hotpots tend to be migrating for several years after TMR surgery [8].

While the previous studies only performed HD EMG measurements and/or pattern classification long after the subjects underwent TMR surgery and prosthetic fitting, the present longitudinal case study is the first to explore longitudinally EMG-signal characteristics and classification from surgery to acquired prosthesis control. The HD-EMG within-block classification was assessed at three time points: before signal training (Session 3), after signal training at the time of prosthetic fitting (Session 4), and after several months of intense prosthetic use (Session 5). In Session 3, which was conducted prior to any signal training, the classification accuracy was already good, but not very high (76%). This indicates that reinnervation together with physio- and occupational therapy allowed for the generation of discriminable patterns. The accuracy in Session 4 was 94% (86%, if only three matrices were used as in Session 3), similar to that reported in previous studies [4]. This significantly higher accuracy was reached after intense signal training, but before the subject was using a prosthesis in daily life. Because the decoding accuracy was much lower in Session 3 than in Sessions 4, the improvement was presumably due to the ongoing reinnervation process and signal training. In Session 5, the accuracy was 96%, showing that daily-life prosthetic use only marginally (not statistically significant) improved the performance obtained in Session 4. In all HD-EMG sessions, high accuracy was obtained even for those movements which were expected to be encoded on the back only, hinting that a rather consistent pattern was observed also for these movements by the chest muscles. It should be noted that even though certain motions can primarily be attributed to particular nerves, the majority of them are generated as a result of compound activation of several nerves, e.g. hand close is primarily driven by the *nervus ulnaris* but at the same time it is highly supported by the *nervus medianus.* Hence, due to the high information content obtained by HD EMG, this phenomenon can be sufficient for distinguishing among the motions which through standard observational means would require careful coverage of all reinnervation sites.

In contrast to the within-block accuracy, the across-block accuracy was much poorer in Session 4 (32%) and still far from optimal in Session 5 (67%; Fig. 3). To exclude that the low accuracy was due to measurement-related issues, the EMG noise (average RMS during neutral condition) and signal-to-noise-ratio (SNR, average RMS during motion divided by EMG noise) of the different blocks were inspected. For Sessions 4, the noise did not differ between the first and three runs, with the SNR being only marginally higher in the last three runs (2%). Hence, the unsatisfying across-blocks classification accurary cannot have been due to noise or SNR issues in Session 4 but most likely resulting from inconsistent movements. Repeating very similar phantom movements was challenging because both visual and proprioceptive feedback were missing in the present experimental setting and the patient had not trained or performed some of the motions for more than a year. The repeatability between blocks could probably be improved by dedicated training. Indeed, there was a significant improvement in the across-block accuracy from Session 4 to 5. This training effect was most likely achieved due to the pronounced daily use of half of the tested movements. Hence, although the within-block accuracy already saturated at Session 4, the consistency of the movement commands strongly improved with daily prosthesis use. For Session 5, the EMG noise decreased from the first to the last three runs by 26% and the SNR almost doubled from the first three to the last three runs (48%). Therefore, the still not optimal across-blocks classification accurary in Session 5 might have been related also to stronger contractions in the second block, which were not trained in the first block.

In summary, the present case study describes the reinnervation time course observed in one TMR patient and longitudinally explores the within- and across-blocks pattern-recognition accuracy observed before and after signal training as well as after continuous prosthetic use. These results provide insights into the different components of the TMR rehabilitation process.

A. Acknowledgments

We thank Daniela Wüstefeld and Erik Andres from the Ottobock Competence Center for the continuous support throughout the study as well as Dr. Silvia Muceli for assistance in one of the measurement sessions.

B. References

[1] L. A. Miller, H. Huang, T. W. Williams III, R. F. Weir, and T. A. Kuiken, “Control of a Six Degree of Freedom Prosthetic Arm After Targeted Muscle Reinnervation Surgery,” *Arch Phys Med Rehabil*, vol. 89, 2008.

[2] L. J. Hargrove, B. A. Lock, and A. M. Simon, “Pattern recognition control outperforms conventional myoelectric control in upper limb patients with targeted muscle reinnervation,” *Engineering in Medicine and Biology Society (EMBC), 2013 35th Annual International Conference of the IEEE.* pp. 1599–1602, 2013.

[3] O. C. Aszmann, I. Vujaklija, A. D. Roche, S. Salminger, M. Herceg, A. Sturma, L. A. Hruby, A. Pittermann, C. Hofer, and S. Amsuess, “Elective amputation and bionic substitution restore functional hand use after critical soft tissue injuries,” *Sci. Rep.*, vol. 6, 2016.

[4] P. Zhou, M. M. Lowery, K. B. Englehart, H. Huang, G. Li, L. Hargrove, J. P. A. Dewald, and T. A. Kuiken, “Decoding a New Neural–Machine Interface for Control of Artificial Limbs,” *J. Neurophysiol.*, vol. 98, no. 5, p. 2974 LP-2982, Nov. 2007.

[5] T. a. Kuiken, L. a. Miller, R. D. Lipschutz, B. a. Lock, K. Stubblefield, P. D. Marasco, P. Zhou, and G. a. Dumanian, “Targeted reinnervation for enhanced prosthetic arm function in a woman with a proximal amputation: a case study,” *Lancet*, vol. 369, no. 9559, pp. 371–380, 2007.

[6] T. A. Kuiken, G. A. Dumanian, R. D. Lipschutz, L. A. Miller, and K. A. Stubblefield, “The use of targeted muscle reinnervation for improved myoelectric prosthesis control in a bilateral shoulder disarticulation amputee,” *Prosthet. Orthot. Int.*, vol. 28, no. 3, pp. 245–253, 2004.

[7] O. C. Aszmann, H. Dietl, and M. Frey, “Selective nerve transfers to improve the control of myoelectrical arm prostheses,” *Handchirurgie, Mikrochirurgie, Plast. Chir.*, vol. 40, no. 1, pp. 60–65, 2008.

[8] K. A. Stubblefield, L. A. Miller, R. D. Lipschutz, and T. A. Kuiken, “Occupational therapy protocol for amputees with targeted muscle reinnervation,” *J. Rehabil. Res. Dev.*, vol. 46, no. 4, p. 481, 2009.

[9] A. Sturma, M. Herceg, B. Bischof, V. Fialka-Moser, and O. C. Aszmann, “Rehabilitation Following Targeted Muscle Reinnervation in Amputees,” in *Replace, Repair, Restore, Relieve–Bridging Clinical and Engineering Solutions in Neurorehabilitation*, Springer, 2014, pp. 775–779.

[10] H. J. Seddon, P. B. Medawar, and H. Smith, “Rate of regeneration of peripheral nerves in man,” *J. Physiol.*, vol. 102, no. 2, p. 191, 1943.

[11] C. M. Light, P. H. Chappell, and P. J. Kyberd, “Establishing a standardized clinical assessment tool of pathologic and prosthetic hand function: Normative data, reliability, and validity,” *Arch. Phys. Med. Rehabil.*, vol. 83, no. 6, pp. 776–783, Jul. 2002.

[12] B. Hudgins, P. Parker, and R. N. Skott, “A New Strategy for Multifunction Myoeletric Control,” *IEEE Trans. Biomed. Eng.*, 1993.

[13] A. Sturma, P. Göbel, M. Herceg, N. Gee, A. Roche, V. Fialka-Moser, and O. C. Aszmann, “Advanced rehabilitation for amputees after selective nerve transfers: EMG-guided training and testing,” in *Replace, Repair, Restore, Relieve–Bridging Clinical and Engineering Solutions in Neurorehabilitation*, Springer, 2014, pp. 169–177.

[14] P. J. Kyberd, A. Murgia, M. Gasson, T. Tjerks, C. Metcalf, P. H. Chappell, K. Warwick, S. E. M. Lawson, and T. Barnhill, “Case studies to demonstrate the range of applications of the Southampton Hand Assessment Procedure,” *Br. J. Occup. Ther.*, vol. 72, no. 5, pp. 212–218, 2009.

[15] T. A. Kuiken, G. Li, B. A. Lock, R. D. Lipschutz, L. A. Miller, K. A. Stubblefield, and K. B. Englehart, “Targeted muscle reinnervation for real-time myoelectric control of multifunction artificial arms,” *Jama*, vol. 301, no. 6, pp. 619–628, 2009.

[16] T. Kapelner, N. Jiang, A. Holobar, I. Vujaklija, A. D. Roche, D. Farina, and O. C. Aszmann, “Motor Unit Characteristics after Targeted Muscle Reinnervation,” *PLoS One*, vol. 11, no. 2, p. e0149772, Feb. 2016.