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Real Time Simultaneous and Proportional Control of Multiple Degrees of Freedom from surface EMG: preliminary results on subjects with limb deficiency*

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Abstract— **We present the real time simultaneous and proportional control of two degrees of freedom (DoF), using surface electromyographic signals from the residual limbs of three subject with limb deficiency. Three subjects could control a virtual object in two dimensions using their residual muscle activities to achieve goal-oriented tasks. The subjects indicated that they found the control intuitive and useful. These results show that such a simultaneous and proportional control paradigm is a promising direction for multi-functional prosthetic control.**

I. Introduction

Electromyoelectric signal (EMG) has been used as the control source signal for multi-function prostheses for decades. The current commercial control approach provides limited functionality [1]. Therefore, efforts have been directed on signal processing algorithms for better extracting the neural control information from EMG for more functional prosthetic control. Pattern recognition algorithms have been extensively investigated. However, with these algorithms it is difficult to realize simultaneous and proportional control over multiple functions or degrees of freedom (DoF) [2], although this is desirable to benefit from the full functionality provided by the latest prosthetic hands. Recently, a novel approach was proposed to estimate the kinematics of joints directly from the EMG, rather than focusing on discrete motions or functions [3]. It has been shown that joint torques [3] or limb positions [4][5][6] can be estimated directly from surface EMG either using supervised algorithms [4][5][6], such as artificial networks (ANN), or semi-unsupervised algorithm [3], such as non-negative matrix factorization (NMF). These methods were validated on both able-bodied subjects [3][5] and trans-radial amputee subjects [4][6]. In this study, we report the first real time tests of the NMF algorithm from subjects with limb deficiency and a control group (CG) of three intact limb subjects.

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II. Methods

A. Subjects

Three subjects with limb deficiency (all male, 14-30 yrs old) and three intact limb subjects (one female, two male, 23-33 yrs old) participated in the study. Two subjects (A1, A2) were missing functionality from trans-radial level, and one subject (A3) was a trans-humeral amputee. For subject A3 a targeted muscle innervation (TMR) had been performed during the amputation surgery. The subject conditions are summarized in Table II. All subjects or their legal guardian read and signed the informed consent, which was approved by the local research ethical committee. The measures were performed at Otto Bock HealthCare Products GmbH, Vienna, Austria.

B. Experimental protocol

During the experiment, the subject seated comfortably, with both upper limbs in neutral position (residual limb pointing downwards, at the side of the body), or at a position that was comfortable for him. A customized electrode mounting system was fixed at the residual limb of the subject. The mounting system was flexible such that it could adapt to

Table II Data on the subjects with limb deficiency

Sub ID	Age	Amp. Time	Amp. Type	Function performed
A1	30	2 years	Right side, trans-radial	Wrist fle/ext, rotation
A2	24	congenital	Left side, trans-radial	Wrist fle/ext, rotation
A3	14	1 year	Left side, trans-humeral	Elbow fle/ext, hand open/close

Table I Summary of the training contractions

Group	Contractions #	Description
Group 1	1-4	Sinusoidal contractions of DoF1
	5-8	Sinusoidal contractions of DoF2
Group 2	9	DoF1 remains constant while sinusoidal contraction of DoF2
	10	DoF2 remains constant while sinusoidal contraction of DoF1

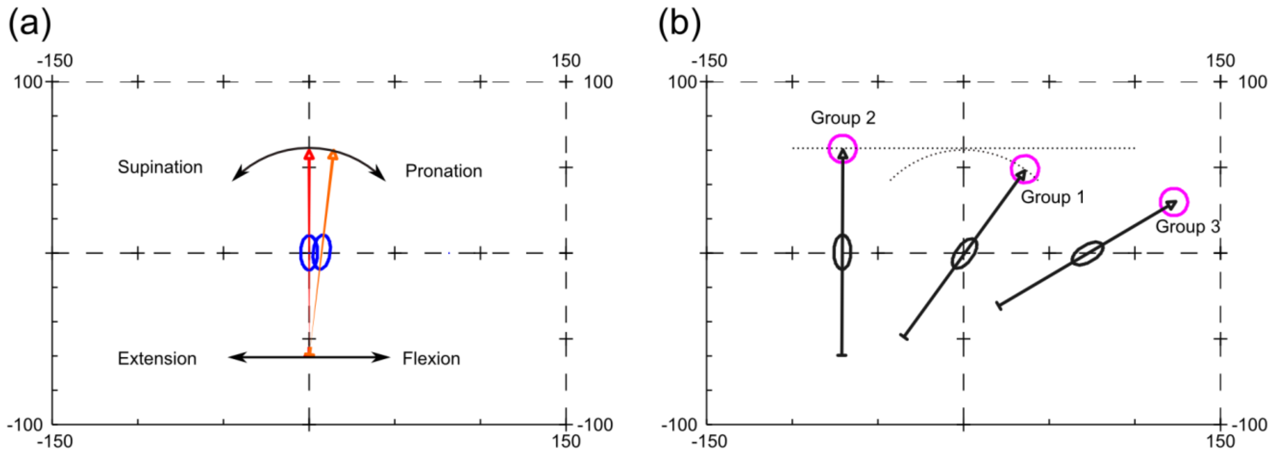

Figure 1 (a) The training for the left hand side with the presented target in red and the mirrored feedback provided by the XSens System in orange. For the right hand side flexion and extension as well as pronation and supination are switched. (b) The different targets presented for the target hitting test. For group 1 only pronation and supination are required, for group 2 only flexion and extension of the wrist. To reach targets of group 3 both pronation or supination and flexion or extension are necessary.

different limb sizes of different subjects, while providing appropriate pressure at the signal sites. A total of eight Otto Bock MyoBock® electrodes were attached to the mounting system, providing equidistance coverage of the residual limb. The surface EMG signal was acquired by a proprietary signal acquisition, amplification and A/D system developed by Otto Bock (Axon-Bus®). The acquired signals were transmitted over a BlueTooth® based wireless interface to a PC, where the signals were further processed using Matlab. At the intact side of the trans-radial subject, 3 XSens® MTx motion capture pods were placed on the dorsal side of the hand, dorsal side of the forearm (close to wrist), and lateral side of the forearm (close to elbow). The three markers were used to capture the following wrist kinematics: pronation/supination angle and flexion/extension angle. For the intact limb subjects the same protocol was applied, allowing the subject to choose a preferred side for the EMG recording system. The XSens® markers were not used for subject A3.

Each experimental session started with a training phase. In this phase, the subject was first asked to perform a series of muscle contractions that articulated either independently or simultaneously the 2 DoFs. All the contractions were performed in a mirrored fashion, as described in earlier studies [4–6]. For the two trans-radial and intact-limb subjects, the selected DoFs were wrist pronation/supination (DoF2) and wrist flexion and extension (DoF1), as these two DoFs are functionally important. For the trans-humeral amputee, the two DoFs were elbow flexion/extension (DoF1) and hand open/close (DoF2), as these were the only functions available by the TMR surgery. The contractions were similar to those in previous studies [3–5], and summarized in Table I. During these contractions, a red arrow (shown in Figure 1a) was presented to the subject. The left-right movement of this arrow represented wrist flexion/extension, and the clockwise/counter-clockwise rotation represented wrist supination/pronation. For the two trans-radial subjects, the joint angles of the intact limb side, acquired by the XSens® system, were also presented to the subjects as an orange arrow, with the same format as the red arrow. The sEMG data and kinematic data (when available) acquired during these contractions were used to train the estimator.

Table III Results of the target tracking test

	A1	A2	A3	CG
r^2 DoF1	0.57	0.18	0.33	0.79
r^2 DoF2	-4.93	-1.21	-1.34	-5.29

The semi-supervised algorithm based on step-wise NMF was used to estimate joint angles from surface EMG [3]. Only the root mean square (rms) values of the 8-channel EMG were used as the mixture to be factorized. The synergy matrix columns were obtained by the data from contractions activating single DoFs, and validated with data from contractions activating both DoFs. The Multilayer NMF procedure [7] was applied to enhance the robustness of the online performance.

The NMF estimator was trained using the data from the training phase, and the testing phase began. In this phase of the experiment, the subject would be asked to perform two online tests with the trained estimators. In the first task (tracking task) the subject was presented with the same red arrow as in the training phase, as well as a black arrow that the subject could control using the EMG. The subject was instructed to control the black arrow to track the movements of the red arrow, as close as possible. The r^2 values for the two DoFs were calculated as the performance measure of this task. In the second task (target hitting task) the subject was instructed to place the tip of the black arrow within circular targets that appeared in different places on the screen (Figure 1b). If the subject successfully placed the tip of the arrow within the target for more than 300 ms within a 20 seconds time interval, the task was considered complete. Three groups of the targets were presented within the reaching range of the subject: the targets of the first group were randomly located on the unit-circle, so that the subject could complete the task by rotating the arrow only; the targets of the second group had the same horizontal height, with random left-right displacement, so that the subject could complete the task by moving the arrow left or right only; the targets of the third

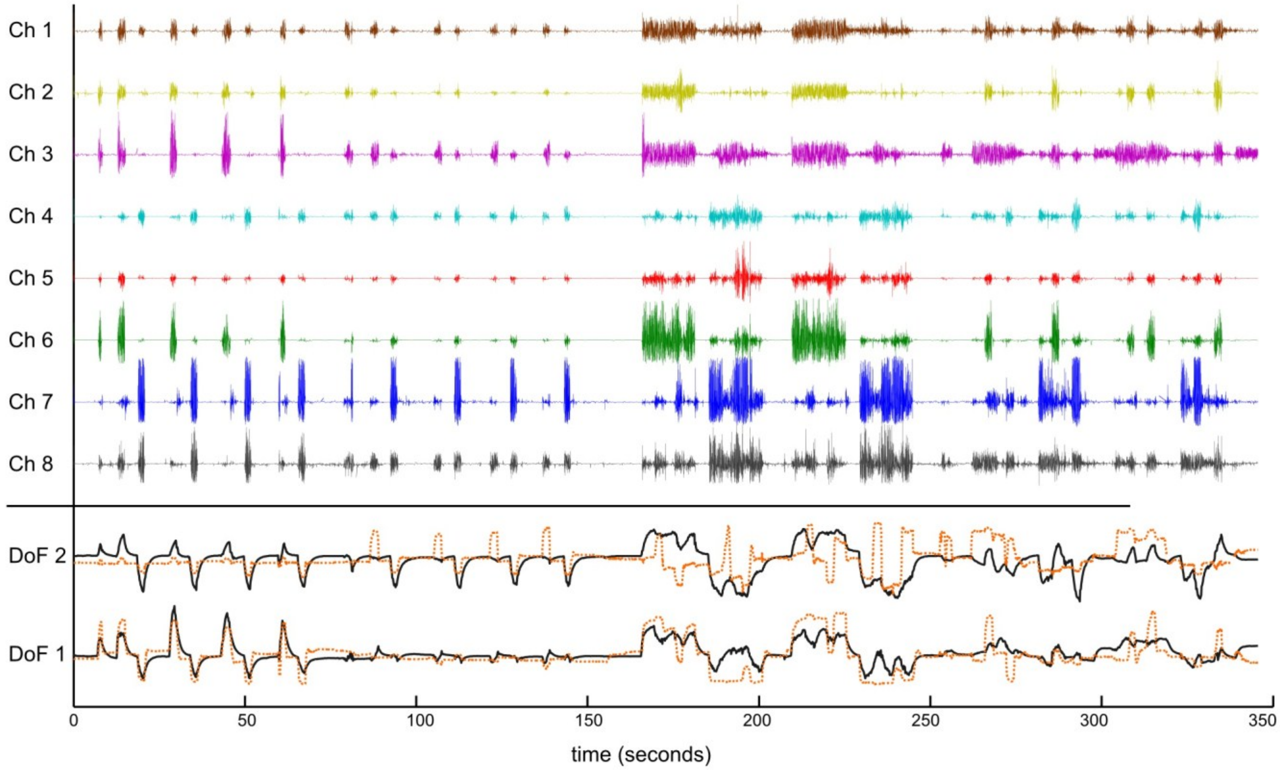

Figure 2 Representative data set (subject A2), showing the EMG raw signal channels (Ch1 – Ch8) in the upper eight traces. In the lower part the angles for the two DoF are shown, both as calculated from the contra-lateral side (in orange) as well as estimated by the presented algorithm (in black).

group were randomly placed so that the subject had to simultaneously control the two DoFs of the arrow. Eight targets per group were presented to the subject. Two performance measures were used for the target hitting task: task completion rate and mean task completion time t_c. The task completion rate α was defined as the number of completed tasks over the total number of tasks attempted. Mean task completion time t_c was the average time taken by the subject to complete the tasks.

The experimental session could be paused upon the subject requests, or by the discretion of the investigator, to avoid fatigue. The training phase of the experiment lasted less than 5 minutes, and the testing phase usually lasted 10 – 30 minutes. A complete experimental session was usually completed in 60 minutes.

III. Results

A representative data set is presented in Figure 2. The measured joint angles of the contra-lateral side and the estimated angles from the NMF algorithm were presented, together with the raw EMG signal. The data was obtained from subject A2 during the target tracking test.

A. Quantitative Results

The r^2 values for both DoFs over all subjects are reported in Table III. On average, the r^2 values of this study were 0.66±0.48 and -3.89±13.76 for DoF1 and DoF2, respectively. This is in agreement with earlier reports from amputee subjects [4][6]. The task completion rate α and the mean task completion time t_c are reported in Table IV. The average α was 94.64%±10.13 and the t_c was 4.48±1.47 seconds.

B. Subjective evaluation

All subjects reported that the training paradigm was short and easy to understand. Moreover, they all indicated that the feedback was engaging and that they would use and practice this protocol on a routine basis if available.

IV. Discussion

We showed that the NMF based algorithm can be used to extract simultaneous and proportional control information from the EMG and we demonstrated the real time performance of such an algorithm for 2 trans-radial and 1 trans-humeral subjects. These 3 subjects positively evaluated this new control paradigm because of the short and simple training phase, and the sense of achievement provided by the immediate real time feedback in the test phase. It is important to note that although the algorithmic performance values of the target tracking test was not as good as reported earlier in the literature in off-line studies, the performance of the target hitting task was similar. This might due to the fact that the subjects could actively adjust and compensate for the error produced by the algorithm, resulting in a co-adaptive scenario.

References

Table IV Results of the target hitting test

	A1	A2	A3	CG
α	100%	100%	95.8%	90.3%
t_c	5.34 s	5.37 s	4.37 s	4.44 s

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