Electromyographic indices of muscle fatigue of a severely paralyzed chronic stroke patient undergoing upper limb motor rehabilitation

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***Abstract*— Modern approaches to motor rehabilitation of severe upper limb paralysis in chronic stroke decode movements from electromyography for controlling rehabilitation orthoses. Muscle fatigue is a phenomenon that influences these neurophysiological signals and may diminish the decoding quality. Characterization of these potential signal changes during movement patterns of rehabilitation training could therefore help improve the decoding accuracy. In the present work we investigated how electromyographic indices of muscle fatigue in the Deltoid Anterior muscle evolve during typical forward reaching movements of a rehabilitation training in healthy subjects and a stroke patient. We found that muscle fatigue in healthy subjects changed the neurophysiological signal. In the patient, however, no consistent change was observed over several sessions.**

I. Introduction

Millions of stroke survivors live with chronically limited motor function or complete paralysis and depend on assistance [1]. Training based on Brain-Machine interfaces is an effective technique promoting motor recovery in these patients [2]. Recent works aim at increasing the efficacy of these approaches by way of including non-invasive electromyographic signals (EMG) in the methodology. Decoding of (residual) muscle activity allows for controlling a rehabilitation exoskeleton in multiple degrees of freedom [3].

There are diverse non-physiological and physiological factors influencing the EMG signal and consequently the decoding and quality of the sensory feedback to the patient. A contingent link between neurophysiological signals and the proprioceptive and visual feedback, however, is key for the efficacy of the rehabilitation. Muscle fatigue might have a detrimental effect on the EMG decoding accuracy and thus might diminish the quality of this feedback loop. This influence has been considered since the earliest works of BMI-based approaches that combine EEG and EMG for control of an exoskeleton [4]. None of the available works, however, have studied muscle fatigue within a rehabilitation framework for severely paralyzed chronic stroke victims.

Muscle fatigue is a physiological factor that changes the surface EMG signal during muscle contraction. The phenomenon is defined as exercise-induced reduction of the ability of a muscle to produce force [5]. Muscle fatigue may arise on the level of the nervous system, comprising all factors that lead to reduction of the numbers of recruited motor units. It may also arise on the level of the muscles. During fatiguing contractions biological changes such as increases in metabolite concentrations and altered conduction velocity of the muscle fibers occur. Amplitude and power spectrum of the EMG are influenced by these changes [6].

This work characterizes muscle fatigue in the Deltoid Anterior muscle during forward reaching. This movement is part of a rehabilitation intervention for chronic stroke patients with severe paralysis of the upper-limb. We describe how EMG indices of muscle fatigue change during performance of the specific movement used for the rehabilitation training in nine healthy subjects and a severely impaired chronic stroke patient. Subsequently, we investigate if the EMG activity of fatigued muscles of the healthy volunteers and the patient changes when performing the movement.

II. Methods

A. Rehabilitation environment

The rehabilitation environment comprises a set of neurophysiological sensors and a rehabilitation robot with 7 degrees of freedom that enables the patients to perform semi-functional multi-joint movements with arm and hand (cf [7] for more details). Furthermore, there are multiple movement targets, a screen and a loudspeaker for presentation of stimuli. In this investigation we focused on frontal reaching movements of the arm (Fig. 1a). This type of movement consists of shoulder forward flexion and horizontal adduction as well as elbow extension. Besides Pectoralis Major and the Triceps, the most prominent muscle involved in successful performance of this movement within the training is the Deltoid Anterior muscle, on which we focus this analysis.

B. Inducing fatigue during reaching movements

In order to investigate muscle fatigue during the rehabilitation exercise, a dynamic frontal reaching movement, we designed a muscle-fatigue apparatus (Fig. 1b). In a preparatory experiment we confirmed that muscle fatigue indices of the EMG can be measured and quantified during dynamic contractions of the Biceps, replicating findings of others [8], [9].

The nine healthy subjects (3 female, 6 male; age 26.8±2.4, all right-handed, no neuromuscular disorders) performed ten repetitions of the reaching movement with the rehabilitation robot using their left arm. Afterwards they performed reaching movements using the fatiguing apparatus in a predefined frequency until they could not perform the movement anymore or until the maximum experimental time of 25 minutes was reached. The reaching movements with the rehabilitation robot

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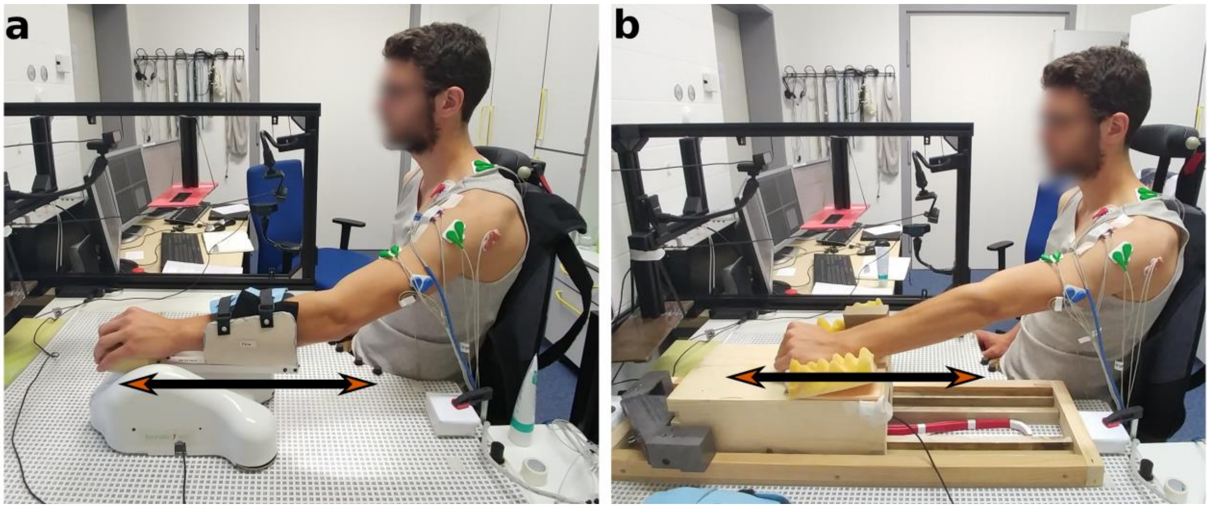

Figure 1. Experimental setup for the healthy subjects. (a) Frontal reaching movements with the rehabilitation exoskeleton. (b) Similar frontal reaching movement using the fatiguing apparatus. The moving block had to be pushed until maximum elongation of the arm using a handle against the force of a strong rubber band that pulled the block backwards. Maximum elongation was measured before and controlled by the experimenter during the experiment using a ruler attached to the apparatus. The frequency of the pushing movements was individually tuned to ensure challenging timing. The chair and seating position were fixed to avoid trunk movements.

were repeated immediately after muscle exhaustion to avoid recovery.

The chronically impaired patient presented no active arm or finger extension (Age: 65, male, Fugl-Meyer score of arm and hand skills: 8, time since stroke: 86 months, location of lesion: right hem., right-handed). He underwent a Brain-Machine interface-based rehabilitation intervention in which he trained different multi-joint movements with his paretic left arm using a rehabilitation exoskeleton for 1 hour per session [3], [7]. Despite not being able to exert any arm or hand movement he produced residual EMG activity that was used to control the robot together with brain activity. The intervention consisted of ten sessions of training. Before and after each training session the patient performed a compliant movement session. During this part of the training the robot moved fully automatically to the predefined targets. The patient was asked to concentrate on the movement and try to actively follow it. We could thus record residual muscle activity for the specific movement of interest despite the complete paralysis. We used the data of the five sessions of the

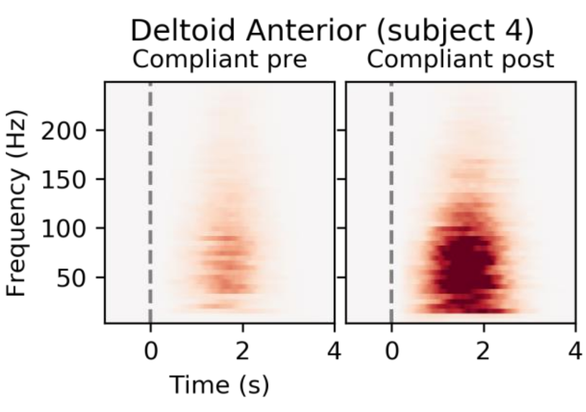

Figure 2. Time Frequency plot of EMG activity in subject 4 (representative healthy subject) before and after the fatiguing session. The color axis is in arbitrary units representing power in both plots.

second week of training assuming that the patient was familiarized well with the rehabilitation environment and able to perform the tasks as instructed.

In both cases the muscle activity of the main extensors and flexors of the arm was recorded using Bipolar EMG electrodes and a 16 channel Brain Products BrainAmp ExG amplifier system. The data were sampled at 1000 Hz. The movements in all experiments were cued by an auditory stimulus.

The EMG signal was filtered between 3 Hz and 250 Hz for the analysis. In the analysis of the data acquired during the fatiguing session the contractions of the Deltoid Anterior during each forward reaching movement were extracted automatically by finding the minima of a moving average of the rectified EMG signal. For quantification of muscle fatigue two established markers were used. Firstly, the mean frequency of the spectrum: Fmean. This index represents

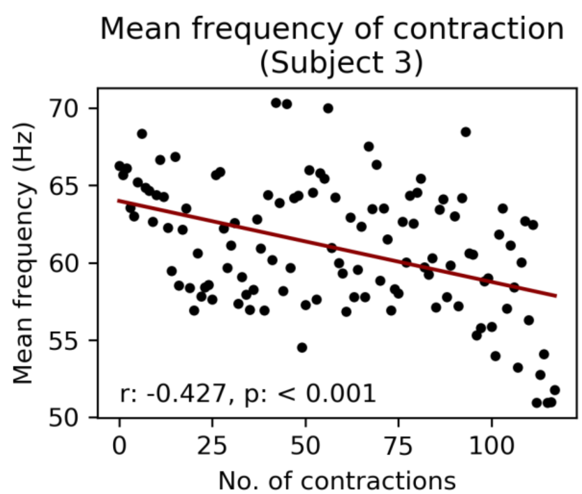

Figure 3. Evolution of the Fmean EMG index of fatigue in the Deltoid Anterior Muscle Subject 3: A linear decrease of the mean frequency of the EMG power spectrum is visible ($r = -0.43$, $p < 0.001$) indicating muscle fatigue

spectral parameters that reflect changes in conduction velocities of muscle fibers, which lead to alterations of the waveforms of motor unit action potentials [10]. Secondly, we used the the Dimitrov spectral fatigue index FInsm5 [11], which emphasizes increases in low frequencies and the decrease in high frequencies by employing moments -1 and 5 of the spectrum. This metric reflects increased negative after-potentials of motor units and increased duration of propagation of intracellular action potentials during fatigue. All the results of the fatigue measures are presented as the percentage of decrease of the fatigue index from the pre- to the post measurement.

III. Results

A. Deltoid Anterior fatigue in the healthy participants

We show a time-frequency plot of activations of the Deltoid Anterior muscle during the frontal reaching movements of a representative healthy participant (subject 4). The belly of the power spectrum of the EMG activity, which is common in dynamic contractions, is clearly visible before (PRE) and after (POST) using the fatiguing apparatus (Fig. 2). The percentage change of the two fatigue indices for all patients are shown in (Table 1).

The difference of the means from zero was tested using a one-sided t-test. For Fmean: $t = -1.0$; $df = 8$; $p = 0.34$ and FInsm5: $t = -1.0$; $df = 8$, $p = 0.34$. Even though both measures indicated fatigue in the majority of the healthy subjects, i.e. a reduction in Fmean and an increase of FInsm5, the test did not reveal a clear difference of the means from zero for either index.

To further investigate fatigue in the Deltoid Anterior muscle and to understand the differences between subjects we analyzed the EMG of the dynamic contractions recorded during the use of the fatiguing apparatus. After segmenting the contractions we computed the fatigue indices for each segment. Fig. 3 shows the evolution of the Fmean index of subject 3 (representative of subjects showing a relatively larger index decrease). The slope of the linear regression indicates a decrease of the mean frequency of the spectrum of EMG activity over time. On the contrary, the slope of the index evolution of subject 9 was zero (representative of subjects showing no index decrease or increase, not shown here).

B. Deltoid Anterior fatigue in the patient

We show a representative time-frequency plot of activations of the Deltoid Anterior muscle during the compliant frontal reaching movements of the patient in one of the sessions (Fig. 4). The patient was not able to elicit activity in the Deltoid Anterior muscle in every trial exactly after the auditory cue because of the paralysis. For this reason the zero line is aligned to the movement onsets, which were manually determined for each repetition. In the plot the activity is stretched along the time axis more than in the healthy participants because the compliant reaching movements the patient performed had a longer duration than the reaching movements the healthy participants performed. The bandwidth of the spectrum, however, is similar.

The quantified fatigue indices for four of the five sessions are summarized in (Table 2). One session was excluded because the patient did not exert activity in the Deltoid Anterior muscle during frontal reaching. In two of the sessions a percentage decrease of the Fmean index is seen. The FInsm5 index decreased in all sessions except session 3.

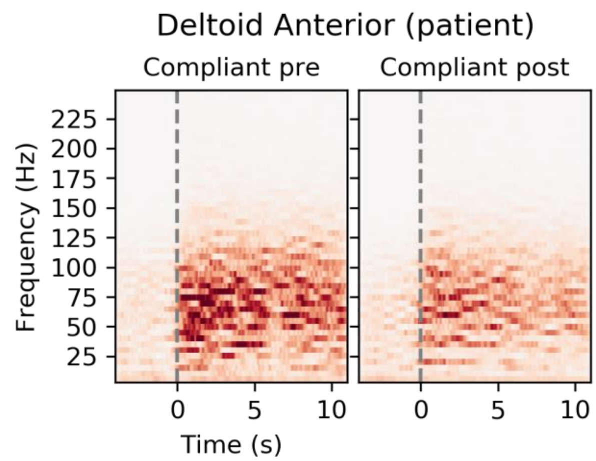

Figure 4. Time Frequency plot of EMG activity in the stroke patient before and after the training session; compliant movement ("0" is movement onset). The color axis is in arbitrary units representing power in both plots.

TABLE I. Deltoid Anterior fatigue healthy participants (PRE vs. POST)

Subject	*Fmean*	*FInsm5*
1	4.4 %	- 20.6 %
2	- 10.9 %	49.4 %
3	- 6.9 %	35.7 %
4	- 11.9 %	77.3 %
5	- 1.7 %	9 %
6	- 1.5 %	- 8.5 %
7	- 0.8 %	2.8 %
8	- 4.1 %	0.6 %
9	9.4 %	- 37.1 %
Mean	- 2.3 %	12.1 %

TABLE II. Deltoid Anterior fatigue stroke patient

Session	*Fmean*	*FInsm5*
1	- 51.2 %	- 6 %
2	2.2 %	- 0.2 %
3	8.9 %	1.2 %
5	- 28.1 %	- 3.6 %

IV. Discussion

In this study we investigated how EMG features of muscle fatigue develop and progress in the setting of a semi-functional multi-joint movement within a rehabilitation paradigm for chronic stroke patients with severe paralysis of the upper-limb.

The Deltoid Anterior muscle is recruited during forward reaching movements as investigated here. Moreover, many paralyzed stroke patients show relatively more control in proximal than in distal muscles. Hence, we focused on investigation of this muscle in the present work. We found that fatigue could be induced and tracked using common EMG indices in healthy individuals during dynamic biceps contractions. These findings were transferred into a fatiguing task as closely related to the movements of the rehabilitation paradigm as possible. In the test with healthy participants muscle fatigue was induced using the fatiguing apparatus. The statistical test did not reveal a general similar change in all participants. Some participants, however, showed a distinct reduction in the mean frequency of the EMG power spectrum from the pre measurement to the post measurement. These subjects also showed a linear reduction of this fatigue feature during the fatiguing session, which is an effect that has been observed before [8]. In some participants the changes of the fatigue features in the Deltoid Anterior muscle were very small and thus a significant mean change for all subjects was not found. Even though elongation of the arm, repetition speed of the fatiguing movement and the strength of the rubber band were controlled, the subjects might have used compensatory strategies for completing the task unintentionally, e.g. using the trunk for the beginning of the movement and thus relieving the Deltoid Muscle. Such movements are hard to control in the described setting that required a lot of force. Monitoring trunk and neck muscles as well as contralateral muscles could help to further increase the number of controlled factors. Moreover, the different levels of fitness of the participants may have influenced the results as trained muscles recover more quickly and they may have partially recovered during the backwards movement of the fatiguing exercise or when switching from the fatiguing apparatus to the exoskeleton for the post measurement, which, however, only took a few seconds.

In the severely paralyzed stroke patient the fatigue features did not show a consistent pattern over the course of the four training sessions. On the first and the last day a decrease of the mean frequency of the EMG power spectrum could be seen. On the other days there was a slight increase. The Dimitrov spectral fatigue index decreased on three days and increased slightly on one day. By definition, the two indices should be anti-correlated. A negative Dimitrov index may indicate a lower-than-expected increase of the low frequency power from pre to post. An increase of the power in the low frequencies occurs due to increased negative after-potential during fatigue [11]. Judging from the time-frequency plots, the bandwidth of the EMG power spectrum is similar to the one of the healthy participants, ranging from around 10 Hz to between 150 and 200 Hz. This indicates that comparison of muscle activity between both populations is possible, even though EMG amplitudes are much lower in the stroke patient.

The investigation of muscle fatigue in the stroke patient was performed under the assumption that the training task is fatiguing for the patient since he cannot perform the task normally and the Deltoid Anterior muscle is weak and easily fatigable due to prolonged non-use. In the training the patient is forced to activate the muscle to trigger the movement of the exoskeleton. However, it may have been the case that the task was not fatiguing for the patient at the peripheral (i.e. the muscle) level. It has been shown some decades ago that healthy individuals with higher percentage of slow-twitch fibers (ST) show lower changes in the EMG spectrum [8]. In paretic muscles of stroke survivors an increased number of slow twitch muscle fibers is innervated [12]. On top of that, it has been shown that the number of slow-twitch fibers is generally increased in the elderly [13]. The muscle of the patient might thus be less susceptible to fatigue and may express less changes in the EMG spectrum.

We conclude from this investigation that if fatigue in the Deltoid Anterior muscle is induced during forward reaching movements within the described rehabilitation framework in healthy participants the measured EMG activity is altered. In the stroke patient we could not find clear evidence that the fatigue features in the same muscles during a similar movement alter the EMG activity in a consistent way. The present experimental results of the measurement with the stroke patient thus hint at no or a negligible influence of the movements performed in the training on EMG fatigue features which might rule out the influence of this factor on EMG decoding. Further recordings of data of paralyzed stroke patients and investigation of potentially more sensitive EMG indices of muscle fatigue may provide more evidence toward either direction.

V. References

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