Academic Research Assignment

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Cortical Fatigue in Stroke Patients

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DECLARATION OF HONESTY

I hereby declare that this thesis is solely my own work and that if any text passages or diagrams from books, papers, the Web or other sources have been copied or in any other way used, all references – including those found in electronic media – have been acknowledged and fully cited.

Milwaukee, 1st of March, 2017

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I also appreciate the effort of all participants. I have been going through the whole protocol myself as a test participant and know how hard it is to get fatigued and how much willpower it takes to continue.

ABSTRACT

Post stroke fatigue is one of the most common symptoms after a stroke and is characterized by an abnormal lack of energy, intense tiredness, and an increased need to rest. Fatigue affects stroke survivors' ability to regain lost functions through rehabilitation and to complete activities of daily living. [1][2] Due to the lack of knowledge surrounding the phenomenon, there is no effective treatment. [3]

This research examines the cortical and muscular effects of fatigue in the post-stroke and neurologically intact populations. It will examine two conditions: before and after fatigue. There is a fatiguing protocol in between the conditions, to induce fatigue as well as control tasks during the after fatigue condition to check if participants are still fatigued. The examined body part in the neurologically intact population was the dominant arm and the paretic arm in the stroke population. To measure brain activity, the participants had to wear an electroencephalogram (EEG), as well as an electromyography (EMG) to measure muscle-activation during the two conditions.

The theory behind the experiment is that fatigue occurs because of a reduction in the firing of neurons due to a reduced energy supply in the post stroke patients, in contrast a muscular fatigue in the intact population. We hypothesized that stroke patients would show fatigue significantly sooner. The event-related-desynchronization (ERD) [4] response would be reduced in stroke patients, and muscular fatigue would be more dominant when comparing the intact group to the stroke population.

The study consisted of six control and two stroke subjects. Due to the low number of stroke subjects, it is hard to draw any solid conclusions. Nevertheless, we could see that muscle activity in the intact participants rose in order to maintain a certain force. This is an indicator of muscular fatigue. In contrast that could not be observed in the two stroke patients. They were not muscularly fatigued.

The EEG signal was very noisy due to muscle artifacts, and it was hard to isolate and remove those artefacts, although to a certain degree it was possible through independent component analysis (ICA).

The conclusion from the EEG was that there was primarily alpha band desynchronization during the isometric contraction in the motor-area and a little bit of beta-band desynchronization, but there was no significant difference between stroke patients and neurologically intact participants. Further studies with more participants will have to be conducted.

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1. INTRODUCTION

1.1. General Background

There are about 4 million stroke survivors in the US alone, and every year, more than 795,000 people in the United States have a stroke [5]. A stroke occurs when brain cells die either through the lack of blood (ischemic) or through cerebral pressure in the form of bleeding (hemorrhagic). A hemorrhagic stroke is caused by a ruptured vessel and an ischemic stroke happens due to a thrombosis or embolus (both trough a forming blood clot that later blocks a vessel); or systemic hypoperfusion (for example trough a shock) or cerebral venous sinus thrombosis. Depending on the area of the brain affected by the stroke, the symptoms could be altered senses, aphasia, memory deficits, balance problems, hemineglect, and/or hemiparesis.

Despite those differences, fatigue effects 72% of all stroke survivors.[2] “Many patients mention fatigue as one of the most difficult sequelae to which to adjust. Fatigue often interferes with the rehabilitation process and impairs the patient’s ability to regain functions lost because of the stroke”. [6] Post-stroke fatigue (PSF) is also associated with “depressive symptoms, anxiety, poor coping, loss of control, emotional, and behavioral symptoms”, [7] and it also contributes to lower quality of life and a higher risk of death. [3] Fatigue is also a common symptom in many other chronic diseases such as multiple sclerosis, rheumatoid arthritis, and HIV [6]. Currently there is no effective treatment, which is partly due to our lack of understanding. [3]

It was commonly thought that PSF was a cognitive problem, but a recent study showed that preparation time for a movement did not take stroke-patients with PSF as long as execution time. This suggests that PSF is a cortico-motor and not a cognitive problem [8].

1.2. Objectives

EEG measurements are highly influenced by nearby muscles, which cause artifacts in the signal. One of the first objectives is to find out if a study like this can be carried out, or if muscle artifacts are too dominant to draw a conclusion from the EEG signal.

Another objective is to pave the way for further research in giving enhancements, by pointing out difficulties and obstacles that have been witnessed during the experiment.

Furthermore, in this research, we are trying to find out if there is a difference between the intact population and the stroke population in the way they fatigue. The hypothesis is that stroke patients fatigue not only due to their muscle fatigue, but mostly due to cortical fatigue. This should result in a lower alpha or beta band desynchronization in the stroke population than the intact population. We expect the intact population to fatigue primarily due to muscle fatigue. On the other hand, stroke will primarily be fatigued because of the lack of brain to activation the muscle.

The hypothesis is that beta and alpha band desynchronization stays the same between pre and post fatigue for the intact population. This research focuses on the sensory-motor region of the brain.

We also expect to see an increase in EMG activity between pre and post fatigue conditions for the intact population. This indicates muscle-fatigue.

1.3. Structure and Outline

After the introduction, where the study is explained and the objectives of the study are presented, the theoretical background follows in chapter 2. This chapter will focus on tools that have been used for the study and explain how they work. It will give a basic understanding of the subject and can be skipped if the reader is already familiar with the field.

In chapter 3, the experiment will be narrowed down. The concept and aims will be explained first. After that, the materials that have been used will be explained. The difference from chapter 2 is that tools like EEG or EMG are explained in the context of the study. The methods and how the data is analyzed will follow after that. In the section methods, the course of the experiment is presented.

Chapter 4 focuses on the results which are divided into the different measurement techniques: EEG, EMG and the load-cell data.

A discussion and an outlook follows in chapter 5 and 6.

2. Theoretical Background

2.1. EEG

Electroencephalography (EEG) It is a recording of the brain's electrical potential found on the scalp. It is measured by placing electrodes over the scalp at specific locations. EEG measurement provides information about the amount of firing neurons projected onto the outer surface of the cranium. Even though all neurons may play a small role in the generation of EEG, the main source of EEG are the pyramidal neurons that are found in the gyri and lie perpendicular to the outer cortex. The inputs to the pyramidal neurons, post synaptic potentials, generate neuronal current flow and cause the pyramidal neurons to resemble dipoles. When large populations of these dipoles are active at the same time, the dipoles sum together and produce an electrical potential detectable on the scalp which when measured is known as EEG. Due to the soft tissue and scalp located between the source and the recording electrode, the brain's electrical signal is low pass filtered giving the EEG a bandwidth of about 100 Hz. The soft tissue and scalp also create a smearing effect that along with the limited number of EEG electrodes causes the signal's spatial resolution to be in centimeters. A huge advantage of this method is the temporal resolution.

EEG is also one of the most common measuring techniques for measuring brain activity, because it offers a very good temporal resolution and is compared to other techniques very cost-effective.

An important factor is the connection from the electrodes to the skin. A conductive gel is used to keep the impedance low. The quality of the signal is critical and a good connection is necessary. The signal that is measured is around a few µV and has to be amplified. Depending on the frequency of the signal, activeness of the region can be derived. It is common to distinguish between

There are mainly two different views on the signal. The time analysis and the frequency analysis. In the frequency analysis, there are five states of frequencies that are common, ranging from very active to deep sleep in this given order: Gamma, Beta, Alpha, Theta, Delta which can be seen in Figure 1. All of those frequencies are active; however, certain bands are more active and therefore specific in certain time of an activity, like the states of sleep.

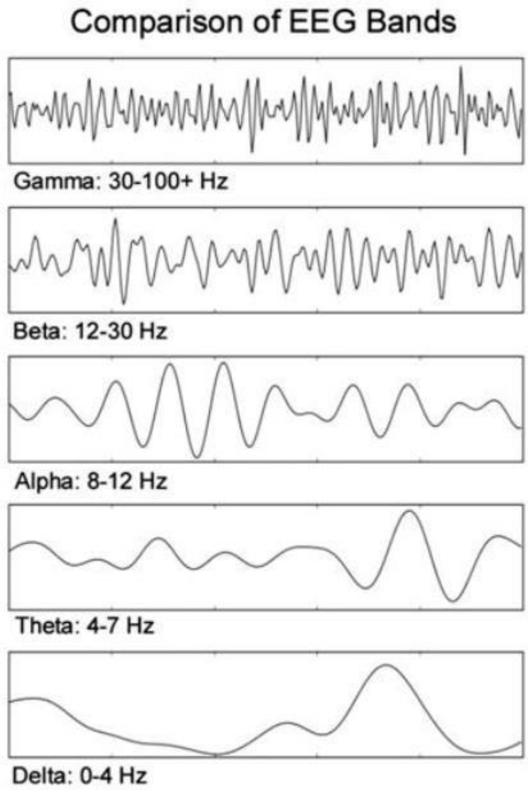


Figure 1: Comparison of EEG Bands [9]

Plotting EEG in a spectrogram is more common nowadays, because it offers more information than the distinction between those bands, also because there are disunities about where to make the cutoff for certain EEG bands. A spectrogram shows the frequency's on the y-axis and the time at the x-axis. The color resembles the activeness of a certain frequency at a certain time period.

In the past, EEG based research mainly included examining evoked potentials that provide information about the time course of the EEG signal. Now it includes areas such as frequency analysis, source localization, time-frequency analysis, and connectivity analysis. Time-frequency analysis of EEG has led to the discovery of beta band (15-30 Hz) power fluctuations above the motor cortex during movement known as beta band desynchronization (decrease in power during movement) and resynchronization (increase in power following movement) [10].

2.1.1. Event related Potentials

Event related Potentials, further described as ERP and also known as EKP for Ereigniskorrelierte Potentiale, are waveforms in an EEG that result from sensory perceptions or correlate with a cognitive process, like attention, or processing speech. Researchers look for those patterns in an EEG signal. There are different ERPs', which can be distinguished by their amplitude, phase, or length of response to stimuli. Another attribute about ERPs' is, that they are phase-locked as well as time-locked. So in an experiment where the same situation is repeated over a certain time, the ERP will still be present if those EEG signals are averaged. Random events are not phase and not time-locked events and would zero out if averaged over trials.

If the time signal is averaged over trials, the amplitude will stay almost the same, but not phase locked signals that are also time-locked will zero out. This cannot be seen in the spectrogram. If the spectrogram is averaged, it will show a high amplitude even in non-phase-locked signals.

2.1.2. Event-related Desynchronization

A focus of this study is on the beta-band-desynchronization or in general event-related-desynchronization or synchronization (ERD or ERS). ERD/ERS is highly frequency-band-specific and different regions of the brain can display ERD and/or ERS at the same time. An internally or externally paced event results not only in the generation of an event-related potential (ERP) but also in a change in the ongoing EEG/MEG in form of an event-related desynchronization (ERD) or event-related synchronization (ERS). [10] ERPs are phase-independent and amplitude-dependent whereas ERS and ERD are phase-dependent and independent of the amplitude. It has been found that strong physical activities result in an ERD in the beta-band (13-30 Hz); more precisely, "voluntary movement results in a desynchronization in the upper alpha (8 -13 Hz) and lower beta bands, localized close to sensorimotor areas" [10], and ERD can be interpreted as an "electrophysiological correlate of activated cortical areas involved in processing of sensory information, cognitive information, or production of motor behavior". [10]

2.2. EMG

Electromyography EMG is a measuring technique that measures muscle-activation. Muscle-potentials can be spontaneous or arbitrary. There is the option to obtain the signal via needles but we use the surface projection since it is not invasive and therefore much more comfortable for the participants. The EMG signal is around a few hundred µV and therefore has to be amplified. Because the amplitude is so low, it is really important to have a low impedance from the skin to the amplifier. The skin must be lightly abraded with an ethanol cloth. After that, an electrode is placed on the observed muscle. Those electrodes are simply stacked onto the skin and mostly contain silver chloride to keep the impedance low.

2.3. Fatigue

Fatigue in a medical sense comprises much more than just tiredness.

Different medical dictionaries describe fatigue as: "overwhelming sustained feeling of exhaustion and diminished capacity for physical and mental work" [11], "loss of ability of tissues to respond to stimuli that normally evoke muscular contraction or other activity. Muscle cells generally require a refractory or recovery period after activity, when cells restore their energy supplies and excrete metabolic waste products." [12], "a physiological state in which muscles become fatigued by the lactic acid accumulating in them as a result of their activity" [13].

There are also many causes for fatigue which can be distinguished by mental and physical causes. Some physical causes are

- "excessive activity which causes the accumulation of metabolic waste products as lactic acid
- malnutrition (deficiency of carbohydrates, proteins, minerals, or vitamins)
- circulatory disturbances such as heart disease or anemia, which interfere with the supply of oxygen and energy materials to tissues
- respiratory disturbances, which interfere with the supply of oxygen to tissues
- infectious diseases, which produce toxic products or alter body metabolism
- endocrine disturbances such as occur in diabetes, hyperinsulinism, and menopause
- physical factors such as disability, environmental noise or vibration"

[11]

Some mental causes are:

- "psychogenic factors such as emotional conflicts
- frustration, anxiety, neurosis, boredom" [11]
- "exposure to psychic pressure, as in battle or combat fatigue" [12]

Mental and physical causes can be related. For example, the mental cause anxiety could be the cause for short breath, which would lead to less oxygenation to the muscle, which makes the subject even more complicated.

There is one more recent factor that can have an influence on fatigue, and that is the disability of the brain to send out nerve-impulses to activate a muscle. The so called "Central fatigue" is a decrease in voluntary activation of the muscle [14].

Another model of fatigue by Boyas et. al. looks at the underlying factors of physiological fatigue.

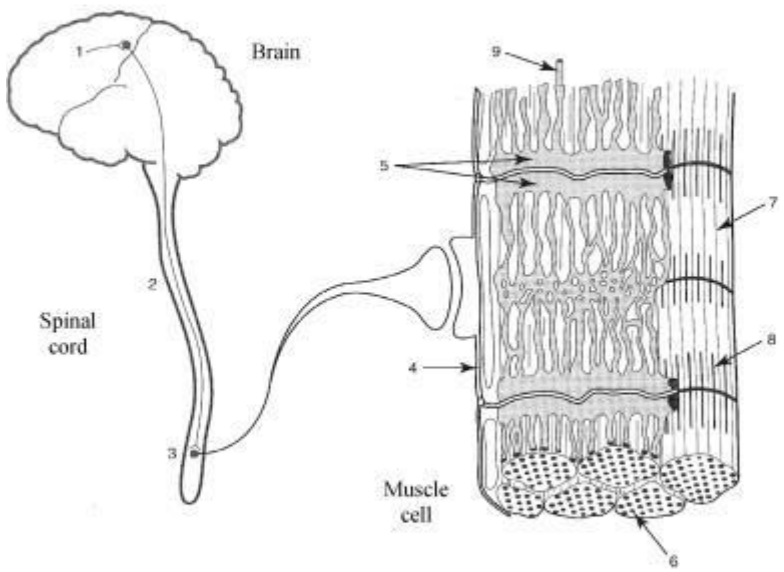


Figure 2: Sites which can contribute to neuromuscular fatigue. [15]

According to Boyas et. Al., fatigue may be due to “alterations in: (1) activation of the primary motor cortex; (2) propagation of the command from the central nervous system to the motoneurons (the pyramidal pathways); (3) activation of the motor units and muscles; (4) neuromuscular propagation (including propagation at the neuromuscular junction); (5) excitation-contraction coupling; (6) availability of metabolic substrates; (7) state of the intracellular medium; (8) performance of the contractile apparatus; (9) blood flow”. [15] The numbers correspond to the numbers in Figure 2.

In this study we are trying to keep non physiological factors to a minimum and just focus on the difference between muscular fatigue and central fatigue.

For example, we told the participants to breathe regular, if we notice that they are holding their breath. In addition, we cheer at the participants to keep them motivated during the fatigue protocol, where they should continue as long as possible. Another thing that keeps them motivated is that the visual feedback is designed like a game and a high-score is shown for the fatigue protocol, which increases for the time they hold their strength. We observed that the feedback really motivated participants. Another important factor was not to give them visual feedback of their strength during the control task. This way we limited their way of cheating.

3. EXPERIMENT

3.1. Concept and Aim

The idea behind the experiment is to measure EEG and EMG when participants are fatigued and before they are fatigued and then compare the differences.

To get a relative equal result between subjects, the whole experiment is based on the maximal strength of a particular participant. All following steps are based on the maximum voluntary isometric contraction.

The Aim is to analyze differences between pre and post fatigue in the EEG signal, as well in the EMG signal. Because this study is one of its first kind, another goal of this study is to find out how the study can be improved, or even if it is possible, to collect a good EEG signals because there are many factors that could cause artifacts in the signal. Another aim is to keep artifacts low while still performing a movement that is distinctive in its brain-signals from the baseline. The movement should also be easy repeatable while isolating the activity to the target muscle and minimizing the activity of the complimentary muscles. In our case, the bicep is examined.

3.2. Devices

3.2.1. EEG Device

For this study, a Brain Products actiCap EEG cap has been used for the EEG recordings. The system consists of 64 EEG channels. The EEG data has been sampled at 1000 Hz and bandpass filtered between 0.3 Hz and 100 Hz, notch filtered at 60 Hz and amplified using the Scan4.5 software and Synamps 2 EEG system made by Compumedics Neuroscoan.

The electrodes have been arranged in the following conventional system as seen in Figure 3.

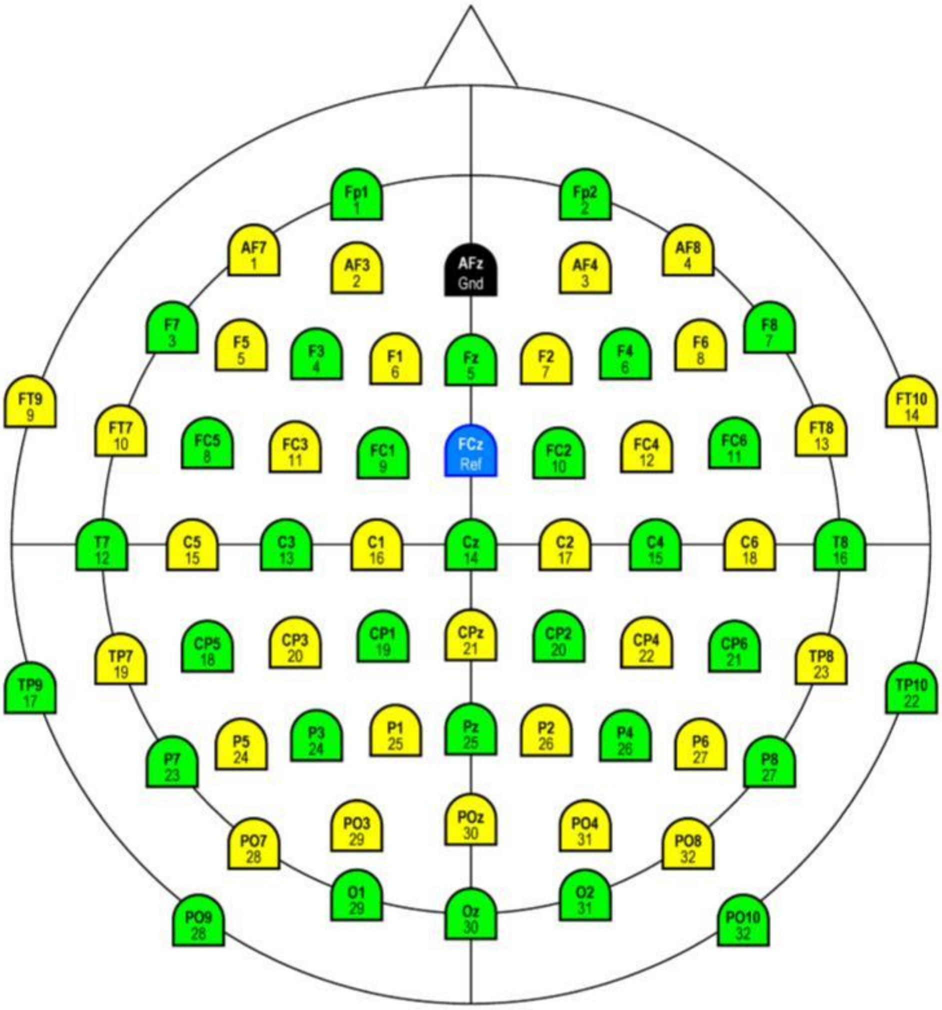


Figure 3: electrode arrangement actiCAP 64Ch Standard [16]

Figure 3 shows the top view of the head, and the triangle symbolizes the nose of the participant. The green holders are channel 1 to 32, and the yellow holders are channel 33 to 64. All electrodes are measured relative the reference electrode (FCz). A common average reference was computed which included the reference electrode after performing ICA on the data.

All EEG analysis has been done using custom made MATLAB scripts and the EEGLAB toolbox as well as AMICA.

3.2.1. Load Cell

The multi-axis load cell from JR3 is placed under the elbow. It measures forces in all three directions Fx, Fy, Fz, as well as the torques Mx, My, Mz. The output of the cell is voltages which have to be multiplied by a calibration-matrix to decrease the influence that the different measurements have on each other and to calculate the forces and torques in Newton or Newton-meter. The calibration-matrix has been taken from the load cells datasheet, which was obtained from the company after sending them the product-number. The corresponding MATLAB code can be seen in Codesegment 1.

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Calibration-Matrix for JR3
    calM = [257.4515 1.2728   2.8379   -16.3030 -0.3915   2.9903;
            -1.5063  256.4283 4.8946    0.8930  -7.4755   6.6240;
            4.3315   6.6633   519.3389 -24.8055 -12.2427 -14.0422;
            0.5118  -0.6559  -0.9117    51.3819 -0.1980  -0.1019;
            0.5431   0.3665  -0.4663   -0.1307   51.9586  0.1797;
            -0.0517  0.5528   0.6838   -0.3226  -0.6192   47.4418];

            ForceMatrix = (calM*Voltages')'; %Calculate Forces and Torques
```

Codesegment 1: Calibration Matrix and Force calculation in MATLAB

The calculation is a simple matrix-multiplication. The Voltage matrix is a time in ms times 6 matrix, for the 3 forces and the 3 torques.

3.2.2. EMG Device

For this study, an IA Trigno wireless EMG system made by Delsys has been used to record EMG signals. The EMG data has been sampled at 1000 Hz, bandpass filtered between 10 and 350 Hz and amplified by 1000. Recordings have been obtained from 7 muscles, which can be seen in Figure 7.

3.2.3. Biodex Chair

The Biodex chair allows us to individually adjust the setup to the measurements of each participant. Measures that are important to make the recordings comparable are the angle between biceps and torso.

Figure 4: Biodex Chair

3.3. Software

3.3.1. LabView

LabView v11.0 has been used for data collection and to control the whole experiment. There are 3 important VI’s: “CPSF” which is the main program, “display” which shows the interface for the participant on the second screen, and “global” which consists of a few global variables for displaying the angle, at which the participant is pulling. The VI “global” has been implemented at a later stage of the program. In hindsight, it would be better to use more global variables for less complicated interactions between the main program and “display”. Another improvement would be the use of a more consistent state-machine as basis because there are parts in the codes, which are redundant.

The main program in Labview “CPSF” is a relatively big program and will be discussed here just on the surface. The entire program was a development over several weeks. The user-interface which is used by the researcher to control the experiment can be seen in Figure 5. It shows two big graphs where in one all normalized EMG activity is displayed over a time of 60 seconds and another graph with the calculated rotated torque in the elbow. It also shows if it is recording or not, and a lot more details which will not be discussed in this paper.

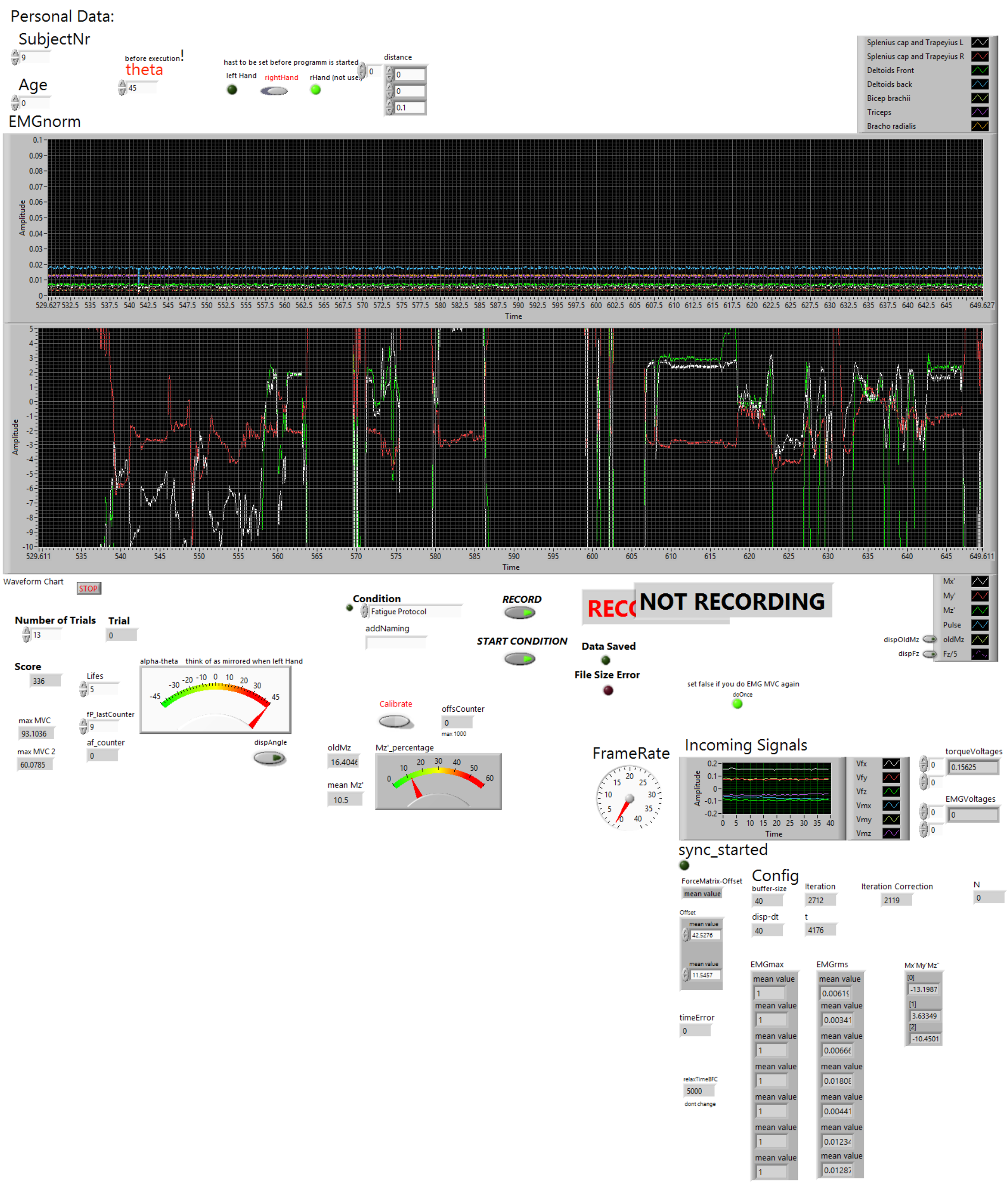


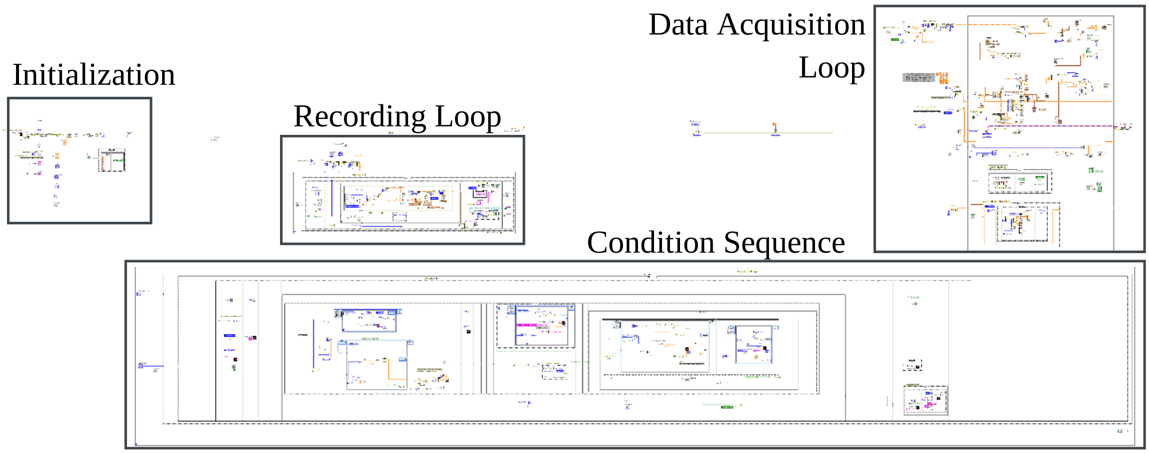
Figure 5: Researcher Interface of the main Labview Program

The backend of the program can be seen in Codesegment 2. The main parts are the initialization of the variables, the recording loop of the program, the data acquisition, the calculation loop as well as the condition sequence. The recording loop initializes a huge array when the program starts. It has enough capacity to store data for 20 minutes. Data gets written into this array and will be saved at the end, when the recording Boolean is set to false. This ensures a much more efficient program, although data gets lost if the program is terminated before the recording loop ends, and the data is saved as a file, under the current condition name.

In the data acquisition loop, the program gets the raw data from the DAQ (Data Acquisition), ergo the DAQ tower (see Figure 9: Experimental Setup). The raw data will be split into EMG and force data, and the mean will be calculated over time, to remove artifacts. Afterwards the force voltage data will be multiplied by the calibration matrix to get the force in Newton and torque in Newton-meters. This data will be transformed to get the torques in the elbow (see 3.5.1. Force Data).

The RMS over the EMG data over a window of 200ms is calculated and normalized based on the first sequence: Baseline EMG, where the subject engages every muscle to a maximum.

In the Condition Sequence every condition (see 3.4.4. Conditions) will be passed through. It also sets the participant view (see 3.4.5. Participant View) by calling "display", a second VI program.



Codesegment 2: LabView Main Program CPSF

The second important program is the "display" which draws the participant view, and instructs the subject. Based on the condition it is given it draws a different window. In the condition "Before Fatigue Condtion" it draws a bird on a fixed x-position, and moves in y-position based on percentage of Mz* (the transformed, rotated torque in the elbow). The given x-position to the VI corresponds to the background, which is a red step that gets closer to the bird and instructs the participant to produce a torque, to get over the step. All in all this represents a game, where the participant tries to steer a bird by creating an isotonic muscle contraction, which creates a torque.

3.3.2. Matlab

Matlab R2016a and 2014a were used for data preprocessing, such as loading in, filtering, calculation from raw data, as well as analysis of the data. The main programs are:

- "Kinematics_analysis" which looks at the muscles involved during the trial, "EEG_Processing" which compares different trials and EEG channels and lets the user reject trials that stand out
- "EEG_ICA" runs the Amica ICA analysis, and lets the user remove components to get rid of artifacts in the EEG signal and
- "EEG_Analysis" which plots the spectrogram or the time signal of a given EEG file
- and many more

The steps for data processing will explained in more detail in section 3.5.

3.3.3. Trigno Control Utility

Delsys Trigno Control Utility 2.6 was used to pair the electrodes with a certain channel, and start the recording. It shows the user also how good the batteries of a certain electrode is. Pairing sensors and placing the right ones on the right muscle has to be done carefully, because those could be interchanged by accident easily.

3.3.4. Acquire

The program Acquire 4.5 from Neuroscan has been used to record EEG signals. It also records the pulses from the DAQ sent by the controlling PC. Those pulses are sent out each time the participant gets the command to move, and have the purpose to synchronize the EEG data with the EMG as well as the kinematics data.

3.4. Methods

3.4.1. Participants

Eight participants volunteered in this study. Two out of which had a stroke. The participants are listed in the following table. The paretic arm of the two stroke subjects was examined, which was in both cases the right hand.

Table 1: Subjects

Subject Nr.	Stroke	left Hand	female	age [years]
1	0	0	0	28
2	0	0	0	22
3	0	1	1	23
4	0	0	0	19
5	0	0	1	22
6	0	0	1	23
7	1	0	0	57
8	1	0	1	67

Both stroke subjects reported that they do not suffer from post stroke fatigue anymore, but did so after they had their stroke.

3.4.2. Experimental Setup

The setup of the devices and their connection can be best described in Figure 6: Overview of Setup and used Devices.

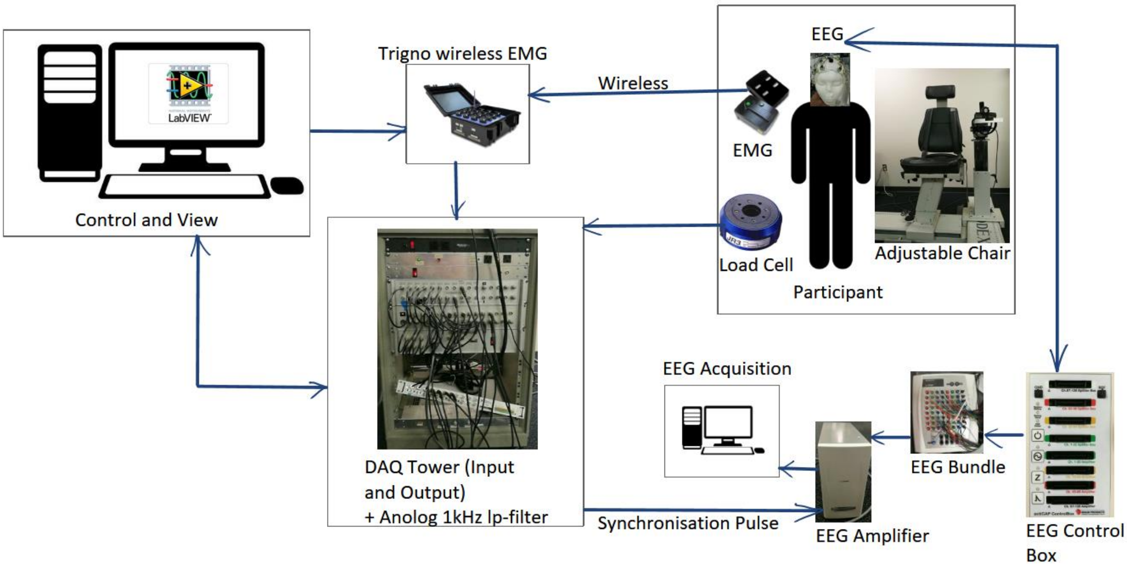


Figure 6: Overview of Setup and used Devices

There were two PC's involved in controlling and recording the experiment. One was used to control the experiment and the other one to record the EEG data. The Control and View of the whole experiment was done through LabView and Trigno Software. The LabView program that was created for this experiment, will be described in subsection 3.3.1. Trigno was used to sync up with the wireless EMG Station and select which of the sensors is on which channels. The channels from the EMG Station, as well as the 6 channels from the load-cell are read through the Data Acquisition (DAQ) tower. The DAQ tower filters the signals via an analog low-pass at 500 Hz (half of the sampling frequency fs=1kHz). The raw voltage data for the EMG and the load-cell is read trough the PC Control and View in LabView. The DAQ tower also sends out a synchronization pulse to the EEG Amplifier source, which is read in and stored at PC2 for the EEG acquisition. After amplifying the EEG signal, it is read in and stored via the software Neuroscan Scan4.5.

3.4.3. Procedure

The first step of the experiment was to introduce the course of the experiment to participants. They were asked to fill out a form, and told that they are participating voluntarily and therefore have the right to abort the experiment at any time.

After that, their head-size was measured and the proper EEG-cap prepared. While all electrodes were inserted in the right manner, the other researcher placed the EMG-electrodes on their proposed position, which can be seen, in Figure 7.

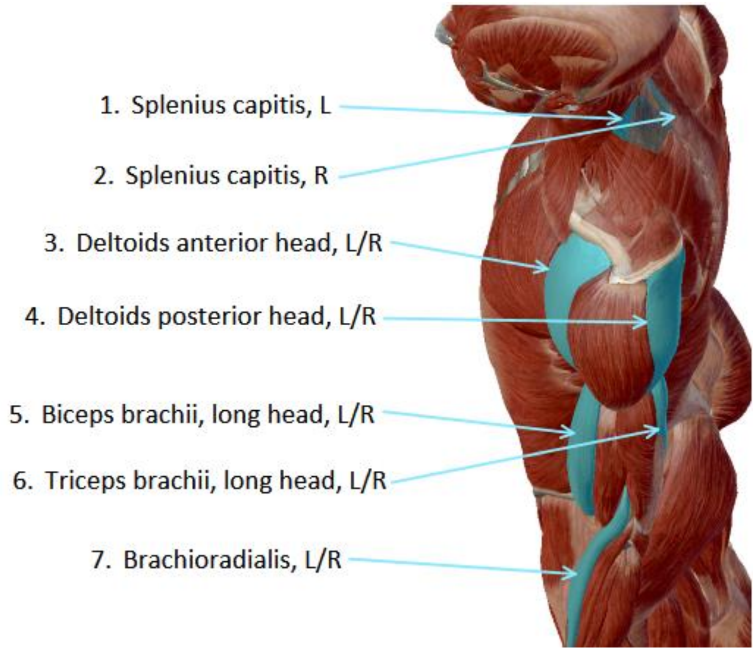


Figure 7: Observed Muscles

The first two muscles are particular hard to isolate by placing the electrodes. It is likely that there is also muscle activity from the nearby trapezoid involved.

All muscles from three to seven are dependent on the arm which was used in the experiment. The skin was cleaned and lightly abraded before placing the electrodes on the muscle. Before the experiments, maximum voluntary isometric contractions were recorded in order to normalize the EMG data for analysis and to make muscle-activity comparable throughout the study.

After that a maximum voluntary contraction of each muscle was performed, to later normalize the EMG data to the maximum.

After the EEG electrodes were placed in the cap, the cap was strapped on the head and aligned so that the reference electrode is symmetrically placed between the ears.

Gel was inserted to ensure low impedance and the participants sat on the chair, which was adjusted. The chair can be seen in Figure 8.

Figure 8: Adjustable Chair

The elbow was placed over the center of the load cell with the forearm resting on the platform which also can be seen in Figure 9 where the origin-matrix is placed. The subjects were strapped down over both shoulders. Their angle between their upper hand and their body, henceforth called theta was measured.

The subjects then used the gripper while performing the isometric elbow flexion. The shoulder abduction angle from the body was measured and the Biodex chair was moved closer to the load cell or elevated to ensure that this angle remained between 25 and 40 degrees. As the torque is measured and calculated at the elbow joint, the shoulder flexion/extension angle was maintained at 0 degrees. The measured shoulder abduction angle was then used for the calculation of the rotation matrix to change the reference coordinate system from the geometric center of the load cell to the elbow location over the load cell.

Participants were later instructed to pull in this angle and guided throughout the experiment verbally to maintain this direction. Figure 9: Experimental Setup shows the direction in which the participants were instructed to pull. Fh (green arrow) was chosen because it best isolates the muscle and this task can be performed for a longer time. If theta would have been around 50 to 90 degrees, blood-flow to the muscles would be constrained over time, which would cause fatigue due to lack of energy supply to the muscle, which should be as low as possible. A higher angle (between 20 and 0) could not have been performed due to the setup.

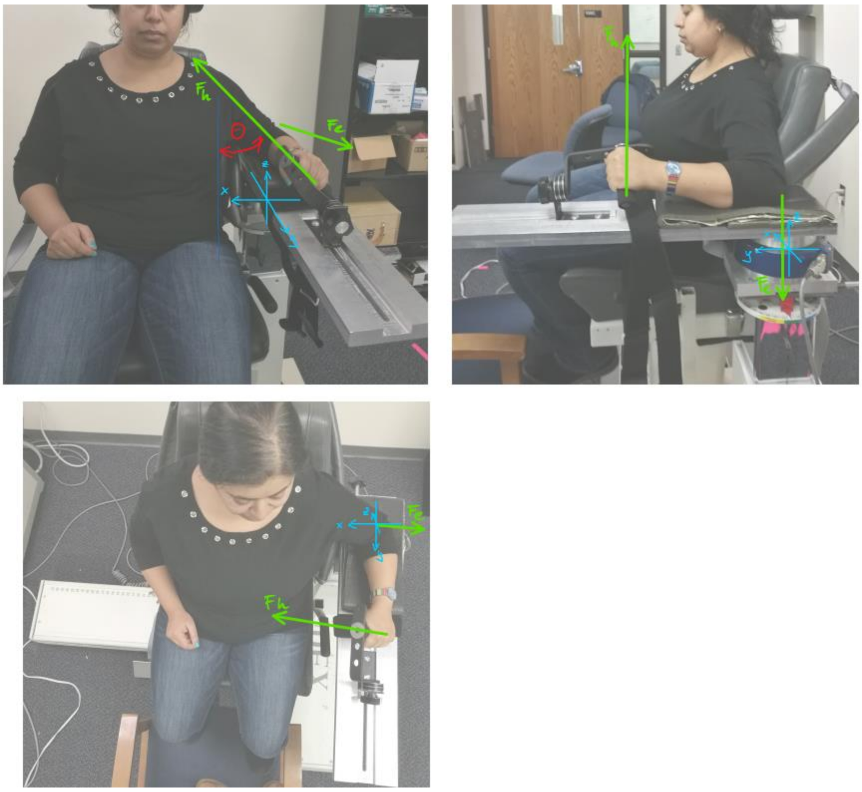


Figure 9: Experimental Setup

Another important issue is how the wrist is placed. We decided to set the wrist parallel to the movement, as it can be seen in Figure 9: Experimental Setup. Having the wrist perpendicular would be more intuitive to isolate the muscle as much as possible, but when the movement is performed over a longer period puts much more pressure on the wrist. This is due to the fact that the wrist is longer on one side, and can therefore withstand a greater moment.

After the participants were placed on chair based on the guidelines, a general baseline EEG signal was recorded for 3 minutes, in which the subjects had to close their eyes and were instructed not to think of anything specific.

After the baseline, the visual feedback was explained to the participants, which can be seen in subsection 3.4.5. Participant View. They had a few trials to get to know the new device, and to get a feeling in which direction they were pulling, they got a visual feedback which was later removed, in order not to influence the EEG signals. When participants were later pulling in the wrong direction, they were guided verbally.

After they were familiar with the interface, and had no further questions, the conditions for the experiment could begin.

A time-lapse of the whole experiment can be found via this link only:

https://www.youtube.com/watch?v=arqt9DdaU_A and is highly recommended.

3.4.4. Conditions

The course of the experiment can be best described by the following diagram seen in Figure 10: Course of the study. The Torque is measured by the load-cell and is the result of an isometric contraction of elbow flexion as well as biceps flection. The grey arrows describe iterations and the percentage values are based on the Baseline MVC.

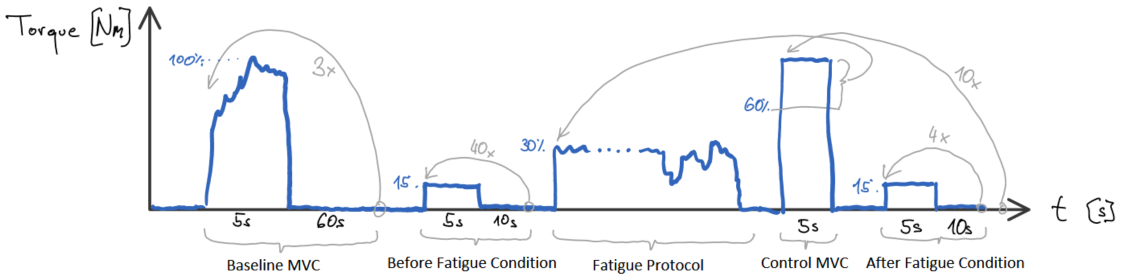


Figure 10: Course of the study

There are 5 conditions in this study. The Baseline MVC to determine the maximal strength (max MVC), the Before Fatigue Condition to determine the brain signals before fatigue followed by the Fatigue Protocol to get the participants fatigued. Right after that, a Control MVC takes place to check if the person is fatigued. If the person is considered as not fatigued (strength is above or 60% of max MVC), the participant has to go through the Fatigue Protocol again. If the persons Control MVC is below 60% of max MVC the After Fatigue Condition can begin. The After Fatigue Condition is the same as the Before Fatigue Condition but different because it is intermitted by Control MVC's to check if the person is still fatigued. A more detailed description of the different condition follows.

3.4.4.1. Baseline MVC

After doing the maximum contraction for every muscle, to later normalize the EMG, the actual experiment starts with 3 Baseline MVCs (maximum voluntary contraction) to determine the maximal strength of the participants. Here we examine the force data. In between those 3 Baseline MVC's one minute of resting is required to recover. This is necessary to adjust the following tasks dependent on the strength of the participants. The max MVC is determined by finding the max value in the recorded data and calculating the median around 100ms before and after the maximum value.

3.4.4.2. Before Fatigue Condition

This condition consists of 40 trials. Each trial starts with a 15% of the max from the previous condition for 5-seconds and a 10-second resting period. The participant gets its instructions to pull from a flying bird that he controls with their arm.

3.4.4.3. Fatigue Protocol

After the Before Fatigue Condition the person has to be fatigued. This is done in the Fatigue Protocol. During the Fatigue Protocol, the subject performs a sustained submaximal contraction. It consists of an isometric contraction at 30% of max MVC. The contraction is held as long as possible. If the contraction drops below 20% of the max MVC for more than 2 seconds for five times the person is considered as fatigued. The participant is engaged by the surrounding people to hold through as long as possible.

3.4.4.4. Control MVC

Right after the Fatigue Protocol the participant has to contract as strong as possible. This condition lasts 5 seconds. If the maximum torque is 60% or over 60% of the max MVC, the participant is considered not to be fatigued and has to perform the Fatigue Protocol again.

If the maximum torque of the Control MVC is under 60% of the max MVC from at the beginning, the participant is considered as fatigued and has to perform 4 trials of the After Fatigue Condition.

3.4.4.5. After Fatigue Condition

The After Fatigue Condition is also at 15% of the max MVC for 5-seconds followed by a 10-second resting period but just for 4 times. After 4 of those trials, a Control MVC is taken. If the person is still considered as fatigued, another 4 trials will follow. 10 groups of those 4 trials will be taken, so that in total there are 40 trials at 15% of max MVC for 5 seconds and 10 seconds resting to compare to the 40 trials of the Before Fatigue Condition.

3.4.5. Participant View

The Participant-View provides a feedback for the movement and instructs. It was created using LabView and is controlled via the main labview program. Following figures in Table 2 show screenshots during the experiment. The number under the pictures corresponds to the position in Figure 11.

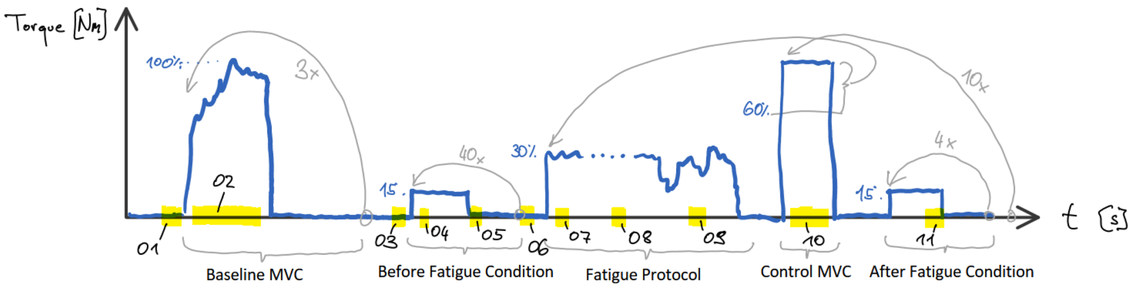
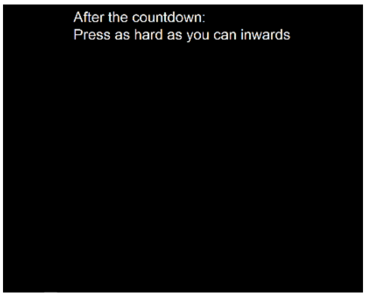
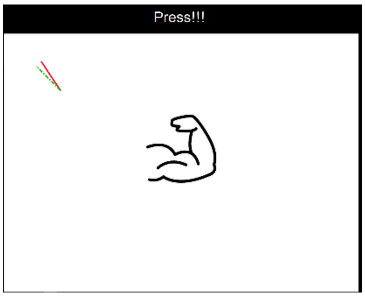
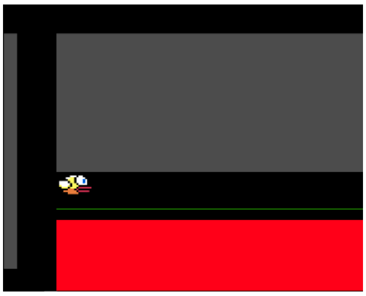
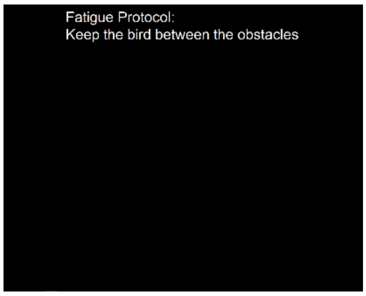
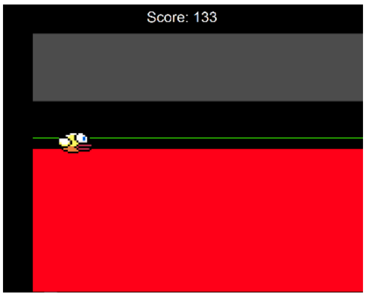
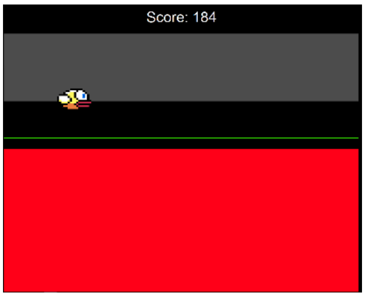
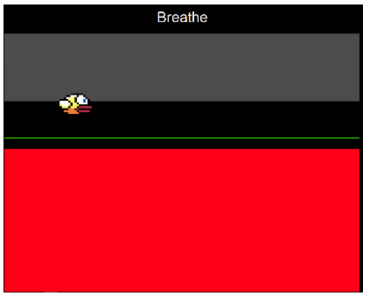
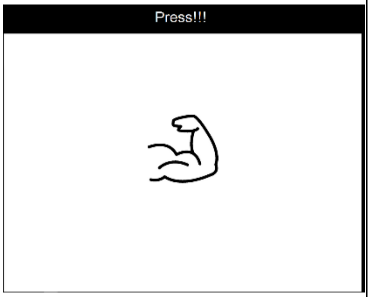
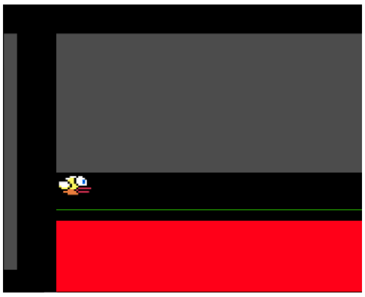


Figure 11: Conditions with corresponding User Interface

Table 2: Participant View Screenshots

		
01User is instructed	02 Baseline MVC	03 Getting ready

		
04 Before Fatigue Cond.	05 Before Fatigue Cond.	06 Instruction Fatigue Prot.
		
07 Fatigue Protocol	08 Fatigue Protocol	09 Fatigue Protocol
		
10 Control MVC	11 After Fatigue Cond.	11 After Fatigue Cond.

In Table 2: Participant View Screenshots, picture "02 Baseline MVC" the visual feedback can be seen, that shows the participants in which angle they are pulling. This feature can be brought up at anytime by the click of a button, but should not be shown during the before fatigue condition and the after fatigue condition.

3.5. Data Processing

3.5.1. Force Data

The force data is in the same file as the EMG data and contains pre-filtered data as well as raw data. The pre-filtered data is usually mean filtered over a period of 50ms, which would account for a 20 Hz Signal. The raw force data is multiplied by the calibration matrix to convert the voltages to forces or torque and later via a "Savitzky-Golay-Filter" of the order 6 over a time-window of 201 ms filtered, because there are many artefacts in the form of spikes in the raw signal. Also there is an offset in the raw voltage data which would have to be calculated either before a movement or once before the whole experiment. It is difficult to find a period, where one can be certain that the arm is resting, by just looking at the raw data. Sometimes participants would also move their hand during a resting period, which would account for a false offset. This is the processed data from LabView is used, which holds the force data without the offset. The offset has been calculated via the median of a certain period. The selected period is selected by looking at the participant and the force data. If there was a shift, which could have happened during the experiment because the participant was moving his arm a little bit, a new offset has been calculated and taken into account.

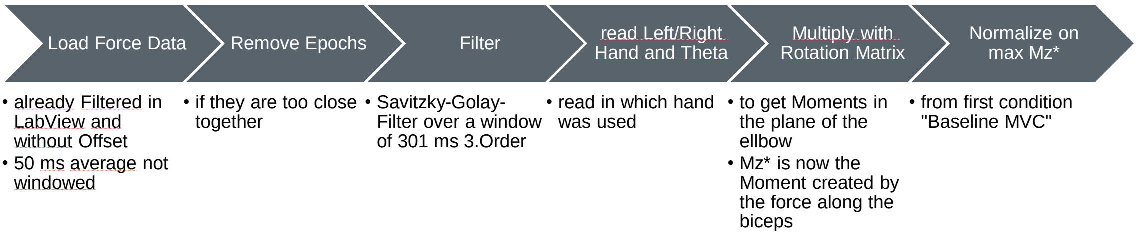


Figure 12: Processing Force Data

To calculate the torque in the elbow, the distance from the load-cell as well as the angle for the rotation has to be taken into account. Both forces and torques are multiplied by the rotation matrix that is based on theta, the angle between the upper-arm and the body. The rotation matrix also changes based on the arm that is used, because the load-cell rotates with the device.

$$rotM_{left} = \begin{bmatrix} \cos(90° - \theta) & 0 & \sin(90° - \theta) \\ 0 & 1 & 0 \\ -\sin(90° - \theta) & 0 & \cos(90° - \theta) \end{bmatrix}$$

$$rotM_{right} = \begin{bmatrix} \cos(90° + \theta) & 0 & \sin(90° + \theta) \\ 0 & 1 & 0 \\ -\sin(90° + \theta) & 0 & \cos(90° + \theta) \end{bmatrix}$$

To obtain the right moments in the elbow, the forces captured the load-cell have to be added by calculating the cross product from the distance of the elbow to the load-cell. The formula follows:

$$\begin{matrix} Fx_{rot} \\ Fy_{rot} \\ Fz_{rot} \end{matrix} = rotM \cdot \begin{matrix} Fx \\ Fy \\ Fz \end{matrix}$$

$$\begin{matrix} Mx_{rot} \\ My_{rot} \\ Mz_{rot} \end{matrix} = rotM \cdot \begin{matrix} Mx \\ My \\ Mz \end{matrix} + \vec{l} \times \begin{matrix} Fx_{rot} \\ Fy_{rot} \\ Fz_{rot} \end{matrix}$$

Mx_rot is later referred to as Mx*, the same goes for My and Mz. The distance vector $\vec{l}$ describes the distance between the elbow and the center of the load-cell.

3.5.2. EMG Data

The EMG files have to be shifted for 48 ms because of their delay. This accounts for a shift of 48 indices, because the data is recorded at 1kHz. After that the EMG Data is also Notch filtered at 59 to 61 Hz to remove the grid frequency with a Butterworth filter of the order of 4. After that it is bandpass filtered with the same filter type at the frequency from 10 to 350 Hz. The filtfilt function in Matlab has been used to minimize the delay a filter would normally cause. After filtering the EMG data, the RMS (Root Mean Square) is calculated over a time-period of 200ms. The EMG is afterwards normalized based on the first procedure in the experiment, which determined the maximal voltage of the particular muscles at maximum voluntary contraction per muscle.

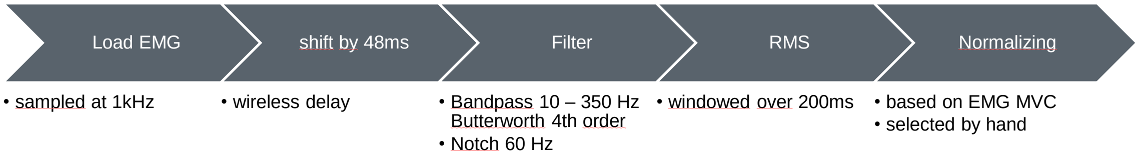


Figure 13: Processing the EMG Data

3.5.3. EEG

After loading in the EEG data it is bandpass-pass filtered at 0.1 to 100 Hz with a Butterworth filter of the order 4. Furthermore, it is notch filtered at 59 to 61 Hz to remove the grid frequency.

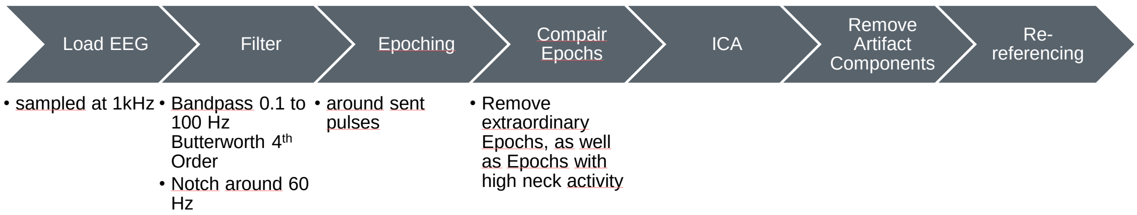


Figure 14: Processing the EEG Data

3.5.3.1. Epoching Data

One epoch represents one of the forty trials in the before fatigue condition or after fatigue condition. The Epoch is referenced in time from the pulse that is sent out, whenever the person should start their 15% MVC movement. The EEG-baseline which sets the offset is set at -5 to -4.5 seconds before the pulse or start of the movement. The movement takes 5 seconds, and the epoch data ranges from -5 to +10 seconds. The baseline is not taken after the movement, because it usually takes time to recover, especially in the after fatigue condition. The baseline should not be taken 3 seconds before the movement, because the brain is preparing the movement and therefore the EEG would not represent the baseline.

3.5.3.2. Neck Activity

One major factor for the quality of the EEG signals are artifacts like clenching the jaw, eye movement, or neck-muscle activity that is picked up by the EEG. This is why one of the first steps was to look at the normalized neck-muscle activity throughout the pulses and select pulses with high neck muscle activity to reject them. Figure 15 shows Subject 5 and the post-fatigue condition. High neck-muscle activity can be seen between trial 24 and 25. After every 4 trials the participant hast to perform a control MVC to check if the participant is still fatigued. This subject had a relatively stable neck-muscle activity throughout the trials. Only neck-activity around trial 1, 16, 22, 28, 31 are a little bit higher than the average. This is why these trials are rejected.

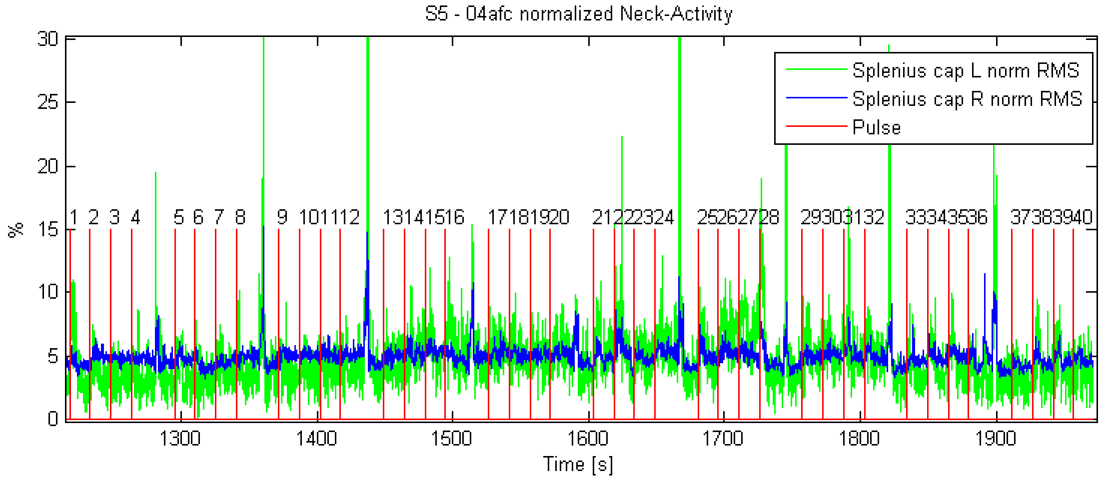


Figure 15: Normalized RMS Neck Activity example

Neck activity did go up a lot in this participant, which can be seen in Figure 16.

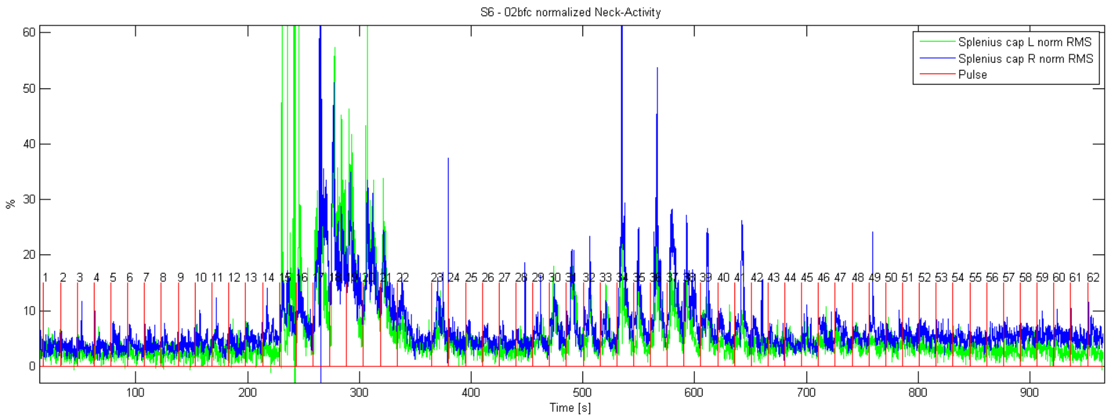


Figure 16: Normalized Neck Muscle Activity Subject 6 pre-fatigue Condition

This is why in this case more trials have been recorded, because a lot of trials had to be rejected because there was high neck activity involved which would interfere with a good EEG signal.

3.5.3.3. Correlation between trials

The second step in analyzing the data is to look at the variance between the different epochs in the before fatigue condition and afterwards between the after fatigue condition. The raw epoched EEG data was compared throughout the trials per subject and per condition. If there were for example trials that were high in variance compared to the other trials, those were excluded from the ICA (see 3.5.3.4. . The same happens with the channels. If one channel has a high impedance for example, it will look a lot different to the other channels. Unfortunately a noisy channel does not stand out after this analysis, this is why during the experiment it will be noted if a channel is noisy, and removed manually later. In general channels have not been rejected because they hold a lot of information and quality might vary throughout the trial, and ICA usually separates those artifacts relatively well.

3.5.3.4. ICA

ICA stands for independent component analysis. It helps to remove artifacts from the raw EEG signal such as eye-movement, eye-blinking, moving electrodes, high impedance on electrodes, as well as muscle artifacts. It is a blind source separation technique that looks for correlations within the data and groups those.

The AMICA [17] plugin is used to perform the ICA on the EEG data. The second paragraph of the Matlab script “EEG_ICA_Aim2” performs the ICA and saves it in the folder “AllComponents” in “ICA”.

The output of AMICA are different components and can be shown as a topographic map for each component. An important note to these plots in Figure 17: ICA Topography Output, where the color represents the source activity, blue meaning negative voltage and red positive voltage, but the sign does not really matter because it could be accounted for in the mixing matrix of the analysis.

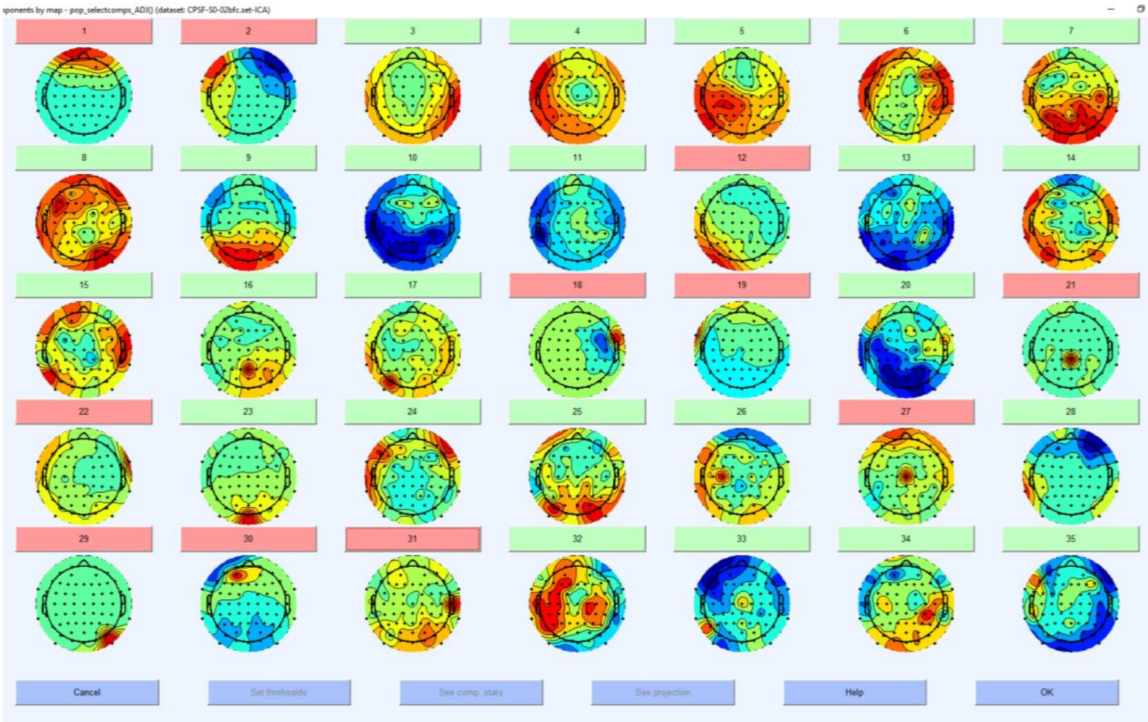


Figure 17: ICA Topography Output

In the first two components can be seen that the activity is mostly in the frontal are, and it seems it is off the scalp. This two components are eye-blink ore eye movements that got separated by the ICA an will be removed. Another strange component is number 21, which is very centered, and probably a bad electrode in a certain time of the experiment. All red selected components have been removed in this example.

Another visualization that one might look at is the spectrogram plot of the components which can be seen in Figure 18: Spectrogram of the Components. It shows the frequencies on the y-axis, and their amplitude as a color-map. The x-axis represents time whereby the whole time that is seen represents one epoch.

In Figure 18, Component number 18 is an artefact, because it is consistent throughout all frequencies. Frequencies above 50 Hz should not be in the components because that would be an indicator for muscle artefacts, which would be at a higher range. Componant 22 has been removed for that reason. Component number 12 is also mostly located at the left bottom of the back scalp (see Figure 17), which indicates neck muscle artifacts.

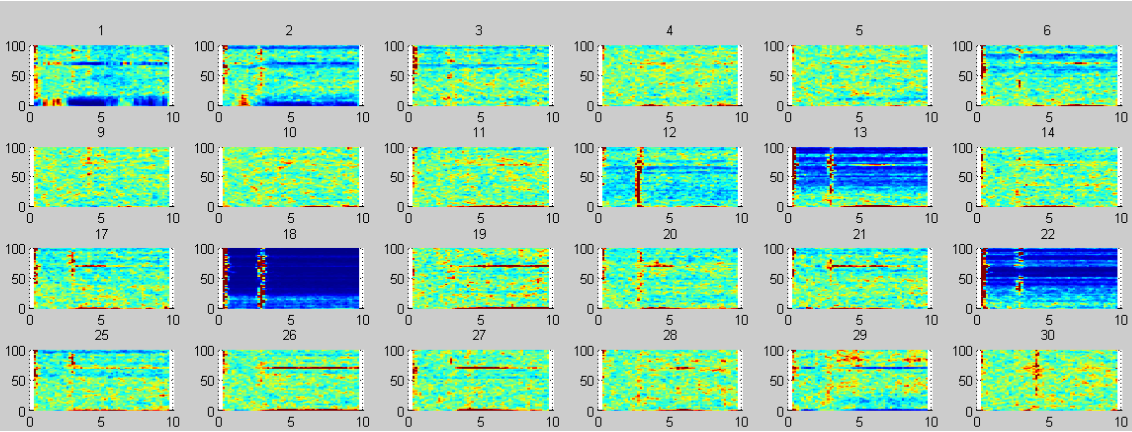


Figure 18: Spectrogram of the Components

After components have been removed, the data will be put together and re-referenced, so that the reference electrode is also taken into account. The output is the clear data, which will be analyzed and also compared to the raw data, to ensure no important components have been removed and the output is not very distorted.

4. Results

4.1. General Results

The following table shows all subjects and their max MVC from the 3 conducted MVC's as well as how long it took them after the pre-fatigue condition, in the fatigue protocol to be considered fatigued.

Table 3: Subject Result Overview

Subject Nr	Stroke	left Hand	female	age [years]	theta [°]	max MVC [Nm]	Time to first Fatigue [min]	Highscore
1	0	0	0	28	30	53.4	17.83	8300
2	0	0	0	22	30	53.3	10.5	12200
3	0	1	1	23	45	79.0	19.17	10300
4	0	0	0	19	30	49.7	28.33	14000
5	0	0	1	22	35	33.0	20.29	5200
6	0	0	1	23	35	33.1	17.1	5700
7	1	0	0	57	28	34.3	24.1	17070
8	1	0	1	67	32	10.0	29.91	36544

4.2. Force and Torque Data

4.2.1. Across the Study

Figure 19 shows all three torques for the baseline MVC where the max Mz* is calculated. To calculate the max, these torques have to be rotated and the forces with the distance have to be taken into account.

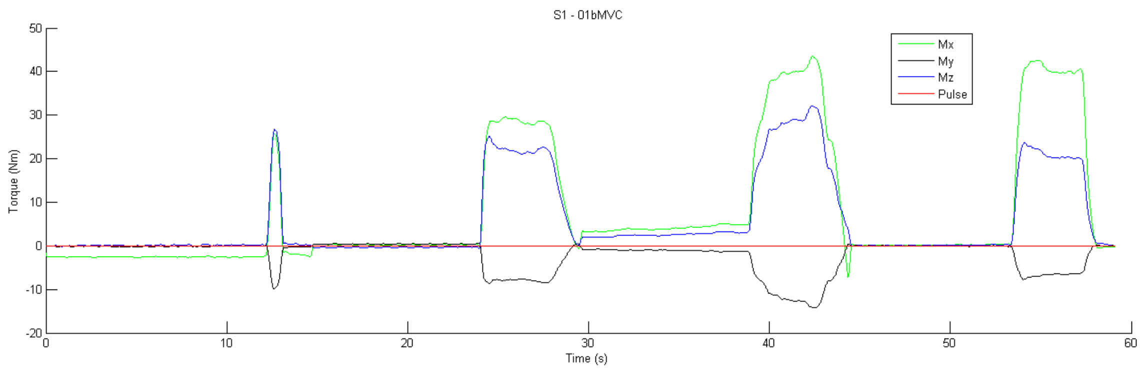


Figure 19: Baseline MVC Subject 1 Load-cell Torque

The torques in the elbow, which are calculated based on the principle in subsection 3.5.1. can be seen in Figure 20. The max MVC can be seen in the 3rd trial around 45 seconds which would be around 53 Nm. All conditions that follow will be based on that number. If the participant would just use his bicep there would almost be no Mx* or My*. The duration of the first MVC was obviously a test trial for the subject to get to know the experiment. The time between the different MVC's is longer then the time that is seen on Figure 20: Baseline MVC Subject 1 Elbow Torque.

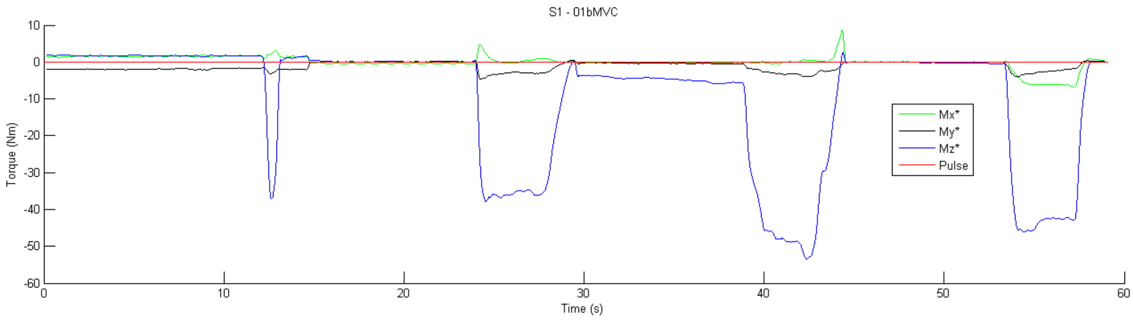


Figure 20: Baseline MVC Subject 1 Elbow Torque

The next condition is the pre-fatigue or before-fatigue condition, which can be seen in Figure 21. The red line stands for the pulse that is sent out to synchronize the EEG and shows around which point the epochs are based on.

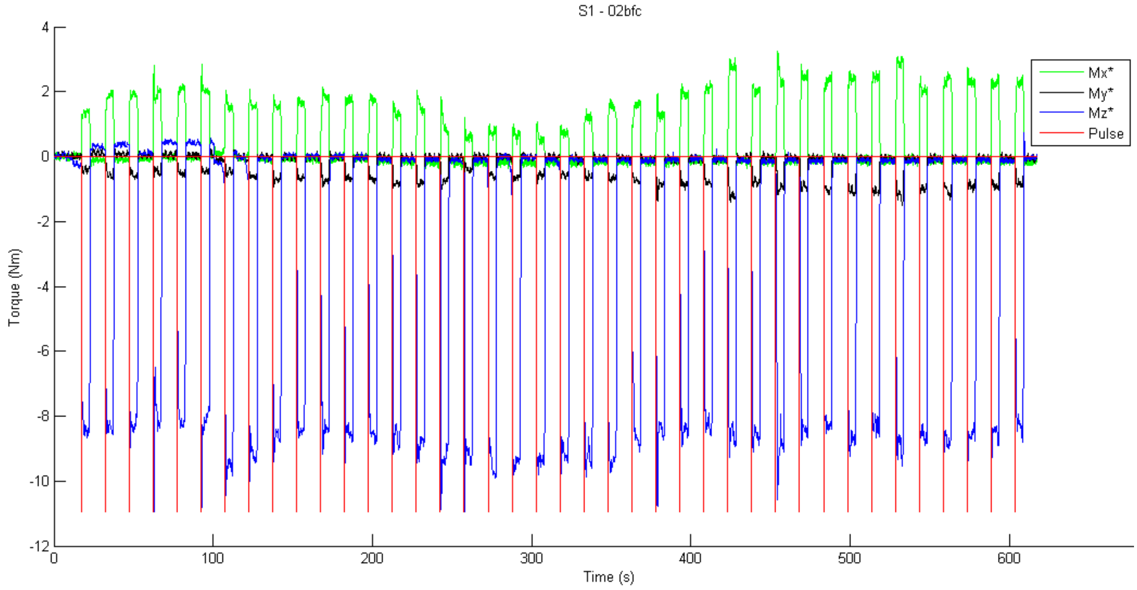


Figure 21: Pre Fatigue Condition Subject 1 Elbow Torque

After this condition the fatigue protocol starts, at which the participant has to hold at 30% of MVC as long as possible. It took this participant 1060 seconds to get fatigued. This would be around 18 minutes.

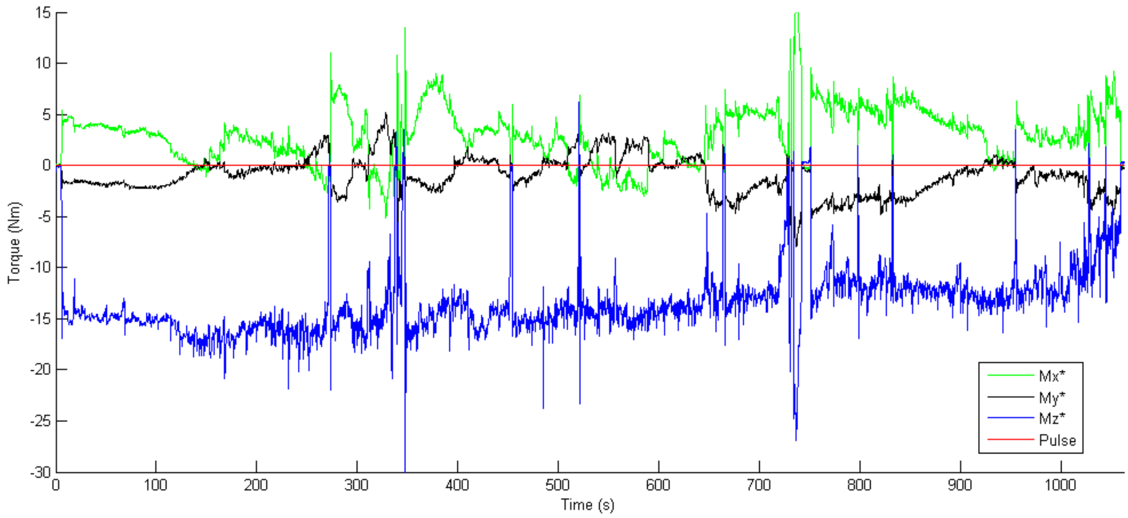


Figure 22: Fatigue Protocol Subject 1 Elbow Torque

After the person is considered as fatigued, a control MVC will be performed to check if the person is fatigued. After 4 trials at 15% MVC the person had to perform a control MVC again. This can be seen in the Figure 23. It also can be observed how the subject recovers over time by looking at the amplitude of the control MVC at around 1150, 1220, 1280, 1350, … There is a clear trend recognizable. If observed closely, one can see an error in Figure 23. There is not control MVC before the fatigue protocol started (at second 17050). This is due to a file size error, in which the program had to be restarted.

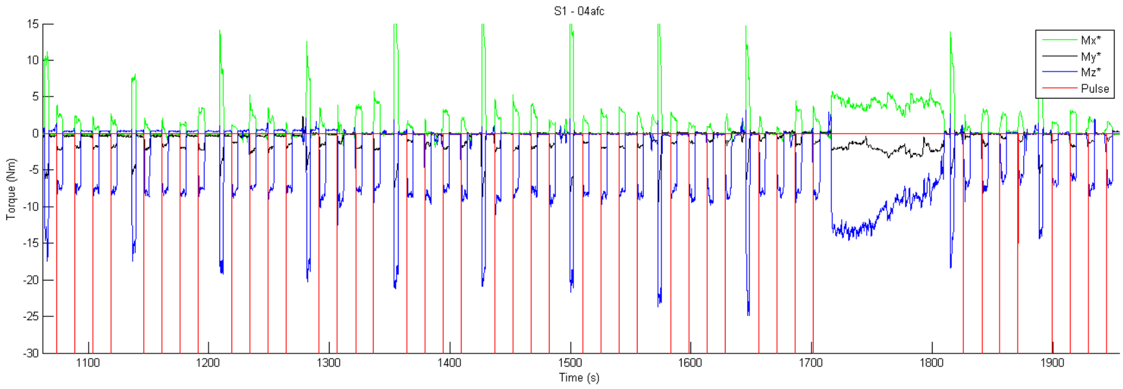


Figure 23: Post Fatigue Condition Subject 1 Elbow Torque

This trend is not always that clear. If we look at subject number 3 which was left handed and therefore the My* is switched in its sign. After 36 trials, the person was not fatigued anymore (second 1790) and had to perform the fatigue protocol again which subject 3 could perform for around 9 minutes and was considered as fatigued after that.

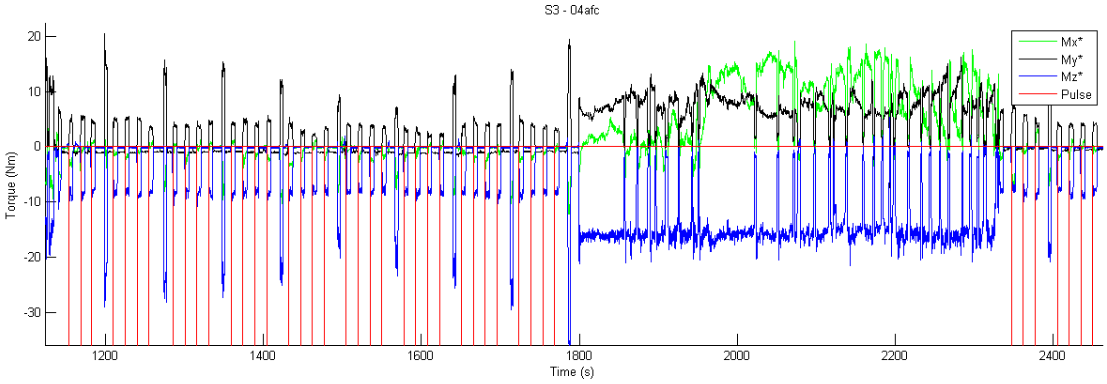


Figure 24: Post Fatigue Condition Subject 3 Elbow Torque

4.2.2. Epoched pre/post fatigue average

Figure 25 shows the data from the load-cell which was multiplied by the calibration matrix. The torques, are the calculated torques in the elbow also based on the maximum MVC Mz*. The forces, are the forces measured by the loadcell, divided by max Mz* from the first condition. It also just shows the epoched data around every 15% movement in the pre-fatigue and post-fatigue condition separate. Trials that have been rejected are taken into calculation.

The mean that has been calculated is a mean across all trials from all healthy participants. The mean across all subjects has not been taken because there is more information and a more accurate standard-deviation than just taking the mean from subjects and taking the mean of that result.

The feedback that the participants have received is based on Mz*, this is why it is relatively stable throughout trials. Fy would correspond to pushing forwards and would result in an Mx which would correspond to Mz* and Mx* in the elbow.

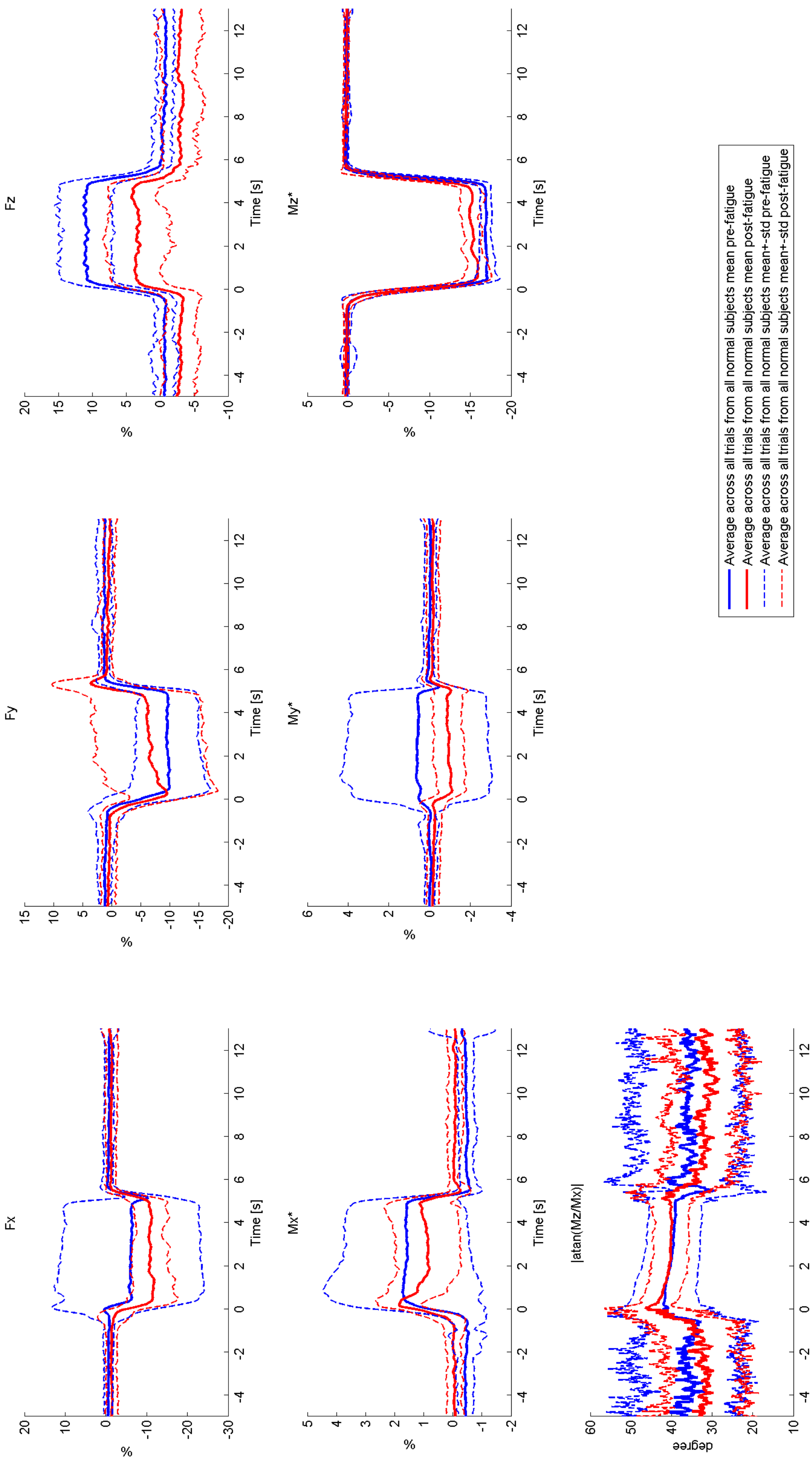


Figure 25: Force Average across Trials and Subjects Healthy Subjects

What can be seen in Figure 26: Force Average across Trials and Subjects Stroke, that most forces decrease on average from pre to post fatigue. The same can be observed in the elbow torque values. Here the standard-deviation shrinks from pre to post fatigue. Mz* is significant lower in post than in the pre fatigue condition in the 15% MVC period from 0 to 5 seconds. The standard deviation of My* decreases, and the mean changes its sign and therefore direction, but is still not significant compared to Mz*. (Note that the subplots have different scales in y direction). The average direction in which subjects were pulling remains the same, but decreases in its variability from pre to post-fatigue.

Because there were just two stroke subjects, it is hard to draw further conclusions. However, it can be noted that the movements from pre to post fatigue stayed relatively the same. This can be observed in Figure 26.

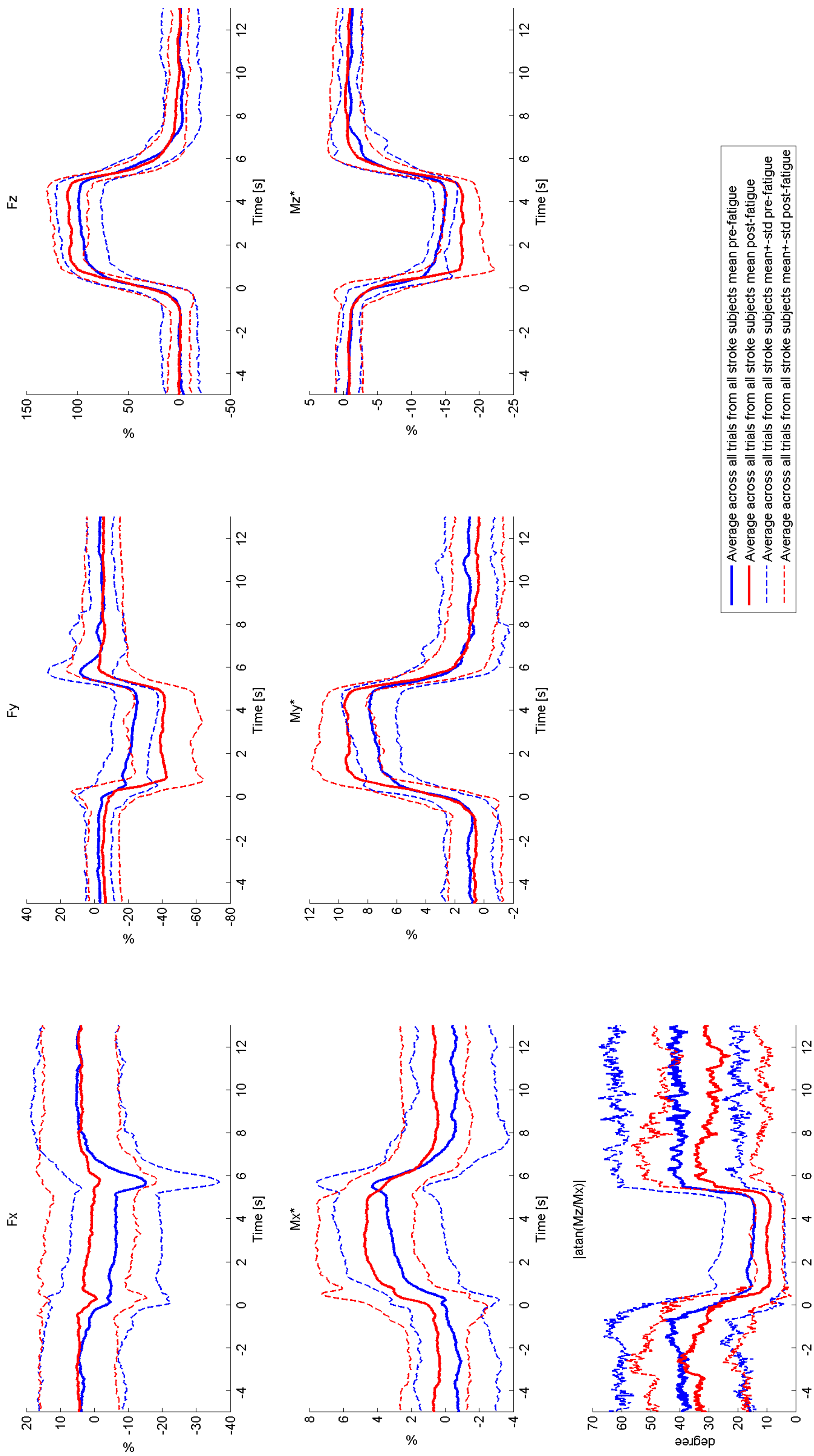


Figure 26: Force Average across Trials and Subjects Stroke

4.3. EMG

The following figures show the average across all valid trials for all healthy subjects (Figure 27) and for all stroke subjects (Figure 28).

Figure 29 shows the data of just one subject, in this case subject 7, a stroke participant. blue represents all epoched data but just for the post fatigue condition. It also shows the force data, normalized EMG RMS and how variable it is throughout the trials of this participant.All Force percentages are based on the max MVC.

Figure 30 shows a whisker boxplot where afc stands for post fatigue condition and bfc for pre fatigue condition. S stands for the Subjects. Subject 7 and 8 are stroke subjects.

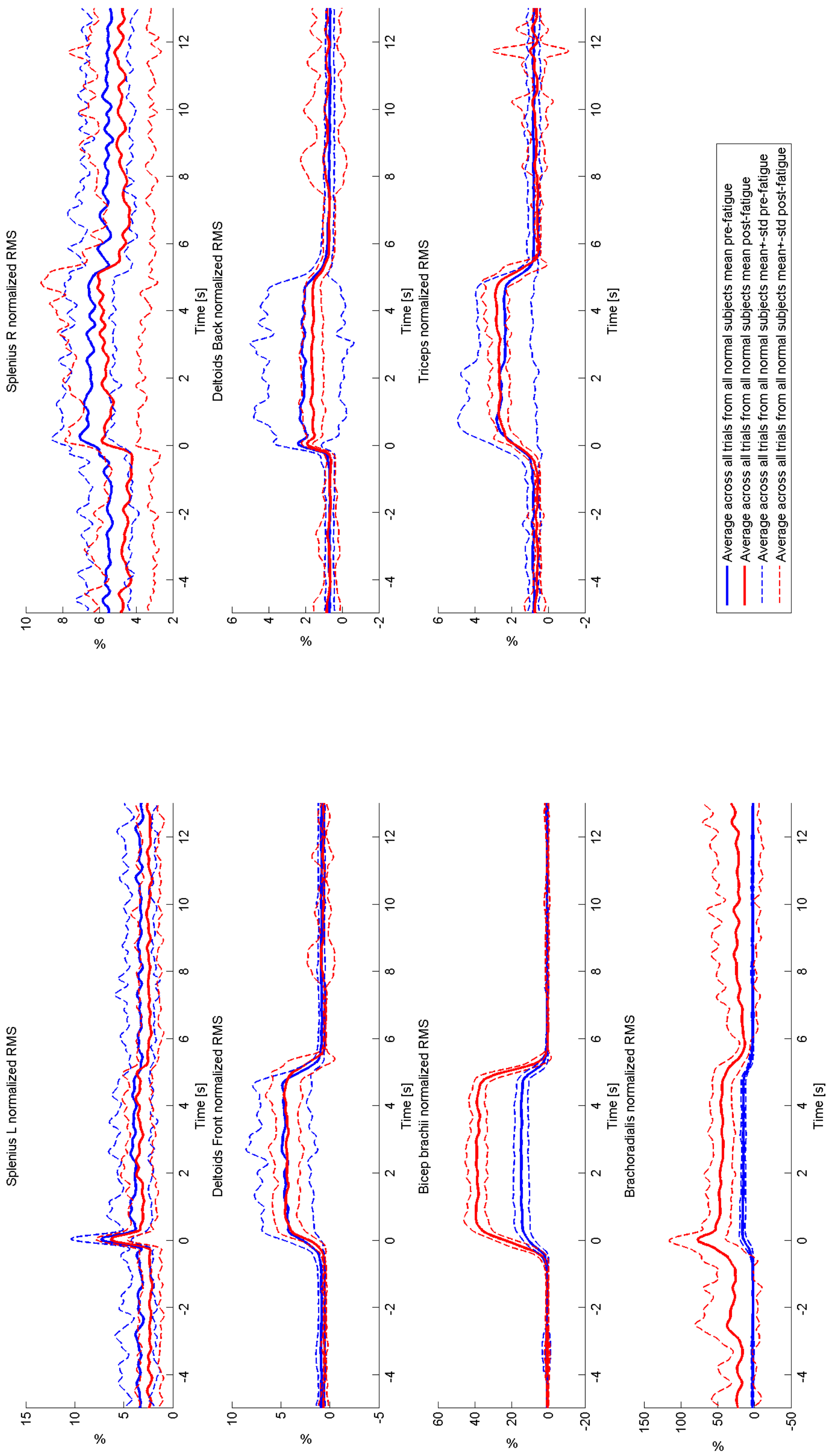


Figure 27: RMS EMG Average across all Trials from all Healthy Subjects

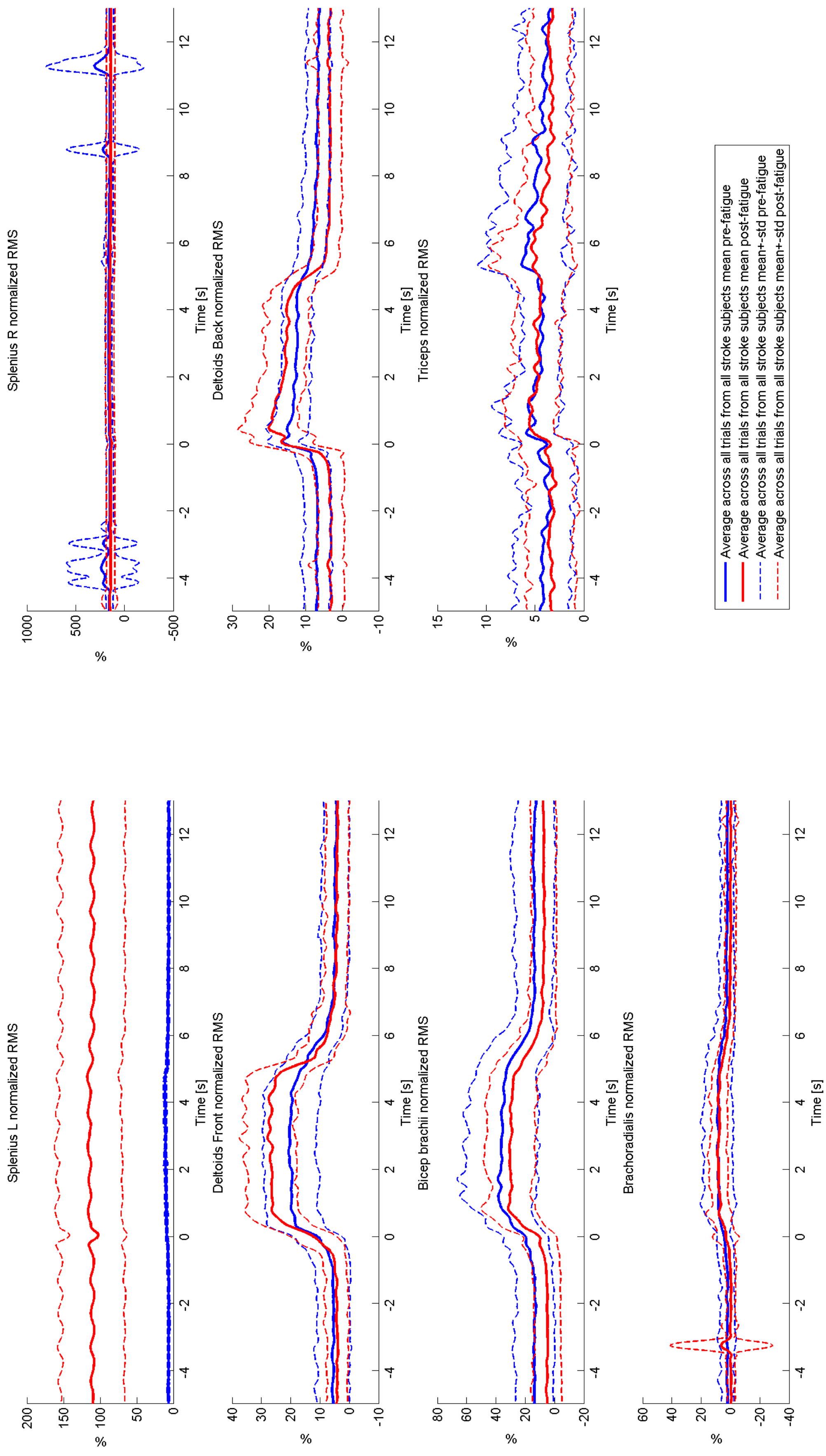


Figure 28: RMS EMG Average across all Trials across all Stroke Subjects

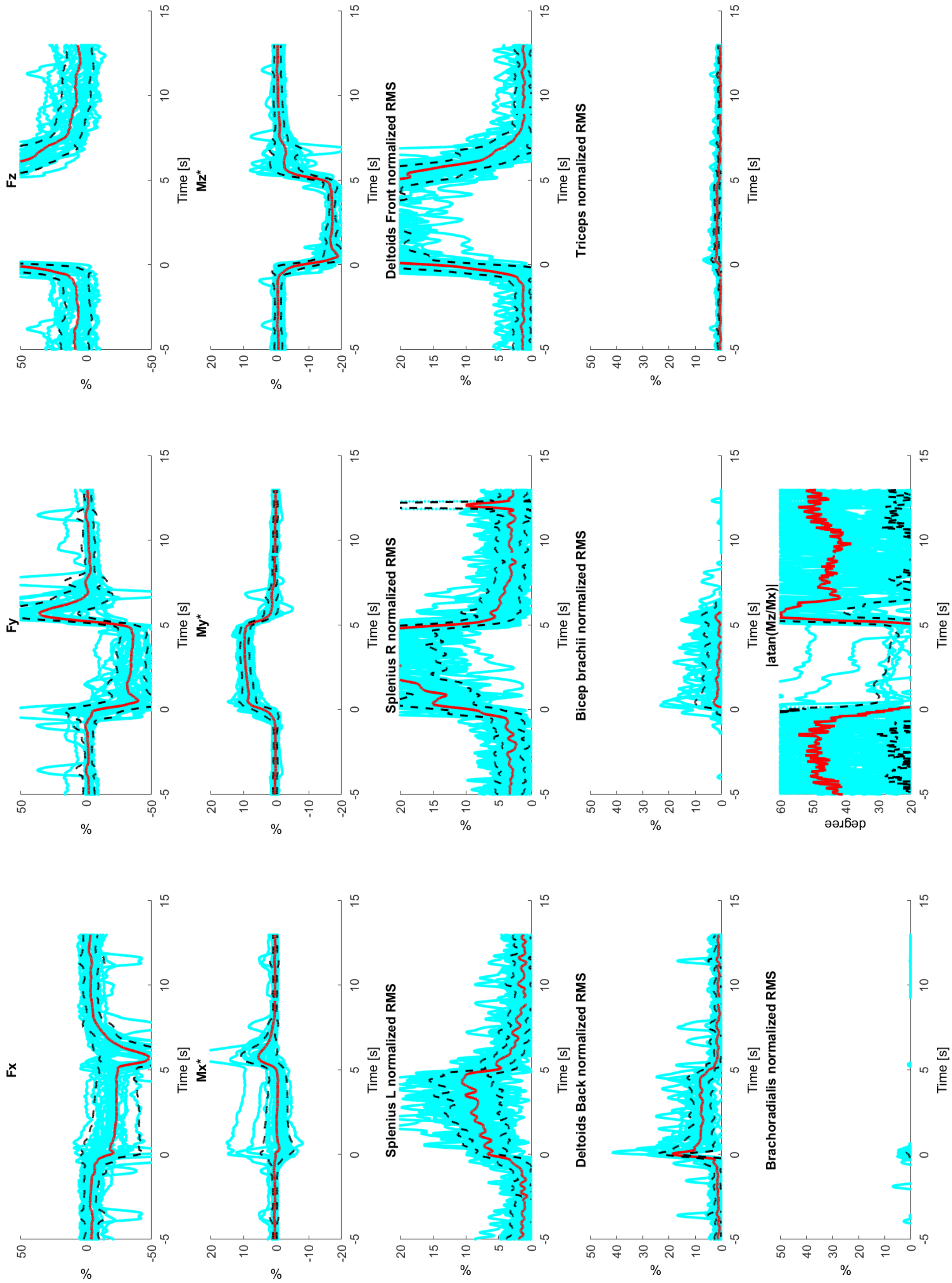


Figure 29: Subject 7 post fatigue condition, blue = all Data across trials, red = mean, black = mean +- std

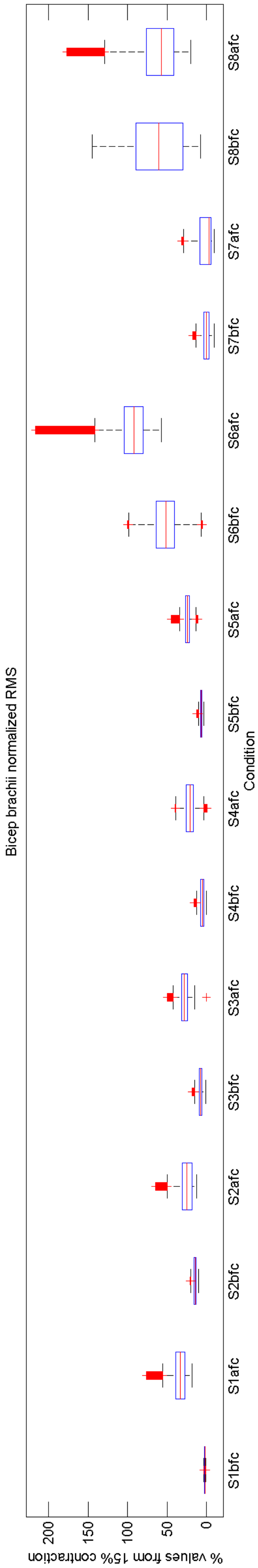


Figure 30: Boxplot for RMS EMG Values from second 1-4 pre and post Fatigue

Because the normalized RMS EMG activity is sometimes off, which can be seen in subject 6 in Figure 30, the difference of post and pre has been divided by the mean of pre. The result can be seen in Figure 31. It shows that healthy subjects had to increase their biceps activity on average by 20 percent of their EMG RMS activity to maintain a 15% MVC contraction, whereby stroke subjects did not increase their biceps RMS activity.

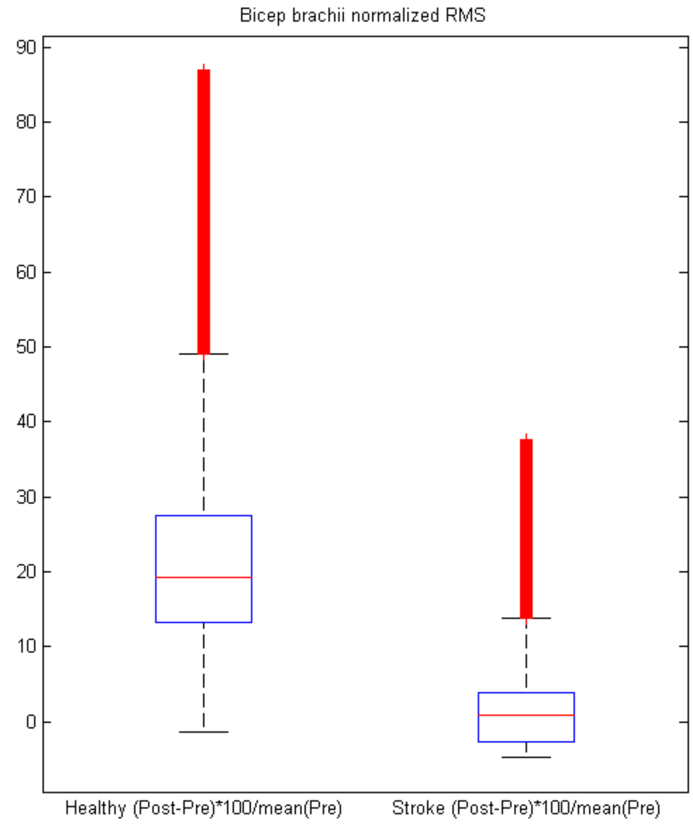


Figure 31: Boxplot for RMS EMG Healthy Values from second 1-4 post minus pre times 100 divided by mean of pre

4.4. EEG

4.4.1. EEG Spectrogram

The following figures (Figure 32 - Figure 39) show the frequency in Hz on the y-axis and the time on the x axis. Time 0 on the time axis marks the onset of the movement. The 15% from max MVC contraction last for 5 seconds. The figures show the frequency activity change in percentage compared to baseline, which has been set from 10 to 13 seconds after the onset of the contraction. The baseline has been set this way, because in the first subjects there was not enough pause between the control MVC and the post-fatigue condition contractions, which would have influenced the baseline if it would have been set from -5 to -3, which would be a more reasonable approach. Never the less it can be seen in the following figures, that there is not much frequency activity compared to the set baseline.

The Spectrogram has been computed over a window of 512 ms, and an overlap of 350 ms. The electrodes have been ordered in a way similar to Figure 3.

4.4.1.1. Healthy (right handed) average pre-fatigue

What can be observed in the following figures are the blue areas, which represent a desynchronization compared to baseline. In the average over the frequency-spectra over all right handed participants,the re-referenced clear data (after removing bad components which have been sorted out by ICA) was used.

It shows that there is a desynchronization mostly in the alpha and beta area. It is hard to distinguish concrete frequencies in this figure. The desynchronization is mostly present in the left hemisphere, but also in the right hemisphere. There is also a little resynchronization going on after the desynchronization. What is also interesting is, that the desynchronization starts around one second before the movement is executed at second 0. It has to be noted that the there was a variability of around half a second between the pulse and the actual onset of the movement.

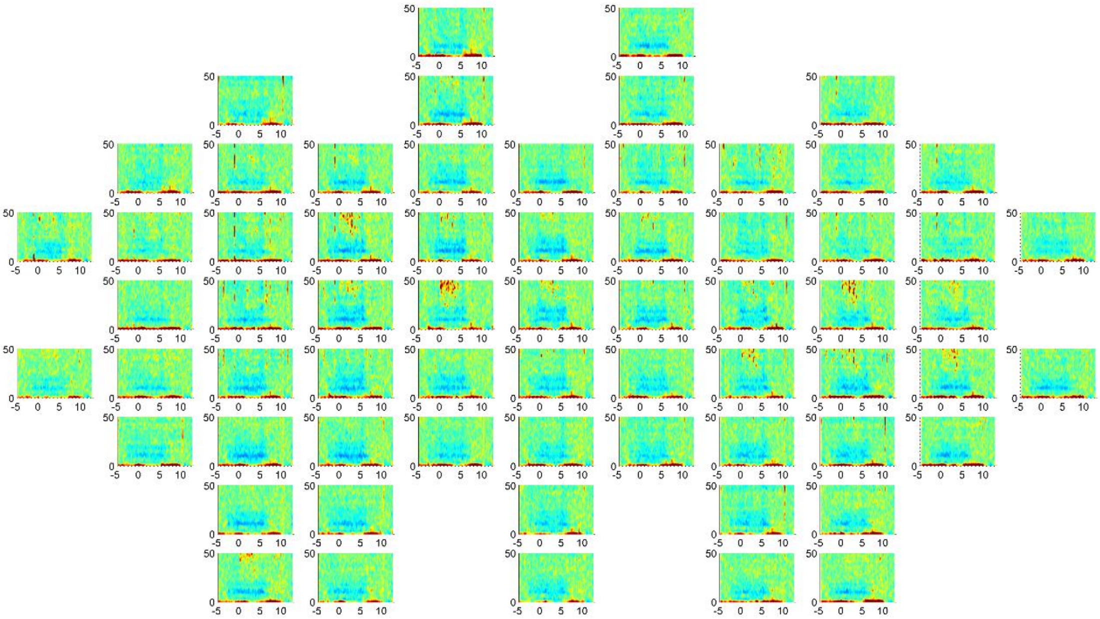


Figure 32: Spectrogram mean of right handed Subjects pre-fatigue re-ref-Clear-Data

Another interesting figure that shows the variability of the spectrogram between subjects can be seen in the following figure. Red areas show a high standard-deviation in a certain time and frequency.

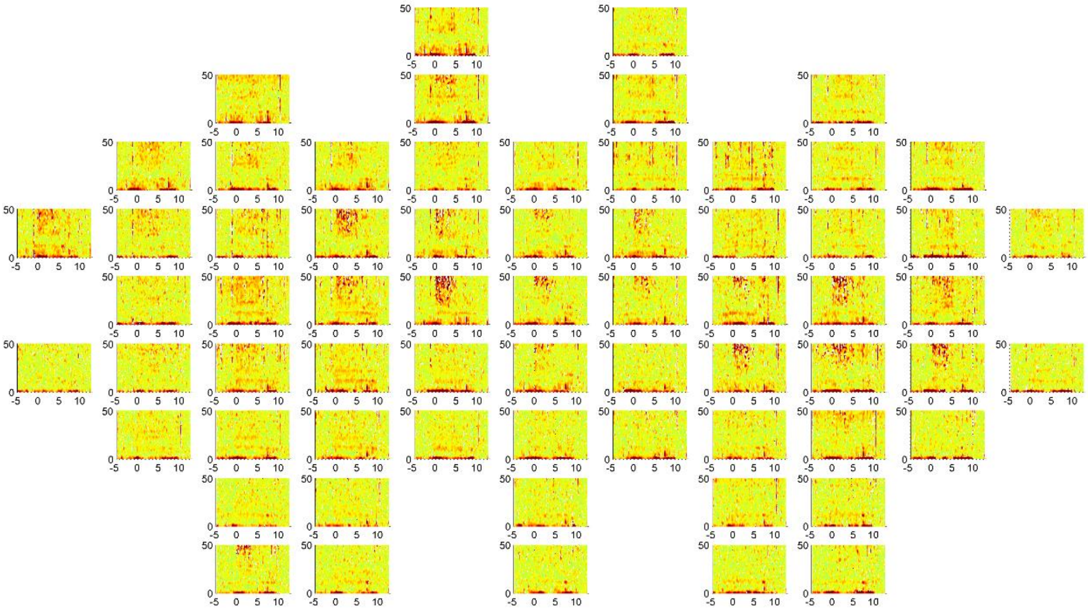


Figure 33: Spectrogram Standard-Deviation between right handed Subjects re-ref-Clear-Data pre-fatigue Condition

Figure 34 shows just specific electrodes. We are particularly interested in electrodes around electrode number 24, which would be P3 on Figure 3, and is one electrode over the motor area.

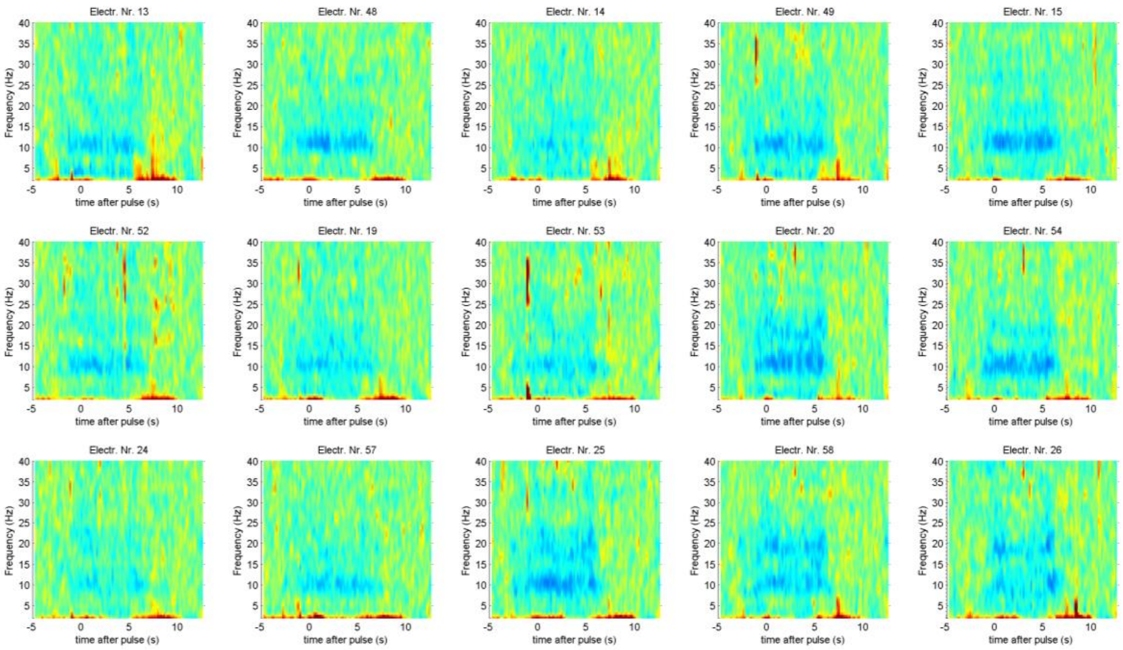


Figure 34: Spectrogram motor-area S1S2S4S5S6 pre-fatigue mean-calculation re-ref-clear-data

4.4.1.2. Healthy (right handed) average post-fatigue

Figure 35 shows again the average of the spectrograms from all right handed subjects but this time for the post fatigue condition. What can be seen is, that there are much more artifacts in the signal (dark red areas), which are most likely due to muscle activity. What is very prominent again in this graph is the beta and alpha band desynchronization which is again over the whole scalp, but a little more in the left side at the motor-area. Desynchronization is more dominant in the post-fatigue condition than in the pre-fatigue condition in the healthy population.

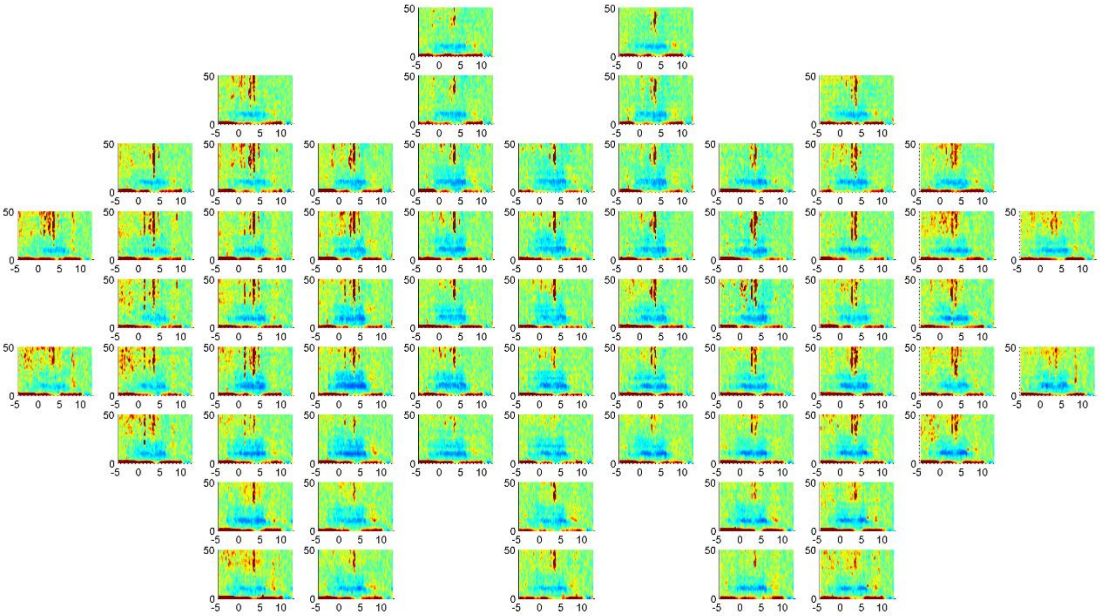


Figure 35: Spectrogram mean of right handed Subjects post-fatigue re-ref-Clear-Data

Figure 36 shows the standard-deviation between all trails and all stroke subjects. It had to be computed over trials, because there were just two stroke subjects.

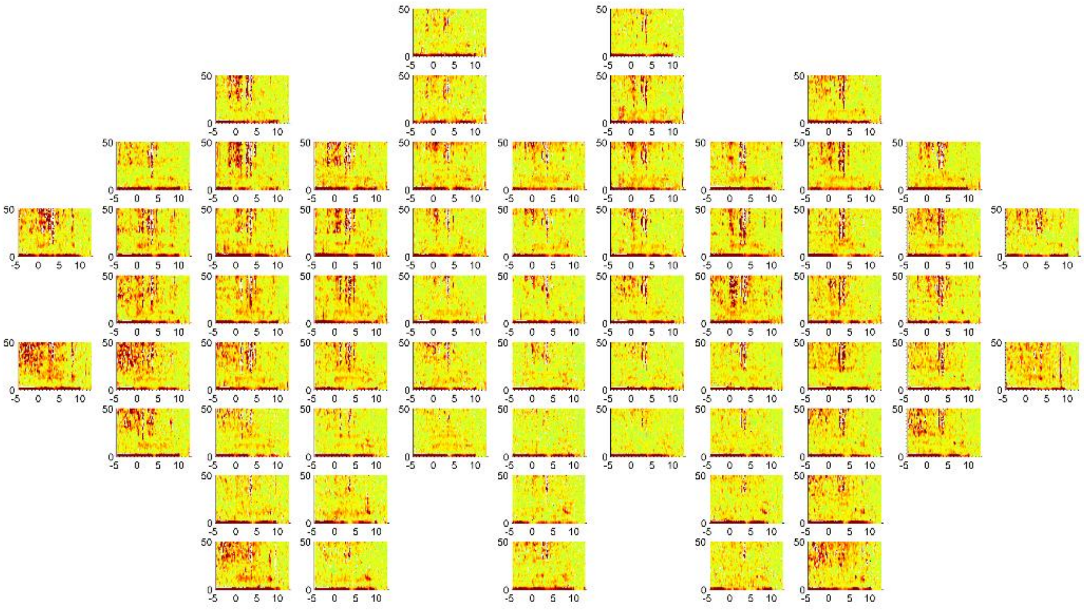


Figure 36: Spectrogram Standard-Deviation between right handed Subjects re-ref-Clear-Data post-fatigue Condition

4.4.1.3. Stroke average pre-fatigue

Unfortunately, there have been just two stroke participants in this study; this is why the results have to be interpreted with caution.

The following figure shows again the average spectrogram over the two stroke participants. The lesioned hemisphere was the left in both stroke participants, and the effected right hand was used. There were a lot of artifacts that distort the picture, even thought a lot of bad ICA components have been removed. The beta and alpha band desynchronization is not that prominent, but mostly located at the motor-area in the left hemisphere.

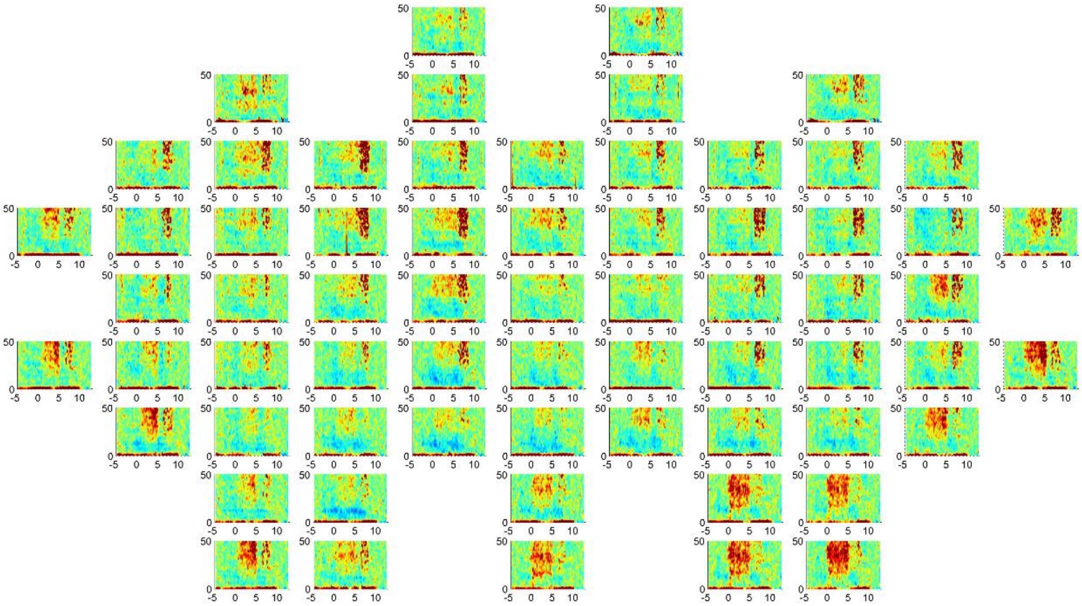


Figure 37: Spectrogram mean across trials and Stroke Subjects re-referenced clear Data pre-fatigue Condition

4.4.1.4. Stroke average post-fatigue

There are even more artifacts in the post-fatigue condition. There is a lot of muscle activity interfering especially when the participants are executing the contraction from 0 to 5.

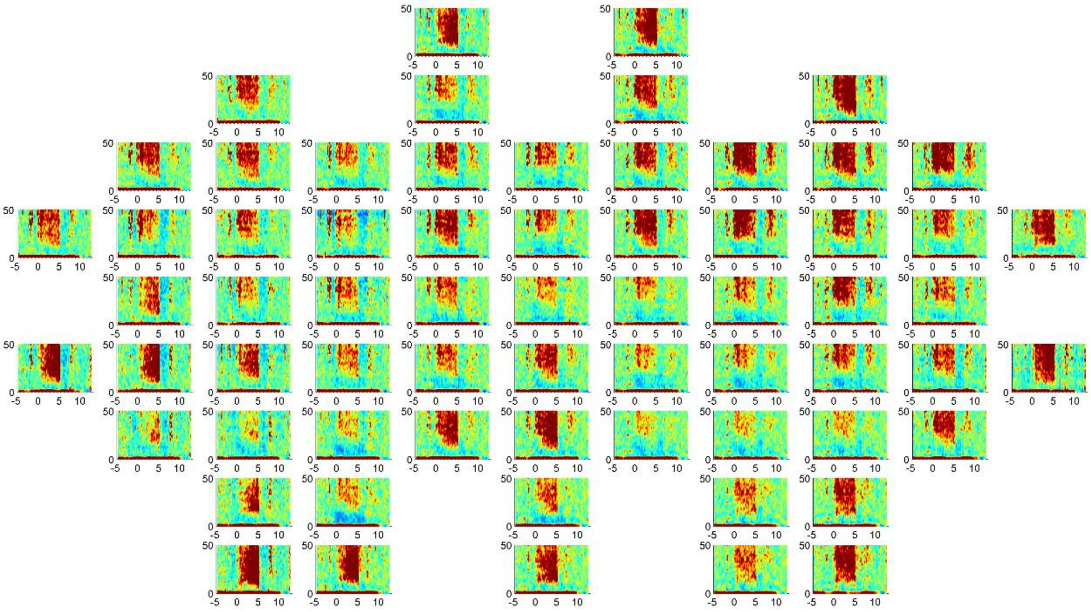


Figure 38: Spectrogram mean across trials and Stroke Subjects re-referenced clear Data post-fatigue Condition

The following standard-deviation has been calculated throughout not only subject but also all trials of both two stroke subjects. It shows that there is a lot of difference in the data, especially at the period of the contraction. It is also spread throughout the frequencies.

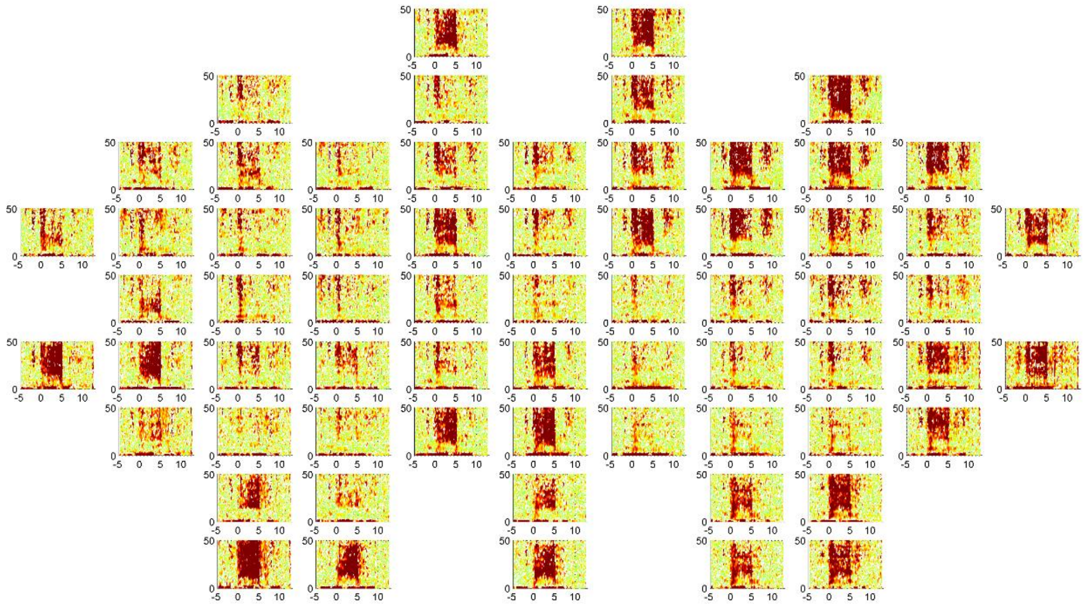


Figure 39: Spectrogram Standard-Deviation across trial average from Stroke Subjects re-referenced clear Data post-fatigue Condition

4.4.2. Alpha-Band Desynchronization

In this study we are focusing on the alpha and beta band. This is what the following figures show. An average across the alpha frequency from 8 to 12 Hz has been computed. In the following figure, we just focused on electrode Nr. 24 (P3) which is above the motor area.

The average amplitude of the alpha frequency retrospective to baseline can be seen in Figure 40. The figure shows the pre-fatigue condition in blue and the post-fatigue condition in red.

It shows that subject 1 had a much more dominant desynchronization than subject 2. It also shows the resynchronization in subject 1, 3, and 6. It is interesting, that even in subject 3 the desynchronization and resynchronization is very dominant although the left hand was used in the experiment.

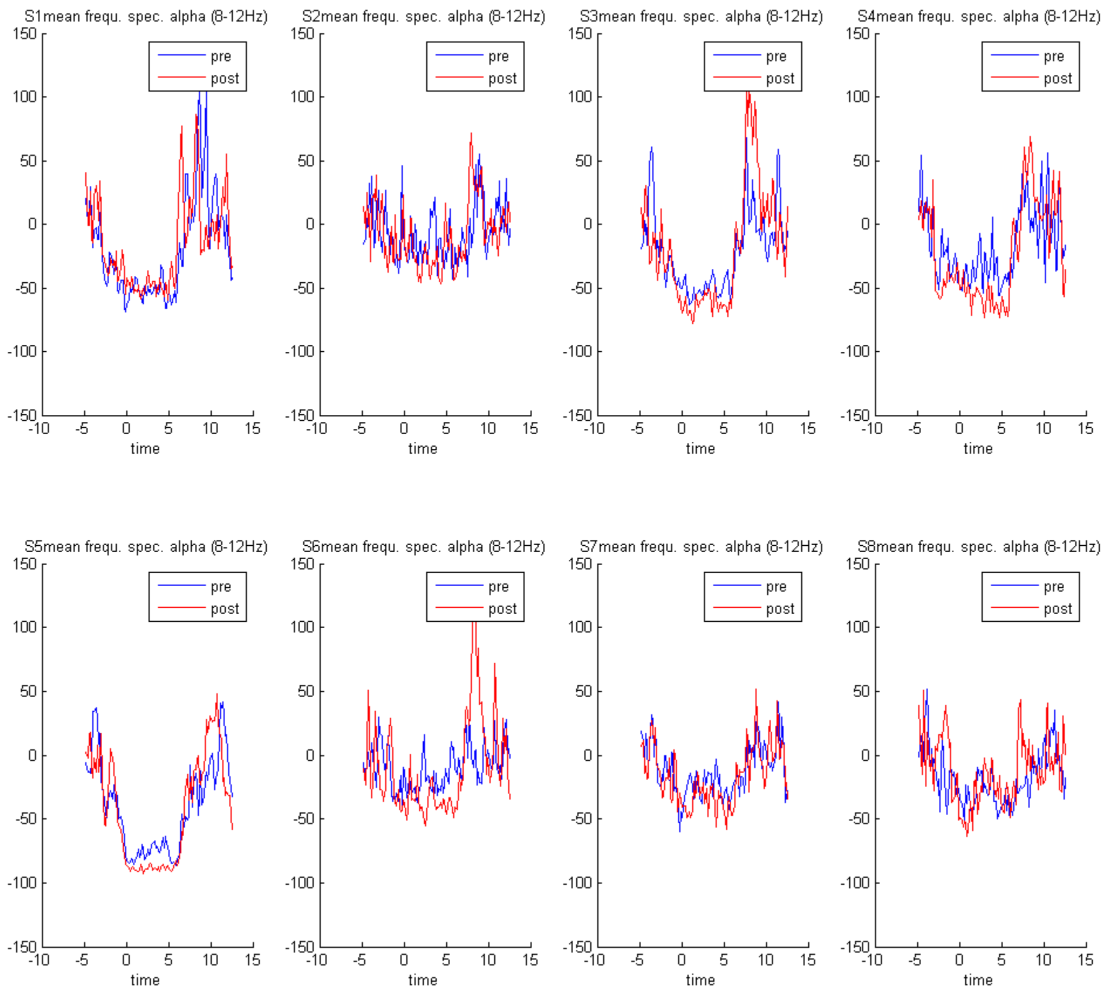


Figure 40: Average alpha (8-12Hz) FFT Amplitude Electrode Nr. 24 re-ref clear epoched EEG Data

The following boxplots visualize the all values from second 1 to 4 for all right handed subjects in the alpha frequency and under electrode 26. Boxplot number 1 shows the data from healthy pre-fatigue condition. Boxplot 2 shows the data from healthy after the got fatigued in the post-fatigue condition. Boxplot 3 shows the data from the stroke participants pre-fatigue and 4 post-fatigue.

What can be visualized with this figure is that the desynchronization is more dominant in the post-fatigue condition for stroke as well as for healthy participants. The healthy participants had a stronger desynchronization at the observed electrode number 26.

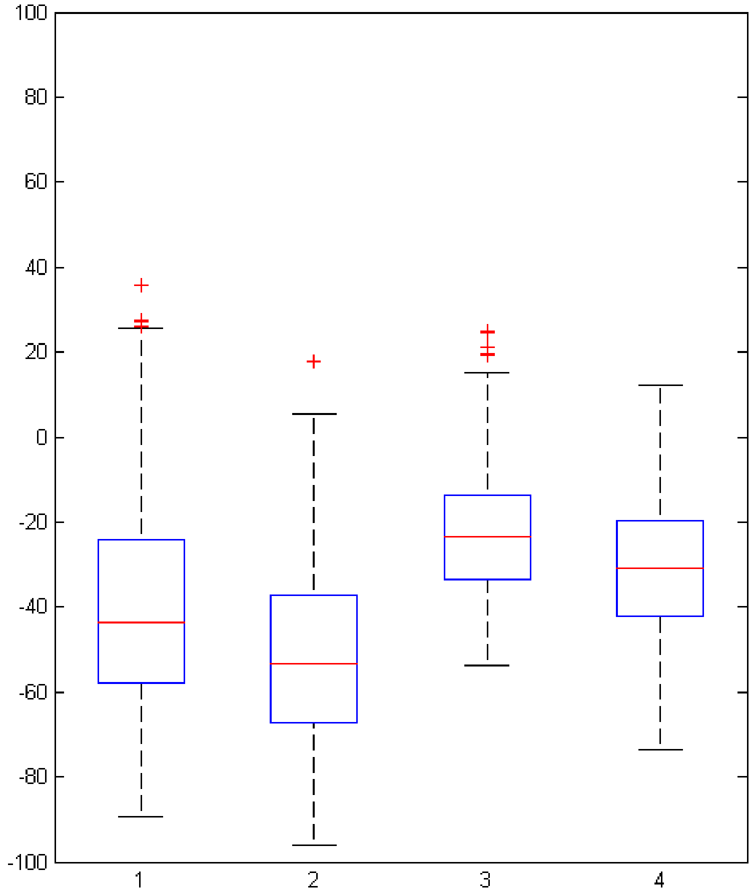


Figure 41: Alpha Band (8-12Hz) Average Spectrogram from 1-4 seconds 1 Healthy pre Fatigue 2 Healthy post Fatigue 3 Stroke pre Fatigue 4 Stroke post Fatigue (re-referenced clear data)

4.4.3. Beta-Band Desynchronization

The same as in section 4.4.2. has been done for the lower beta-band from 13 to 26 Hz.

What can be observed is that beta-band-desynchronization was very prevalent in subject 5.

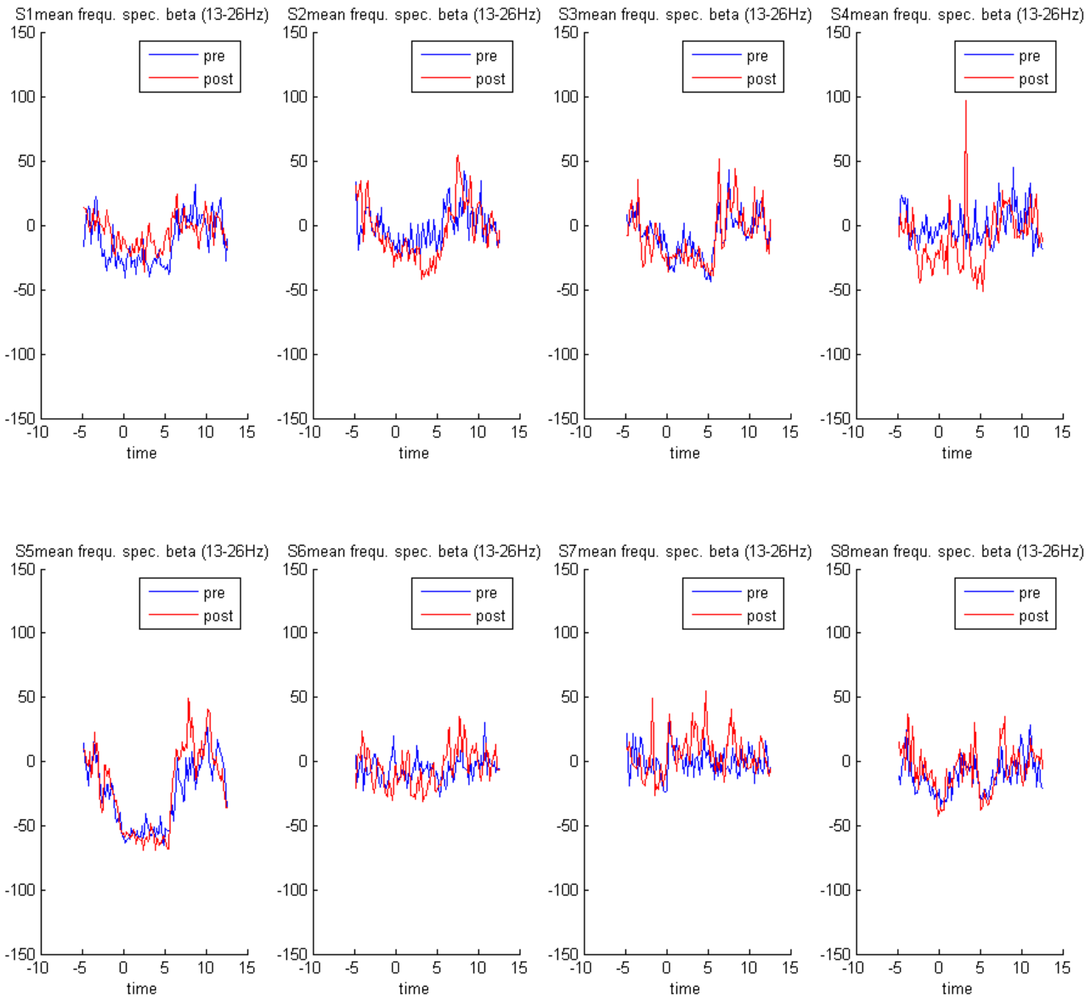


Figure 42: Average beta (13-26Hz) FFT Amplitude Electrode Nr. 24 re-ref clear epoched EEG Data

The beta-band boxplot can be seen Figure 43, which takes again the values from second 1 to 4 from electrode 24. Alpha band-desynchronization was more prevalent than the beta-band desynchronization.

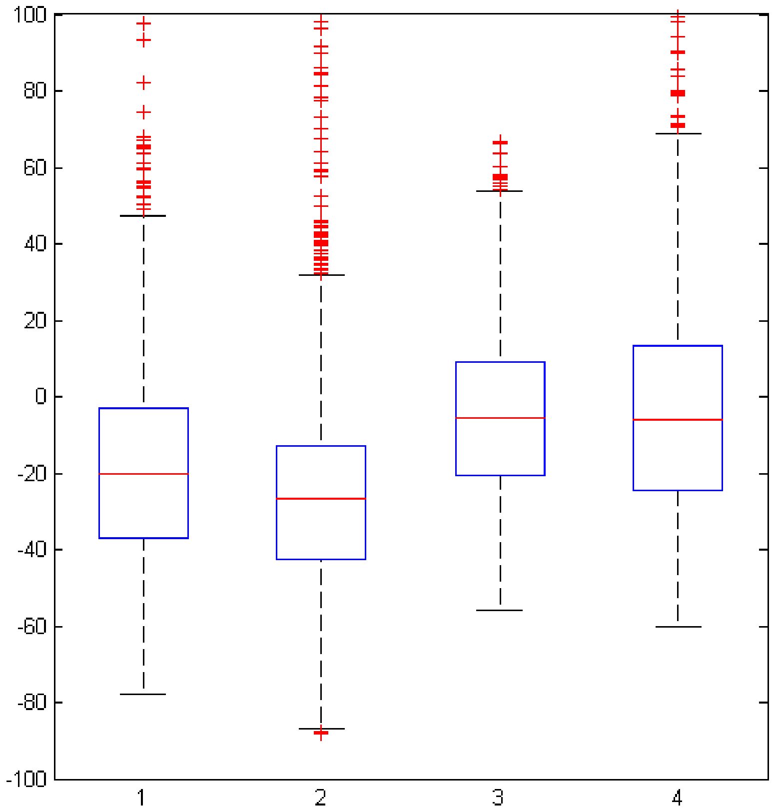


Figure 43: Beta Band (13-26Hz) Average Spectrogram from 1-4 seconds 1 Healthy pre Fatigue 2 Healthy post Fatigue 3 Stroke pre Fatigue 4 Stroke post Fatigue (re-referenced clear data)

5. Discussion

5.1. General

All conclusions have to be taken with care, due to the relatively low amount of participants, especially because there were just two stroke participants. For example, the data would suggest that hypothesis one turned out to be false, because it took the two stroke subjects longer to fatigue than the average healthy subject, but a further study will have to be conducted to draw a more definitive picture, because just two stroke subjects are simply too few to confirm a hypothesis.

5.2. Baseline MVC

One challenge in the experiment was to get the “real” MVC from the participant. This was particularly hard in one of the stroke patients. Her max MVC of the 4 MVC’s that we did at the beginning was 3 Nm. Her pre-fatigue force would have been around 0.5 Nm, but she pulled around 1.5 Nm. After the fatigue protocol which took her around 30 minutes (highest value of all subjects) she pulled 9.7 Nm in one of the control MVCs. We therefore changed the max MVC to 10 Nm and she pulled around 1.5 Nm again at the post-fatigue condition, and it did not take her that long to get fatigued again. This example shows how important the first 3 MVCs are. In this case, the data could be used, because pre- and post-fatigue have been performed at a similar force, but it was way harder for the subject to steer the bird, simply because it is much finer tuned if the max MVC is very low.

5.3. Cheating

It is also possible to tweak the setup in a way that an arm rotation would produce mostly a My but also Mx and small proportions of Mz in the range from 4 Nm. This would enable participants to produce the postulated torque with less activation of their biceps. We want a consistent activation of the biceps to make the trials comparable, and ensure that the fatigued muscle is used. We particularly looked out for patterns that showed us if they changed their movement.

5.4. EMG

The average difference in Figure 27 between pre and post fatigue does not change much for all of the muscles except the biceps. If we look at the bicep, it can be seen that on average the RMS EMG signal doubles from pre to post fatigue, although the forces stay almost the same. Healthy subjects therefore had to expend twice as much muscle activity to maintain a 15% MVC contraction. In contrast, there is almost no change in the RMS EMG of the two stroke participants, which can be seen in Figure 28: RMS EMG Average across all Trials across all Stroke Subjects. This can be also seen in Figure 30: Boxplot for RMS EMG Values from second 1-4 pre and post Fatigue

The EMG results were relatively clear. A problem that occurred was in normalization. There were spikes over 300 ms long in the RMS signal that should have been used as 100% RMS EMG. This is why no easy solution could detect the appropriate 100% RMS EMG, and it has been therefore selected by hand. In some subject even though the 100% RMS EMG has been selected by hand it was not an accurate normalization, most likely due to the participant not understanding the task correctly or not giving it all. A normalization gone wrong can be seen in Figure 28: RMS EMG Average across all Trials across all Stroke Subjects, at the left deltoids, but also at the boxplot of Figure 30: Boxplot for RMS EMG Values from second 1-4 pre and post Fatigue, where subject 6 is clearly off in its normalization of his bicep.

There is no easy way to tackle this problem. Assuming that a certain strength percentage was used, and base the max of of that would distort the result.

This is why the difference divided by the mean has been taken in Figure 31: Boxplot for RMS EMG Healthy Values from second 1-4 post minus pre times 100 divided by mean of pre. This figure shows clearly that healthy subjects had to put 20% more EMG RMS in order to maintain the contraction, whereby stroke patients did not. This supports previous similar findings.

What is also different from the normal subjects to the stroke subjects is that the stroke subjects pulled more upwards than they were supposed to.

5.5. EEG

There are a lot of artifacts in the EEG signals. These artifacts can be spotted as short spikes in a higher frequency range. EEG signals in a higher frequency range would be filtered out due to the low-pass filtering effect of the skull. Artifacts in Figure 35, as well as in Figure 37 also appear for a very brief time in the middle of the task across all electrodes which is most likely due to electrode wires that got pulled, as opposed to cortical activity.

Figure 36 shows the standard-deviation in the spectrogram in the post fatigue condition between subject also suggests that the dark red lines in Figure 35 are artifacts. They distort the mean. Also there is a lot of variability on the left middle side which could be due to tensed neck muscles that interfered with the EEG signals. There is a high neck activity that can be observed in Figure 29 for Subject Nr. 7, which is most likely the cause for the misleading high activity.

Figure 38 and Figure 39 show a much longer artifact and this can be explained by Figure 29 where if one looks at the neck muscles at this stroke participant, it can be seen that those increase a lot during the contraction. Those EEG signals with high amplitude and at frequencies beyond 35 Hz are artifacts too.

Alpha and beta band is retrospectively relatively clear. Beta band in stroke patients is altered in the higher beta-band as can be seen in Figure 38. This is also why the beta band average over 13 to 26 Hz has been taken in the average in

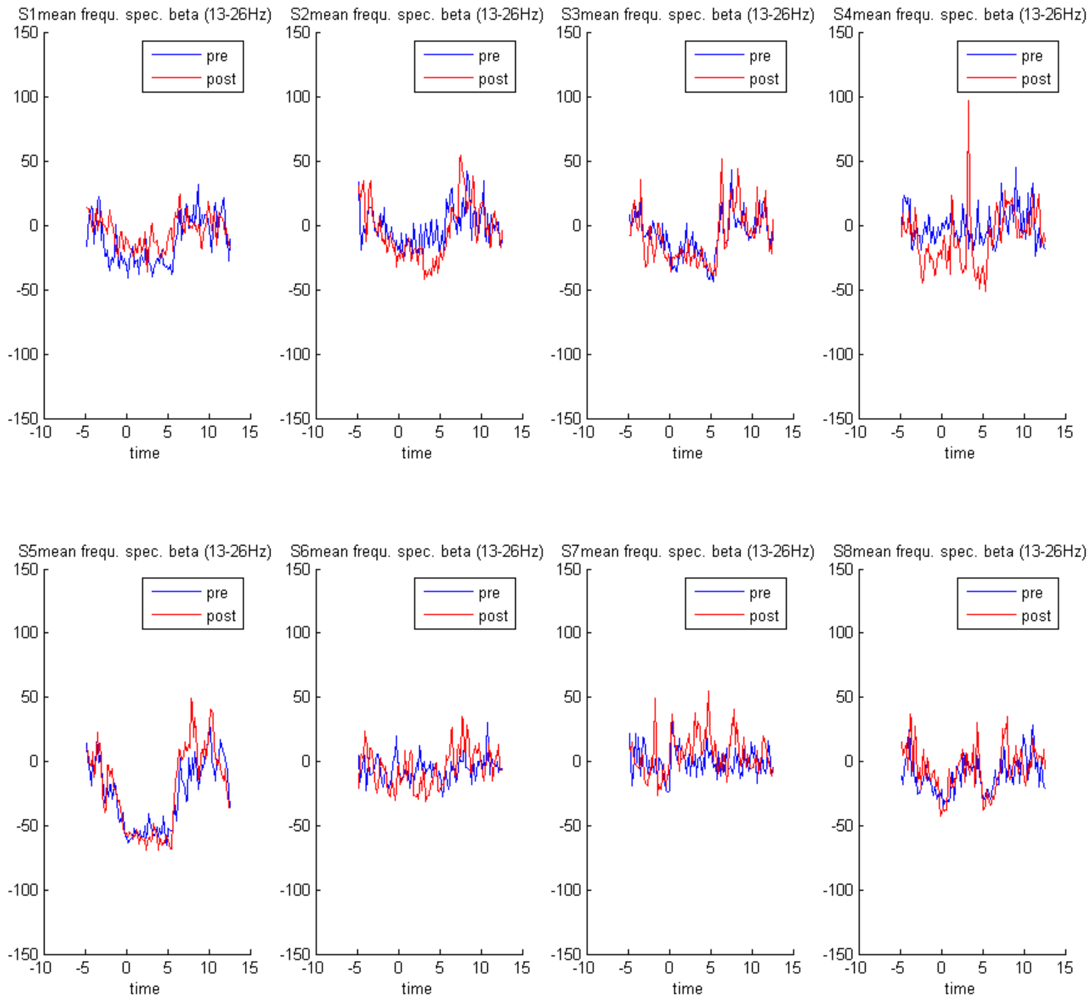


Figure 42 and Figure 43, and not 13 to 30 Hz as usual.

Alpha band desynchronization has been shown to be more prominent in the alpha band then in the beta band, at least in electrode 24 or P3 (look at Figure 3). The situation across the subjects can be seen in Figure 40 and

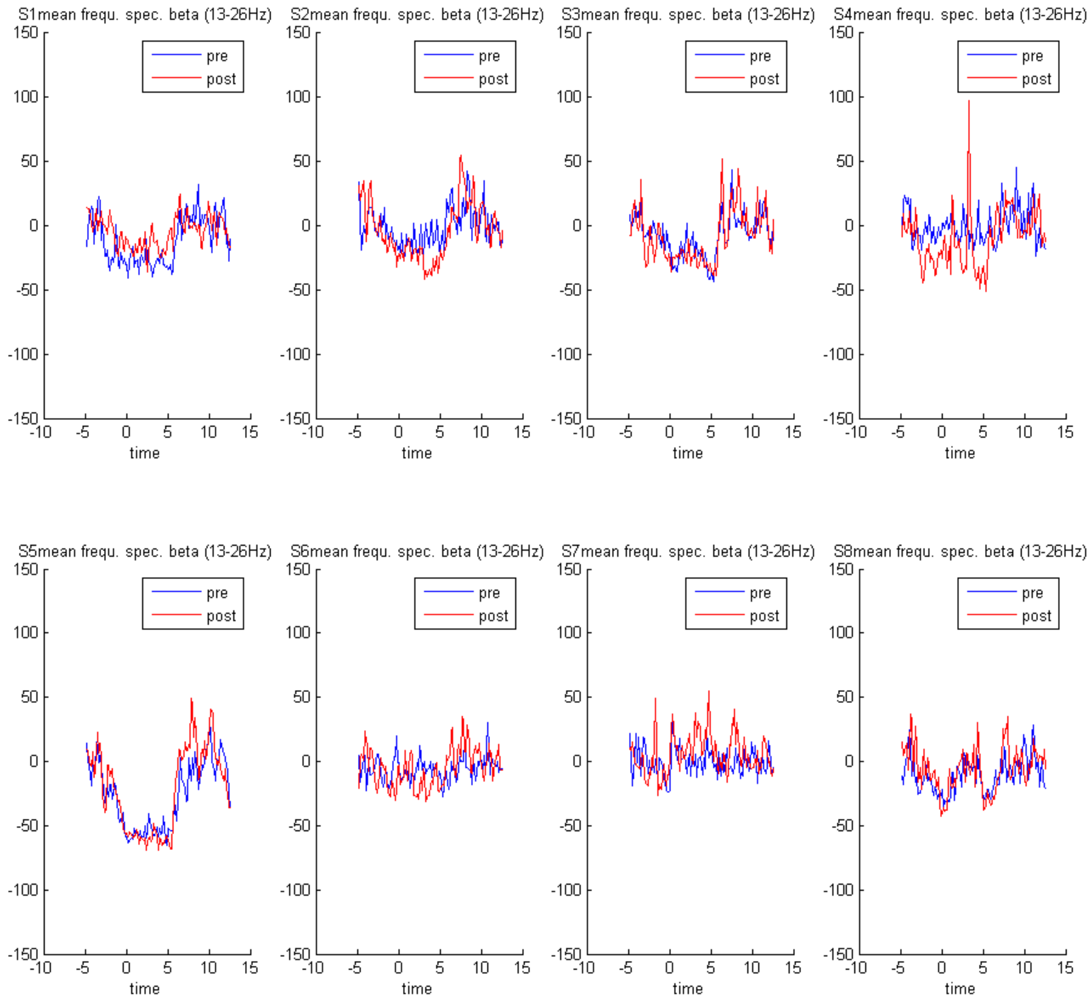


Figure 42. The desynchronization and also resynchronization after the desynchronization is very different throughout the subjects. For example in Subject 2 there is a distinctive resynchronization as well as in Subject 3 and 5, but not that distinctive in Subject 1. If you look at the two stroke Subjects (Subject 7 and 8) the desynchronization at second zero is followed by a resynchronization after 2 seconds which seem strange.

Never the less it is hard to draw definitive conclusions from such a low amount of stroke subjects.

6. OUTLOOK

This study was one of its first kind. Additional studies have to be performed, especially with more stroke subjects.

Following similar studies should be performed at 10 percent of max MVC. The current 15 percent have been selected because steering the bird is a little bit easier at a low max MVC at 10 Nm or less (Fz*).

Another option that could be taken into consideration is to base the max MVC off of the dominant arm from the participants. This could overcome some of the problems that occurred with stroke participant 7 where the max MVC that was performed was not near the possible max MVC. It would also lead to a faster fatigue. The downside is that the 15 or 10 percent at the pre or post fatigue condition will have to be altered too, in order to reduce neck muscle activity.

Another thing that would be worth looking at is the differences between the hemispheres between right and left hand. In this study, the desynchronization was relatively wide spread and there was not a definitive region that was very prominent.

The results that intact participants had to put in 20 percent more effort in order to obtain the same force after fatigue points out that they were muscularly fatigued, as opposed to the stroke subjects which were not muscularly fatigued. These results are very promising for further studies of this kind.

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