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Comparison of algorithms to quantify muscle fatigue in upper limb muscles based on sEMG signals

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ABSTRACT

This work compared the performance of six different fatigue detection algorithms quantifying muscle fatigue based on electromyographic signals. Surface electromyography (sEMG) was obtained by an experiment from upper arm contractions at three different load levels from twelve volunteers. Fatigue detection algorithms mean frequency (MNF), spectral moments ratio (SMR), the wavelet method WIRM1551, sample entropy (SampEn), fuzzy approximate entropy (fApEn) and recurrence quantification analysis (RQA%DET) were calculated. The resulting fatigue signals were compared considering the disturbances incorporated in fatiguing situations as well as according to the possibility to differentiate the load levels based on the fatigue signals. Furthermore we investigated the influence of the electrode locations on the fatigue detection quality and whether an optimized channel set is reasonable. The results of the MNF, SMR, WIRM1551 and fApEn algorithms fell close together. Due to the small amount of subjects in this study significant differences could not be found. In terms of disturbances the SMR algorithm showed a slight tendency to out-perform the others.

1. Introduction

Muscle fatigue is described as the muscles' inability to sustain a constant force. In everyday life, the healthy exercising subject will sooner or later react on the accompanying sensations and stop his/her work-out. According to Merletti et al. [1] fatigue can be grouped by definition into central fatigue, fatigue of the neuromuscular junction and muscle fatigue. Together they are also known as neuromuscular fatigue.

Neuromuscular fatigue can have several, mainly biochemical causes. They are usually attributed to various biochemical processes running in parallel with an evolving exhaustion in the muscle [2]. Furthermore the reasons of neuromuscular fatigue are not limited to the muscle itself. A noticeable change in neuronal recruitment may affect fatigue, too and is part of central fatigue.

It is possible to detect neuromuscular fatigue based on changes in electromyographic signals from the affected muscle. A seminal study by Piper [3] noted that dominant frequencies in the EMG's power spectrum are shifting to lower frequencies for ongoing exercise and developing fatigue. During evolving fatigue the frequency content seems to be subject to an ongoing compression towards lower frequencies. Lindström and colleagues [4] connected the spectral changes in the EMG recordings during evolving muscle fatigue with a decrease of the muscle fiber conduction velocity. In 1977 Lindström and Magnusson [5] postulated a numerical fatigue index to denote the progress of a muscle under load towards the state of not being able to deliver a required force anymore.

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Today various methods [6] are known to calculate fatigue indices from electromyographic recordings. The fatigue algorithms used can be divided into two main classes. The first class consists of the classical frequency based algorithms that quantify the changes in the spectrum. The classical mean frequency (MNF) as well as spectral moments ratio (SMR) [7] and wavelet based methods [8] fall into this class.

The second class consists of fatigue detection algorithms that take into consideration of other nonlinear components like recurring patterns or fractal measures of the signal. Recurrence quantification analysis (RQA) [9] and entropy based methods like sample entropy (SampEn) [10] and fuzzy approximate entropy (fApEn) [11] belong to this class.

This study aims to quantitatively compare the various methods to detect neuromuscular fatigue in surface EMG data. It seeks to find a fatigue algorithm for noninvasive measurements that is real-time capable and yields a high quality fatigue index. A good fatigue index should comply with two criteria. Firstly it should demonstrate little disturbances leading to sparse deviations from a smooth course of the resulting fatigue index and secondly it should be a good measure for different levels of fatigue. Potential applications cover a broad field including sports, recreational and rehabilitation exercise and medicine.

We base our comparison on surface EMG data recorded from the biceps while performing contraction tasks with a bend arm under different loads. The focus of this work is the comparison of the algorithms under consideration of three different load levels. This is combined with the investigation whether there are significant differences in the performance of the fatigue detection algorithms. Furthermore the potential of channel sets containing only selected channels was examined for both subject-individual as well as globally optimized channel sets. A study based on a simplified subset of the same experiment with only two load levels focused on the performance of the fatigue detection algorithms depending on the sEMG sampling rate. It was already published by Kahl et al. [12].

2. Methods

2.1. Data collection/experiment

To build a data set to compare the different fatigue algorithms, an experiment was performed to record surface electromyographic signals from contractions of upper limb muscles. 12 healthy volunteers (6 female and 6 male) took part in the experiment. The subjects' age was between 17 and 56. Prior to the start all subjects gave written consent to participate in the experiment. The experiment was approved by the ethics authorities at the University of Lübeck.

To exert a defined force each subject was asked to pull on a rope attached to his/her wrist. The subject was instructed to sit upright. The elbow was supposed to remain on a flat support in front of the subject. See Fig. 1a for a sketch of the setup. With a block and pulley construction redirecting the gravitational force of a weight it was assured that subjects were pulling with a constant force.

Initially the weight was replaced by a spring scale. Subjects were instructed to pull against the rope with their maximal achievable effort for a short time. With the help of this calibration run the maximum voluntary contraction (MVC) was determined for each subject individually. During the three following trial runs, the weight to be lifted was adjusted according to each subject's MVC. In the three trial runs the subject was asked to pull weights of 20%, 40% and 60% of her/his MVC for 3 min each. They were allowed to stop the trial when feeling exhausted by dropping the load and relax. All subjects persevered the designated duration of 3 min in case of the 20% and 40% MVC loads. At the 60% MVC load level the trials lasted between 60 s and the full length of 3 min. On average the 60% MVC trial lasted for 135 s. After each trial the subject had a break of at least 30 min to rest.

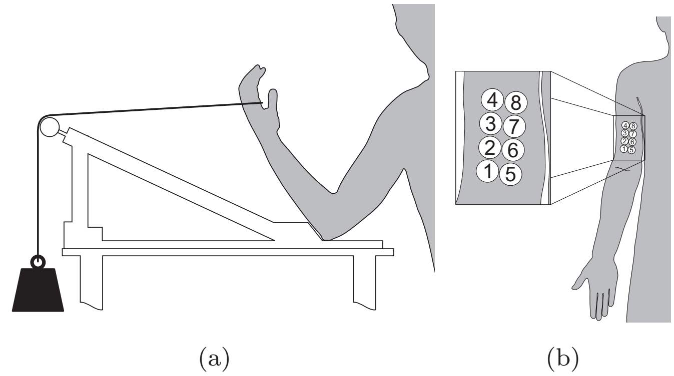

Fig. 1. Setup of the experiment (drawing adopted from [12]). The block and pulley construction is shown in (a). The seated subject was asked to hold his/her arm in a bent position (approximately 90° between upper and lower limb) keeping the weight suspended. (b) shows the positions of the electrodes on the subject's biceps. Electrodes 3 and 7 were placed above the thickest point of the biceps whereas electrodes 1 and 5 were placed on the distal end of the upper arm.

Eight self-adhesive electrodes (Covidien Kendall, H124SG) were placed on top of the biceps. The electrodes were attached in two rows next to each other without any space in between. In accordance to their diameter the centers of adjacently placed electrodes were 24 mm apart. See Fig. 1b for an illustration of the electrode positions. The sEMG was recorded with a sampling rate of 1024 Hz by a Porti amplifier (TMSI, Oldenzaal, Netherlands) including a 22 bit AD converter. The Porti amplifier was configured as reference amplifier. In the reference amplifier mode the input signal of each channel is amplified against the average value of all eight connected input channels [13]. The amplifier's ADC internally operates with a sampling frequency of 512 kHz. The recorded sEMG signal with a sampling rate of 1024 Hz is obtained by decimation and linear phase digital low pass filtering (cutoff frequency: 276 Hz) within the Porti. The amplifiers common electrode was attached on the back side of the upper arm opposite to other electrodes.

2.2. Signal processing and fatigue detection

A personal computer with the software R [14] was used for the further offline signal processing of the recorded sEMG. Based on the eight electrodes all 28 possible differential channels were calculated. Afterwards a 3rd order Butterworth high pass filter with 2 Hz corner frequency was applied to suppress possible baseline offsets. Exemplary baseline filtered sEMG signals are shown in Fig. 2.

Six subsequently described fatigue detection algorithms (see Table 1 for an overview) were utilized to calculate fatigue signals based on all 28 high pass filtered differential channels. The fatigue calculation was performed epoch wise with an epoch length of one second corresponding to 1024 samples. The epoch length of one second is in line with epoch lengths already reported. According to Clancy et al. [15] the epoch length used in spectral analysis of EMG signals ranges between 0.25 and 1 second. Xie et al. [11] calculated the fuzzy approximate entropy with epochs of different durations between 0.25 and 2.5 s. Dimitrov et al. [7] used the spectral moments ratio for detecting fatigue in dynamic contractions in connection with epoch sizes of 1 and 2 s.

2.2.1. Mean frequency

Spectral fatigue algorithms were calculated based on an epoch-wise estimation of the power spectral density (PSD). The PSD was estimated by the Welch method with $k = 15$ sub segments and 50%