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Muscle activity detection in electromyograms recorded during periodic movements

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ABSTRACT

Muscle coordination during periodic movements is often studied using the average envelope of the electromyographic (EMG) signal. We show that this method causes a loss of important information, and potentially gives rise to errors in analysis of muscle activity coordination. We created four simulated two-channel surface EMG signals, in order to compare the results of muscle onset/cessation detection, performed on the average EMG envelope and the EMG envelopes in every single movement cycle. Our results show that the common method using the average EMG envelope is unable to reveal certain important characteristics of the EMG signals, while the analysis performed on individual cycles accentuates this information. This ability was verified on 16-channel surface EMGs obtained during walking and cycling. By detecting muscle activity in individual movement cycles, we could observe fine changes in muscle coordination. Moreover, muscles with questionable reliability of activity detection were distinguished and highlighted in the presented summary figures. In the second part of the paper, our publicly available set of MATLAB files for surface EMG signal processing is described.

1. Introduction

An electromyographic signal is induced by contraction of muscles. During the 20th century, electromyography became used widely in medicine and kinesiology. While the medical applications focus mainly on diagnostics of neuromuscular diseases [1,2] controlling of prosthetic limbs [3,4] and therapy, a large area of applications also exists in sports. A comprehensive summary can be found in [5].

Exploration of muscle activation patterns is a common task of kinesiologists. There are several ways of detecting muscle onset and cessation points delimiting intervals of muscle activity. For a practised expert, it is easy to mark the required points on the raw EMG recording, especially when a synchronized video recording of the performed movement is available. Computer-based methods require various signal pre-processing, and apply varied decision rules to detect the onset or cessation.

It should be noted that, for muscle coordination studies, neither the extraction of several motor unit action potentials [6], nor the analysis of separate neuromuscular compartments [7], are usually necessary. When detecting muscle onset and cessation, the frequency content [8] and the signal bandwidth is also of minor importance, compared to the overall signal amplitude. Although some authors use advanced methods, such as Bayesian change-point analysis [9], generalized likelihood ratio [10], the Kalman smoother [11], singular spectrum analysis [12,13], wavelet transform [4,14,15], empirical mode decomposition [16], or sample entropy analysis [17], it is more usual to perform rather simple pre-processing and detection. Extensive comparisons of traditional methods can be found in [18–20], while [21] provides a more general overview regarding EMG signals in kinesiology.

Sometimes, thresholding of a (filtered) EMG signal is applied, using a threshold based on a certain multiple of the standard deviation of the EMG, measured during a resting state [18–20,22–24]. Gazendam et al. [25] defined the threshold as a fixed voltage, expected to be exceeded upon muscle activation.

In methods that use the so-called EMG envelope signal, the procedure of EMG signal pre-processing includes two main operations: full-wave rectification and low-pass filtering. Optionally, band-pass filtering is sometimes applied before rectification. The suitable cut-off frequencies depend on the muscle recorded, the kind of the movement, and the movement velocity. Hence, various filters such as high-pass 20 Hz [26] or band-pass 120–350 Hz [27] appear before rectification. The cut-off frequency during low-pass filtering after rectification usually varies from 2 Hz [7] to 50 Hz [24], including values such as 4 Hz [12], 9 Hz [28], 10 Hz [29] or 24 Hz [26]. Solnik et al. [24] and Li et al. [23] recommend pre-form

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signal conditioning, using the Teager–Kaiser energy operator prior to rectification.

Muscle activity can be detected using the EMG envelope: a traditional method is simple thresholding related to the maximum value of the EMG envelope [28,30,31], with thresholds e.g. 25% [31] or 20% [28,30,32]. Thexton et al. [33] describes a sophisticated method for threshold adjustment.

Analysis of the curve shape (detection of relative minima, maxima, inflexion points etc.) provides an alternative to thresholding, eliminating problems with proper threshold adjustment and with variation in effort during the recording [10,30].

Periodic movements are often analyzed because of their great predominance in many human activities, including sport. We consider a movement periodic if it is repeated in regular intervals, even though slight alterations are caused by the limited ability of the human body to perform a perfectly periodic movement. Recording many cycles of periodic movement and averaging the extracted patterns are frequent ways of obtaining more stable and reliable results, assuming that the movement is always performed in the same way. The signal is segmented according to the physical movement; several segments are then interpolated to a uniform length and averaged [1,26–30, 34,35,37,38]. Further analyses usually follow on the average EMG envelope. Campanini et al. [29] add useful measures for the repeatability of the envelope time series obtained during a periodic movement.

We think that for certain situations this method is not optimal because it causes a loss of important information and potentially gives rise to errors, since human movement is not exactly periodic. A considerable error can occur when the movement is performed in two (or more) slightly different ways (because of the movement optimization during recording, posture adjusting, increasing fatigue etc. [25]). As reported in [30,34], one certain movement can be performed using various muscle coordination strategies.

We assume the following:

1) For every muscle, there is a constant number of activity intervals per movement cycle during a given periodic movement. This number can differ between muscles.
2) The onsets/cessations of the mentioned muscle activity intervals appear at similar points in several movement cycles. However, certain variations (e.g. $\pm 10\%$ of the movement cycle) are to be expected, since the human body is unable to perform a precisely periodic movement.
3) Considering the previous point, the evaluation of muscle coordination can be highly unreliable for pairs of muscles that have similar timing, if the evaluation is based only on the average muscle activation profile (the average EMG envelope).
4) The intensity of muscle activation can vary between several movement cycles during the workout.

We require a method that provides:

1) muscle activity intervals for every single movement cycle to allow for evaluation of whether there are differences in muscle coordination among cycles,
2) summarized (averaged) results with a clear indication of possible irregularities in de/activation of several muscles.

2. Material and methods

2.1. Signal database

2.1.1. Simulated EMG signals

In order to study the influence of envelope averaging, we created four sets of simulated two-channel EMG signals and a segmentation signal. The first set of signals (A) simulates a pair of muscles, with activity intervals shifted 10% of the movement cycle apart, and with fine variations of onset/cessation positions within movement cycles. Set B simulates muscle 1 having onset at about 40% of the movement cycle, and muscle 2 with onset after (in the first half of recording) and before (in the second half) muscle 1. In set C, both onset times and orders of activation vary. Set D simulates a pair of muscles with great variability of onset times but with no change in the order of activation. Muscle cessations follow the same arrangement as muscle onsets in each set.

We decided to base these sets on real EMG recordings (as in [24]) rather than using a completely synthesized EMG signal, as described, for example, in [8–10,15,23,36,39]. However, the measured signals were modified (primarily time-shifted) in order to meet the required characteristics. We used two-channel EMG measured by a ME 6000 Biomonitor (Mega Electronics Ltd, Finland) on m. peronaeus longus dexter (dx.) and m. adductor magnus dx. during cycling on rollers (male, recreational cyclist), and a segmentation signal dividing several movement cycles. These muscles and movements were chosen because the contraction and relaxation of both muscles alternate regularly during this activity, making the muscle activity intervals clearly visible and regular and the EMG signal easy to process. The sampling rate was 1 kHz and we processed approx. 20 s of the steady part of the recording. Signal preparation was performed using MATLAB (version R2012b; The MathWorks, Inc.). First, we chose the required muscle activity intervals for both channels of the simulated EMG signals (sets A, B, C and D) using the timings mentioned above (example shown in Fig. 1(a); the figure and the following description only mention one channel as the processes for the other channel were identical). The average position of muscle onsets (cessations) was prescribed and each data point in the sequence of onsets (cessations) in the individual movement cycles was generated as a sum of the prescribed average position and a randomly generated value. The random values had a Gaussian distribution and standard deviations up to 5% of the movement cycle (depending on the set).

In the second step, the measured EMG signal was full-wave rectified and its linear envelope was computed using a low-pass filter (FIR order 1001, cut-off frequency 4.5 Hz, stop-band rejection 50 dB). The muscle activity intervals were identified using EMG envelope thresholding where parts exceeding 20% of maximum, observed in the corresponding movement cycle, were marked as

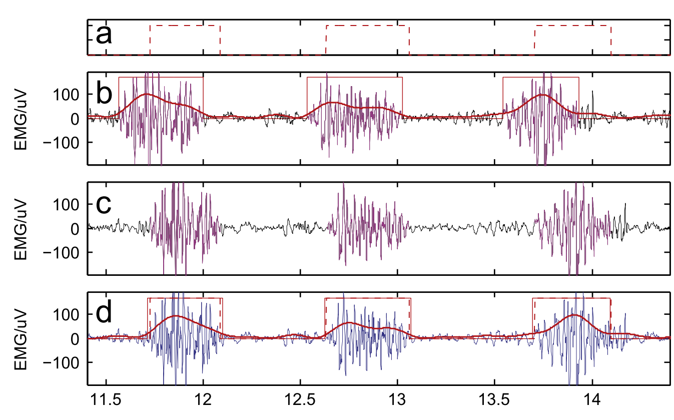

Fig. 1. Preparation of simulated EMG signal (shown one channel): (a) required activity pattern; (b) measured EMG signal (thin) with envelope (bold, red) and activity intervals (thin, red), detected using thresholding; (c) interpolated segments matching the lengths required by pattern (a); (d) simulated EMG signal (thin), its envelope (bold, red), required and detected activity pattern. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)