Analysis of surface electromyographic parameters for the assessment of muscle fatigue during moderate exercises

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Summary

Muscle fatigue is a neuromuscular phenomenon which prevents the muscles to generate the required force. Although there are multiple studies about detecting this condition with surface electromyography, this method has still some limitations. The objective of this study was to determine the viability of some biomarkers as early indicators of fatigue during moderate exercise. Eight healthy volunteers performed 2 dynamic exercises involving the flexo-extension of the knee lifting 2 and 4kg attached to the ankle. A bipolar electromyographic signal was recorded simultaneously from: Rectus Femoris, Vastus Lateralis and Biceps Femoris. Muscle activations were extracted by supervised automatic segmentation and their root mean square, bandwidth, entropy and spectral moment were calculated. The maximum of the normalized coefficient of the linear cross-correlation between each muscle pair were also computed as well as the slope throughout the execution of the exercise repetitions of all above mentioned parameters. Results from 2kg exercise did not reveal clear signs of fatigue. By contrast those from 4kg showed an increase of the root mean square and spectral moment ratio, and decrease of bandwidth, sample entropy and linear cross correlation coefficient, pointing out fatigue. In this study, it has been confirmed the viability of the cross-correlation technique as a possible new biomarker related to the first signs of muscle fatigue.

1. Introduction

Muscle fatigue is a complex neuromuscular condition developed by a chain of structural, energetic and metabolic variations due to lack of oxygen and other necessary nutritive substances in combination with changes in the performance of the nervous system. These changes make it impossible to the muscle to generate the required force. This phenomenon can appear in healthy and pathological subjects and is one of the most common symptoms in some neurological disorders such as Parkinson or multiple sclerosis [1, 2].

There are several methods to estimate muscle fatigue such as measuring the lactate concentration in a muscle taking blood samples, being an invasive procedure. Another method is timing a person doing certain task until their surrender. This last method is known as the 'mechanical manifestation of muscle fatigue'. One of the main problems of this method is that there is no insight to the physiological manifestations of the muscle during the activity and detects the fatigue only after it has already occurred. Moreover, it cannot be distinguished the origin of fatigue between physical or psychological factors [2].

Surface electromyography (sEMG) is a non-invasive method that can be used to assess local muscle condition in real time. Thus, EMG could target the fatigue of specific muscles and can provide early biomarkers of fatigue. The parameters most frequently used to determine muscle condition from EMG are their Root Mean Square (RMS), mean frequency or median frequency [1,2]. During the contraction of the muscles, the increase of RMS and the shift of the spectrum to lower frequencies are indicators of muscle fatigue [3]. However, despite the multitude of studies aiming the detection of fatigue, and the advances in new signal processing algorithms, it is still very complex to analyse these biosignals due to their variations, their lack of repeatability and their sensitivity to electrode location. On the other hand, there is great controversy about the performance of EMG-derived biomarkers for the early detection of fatigue [1,2,4].

The aim of this study is to analyse and compare traditional and novelty s-EMG parameters, during a non-extenuating protocol to assess the viability of these biomarkers as possible indicators of mild fatigue.

2. Materials and methods

The sEMG signals were recorded using an electromyograph designed and manufactured by our research group. This is a portable device, with three acquisition channels with a sampling rate of 1000Hz, bandwidth between 8.75 and 500Hz, and a gain of 24V/V. It is based on the microcontroller PIC24FJ128GC006 and the analog front-end ADS1299-4. The communication is wireless using Bluetooth technology, specifically a RN-42 module.

Eight healthy subjects, 2 women and 6 men, with an age of 33 ±13 years and with no history of neurological or neuromuscular disorders participated in this study. Three bipolar sEMG signals were recorded placing two Ag – AgCl disc type disposable electrodes with an inter electrode distance of 20mm over the muscle belly of Rectus Femoris (RF), Vastus Lateralis (VL) and Biceps Femoris (BF). Previously skin was cleaned with alcohol and shaved when needed.

The subjects warmed up for 3 minutes walking on a treadmill. Then, 2 dynamic exercises of flexo-extension of the knee were executed with 2 minutes of rest between exercises, lifting 2kg attached to their ankle and doing 15

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repetitions with each leg, the same protocol was repeated for 4kg. Muscle activations from the 3 bipolar sEMG recorded signals (one from each muscle) were automatically segmented [5] and 15 muscle activation signals (one for each repetition) were extracted from each muscle and exercise.

Afterwards, a set of parameters from sEMG activations was obtained: bandwidth - difference in frequency between 5% and 95% of the total power in the spectrum, RMS [6], sample entropy [7], Spectral Moment Ratio (SMR) [8] and the maximum of the normalized coefficient of the linear cross-correlation (MCC) between each pair of muscles [9] and the slope of these parameters over the 15 muscle activations was analysed calculating the slope for each muscle.

3. Results and discussion

In Table 1 it is displayed the mean of the sEMG features for the first and last 5 muscle activations for the exercises lifting 2 and 4kg.

Mean ± std values	Activ.	RF	VL	BF
Bandwidth [Hz] 2kg	[1-5]	317.9 ± 15.3	285.2 ± 17.6	365.8 ± 20.9
	[10-15]	308.3 ± 9.4	284.0 ± 15.4	373.1 ± 12.0
Bandwidth [Hz] 4kg	[1-5]	317.4 ± 11.1	285.2 ± 14.2	369.2 ± 13.2
	[10-15]	307.8 ± 8.8	281.6 ± 13.9	363.2 ± 15.2
RMS [µV] 2kg	[1-5]	49.1 ± 7.0	68.2 ± 12.1	27.0 ± 3.9
	[10-15]	52.7 ± 6.1	74.0 ± 8.5	28.3 ± 2.5
RMS [µV] 4kg	[1-5]	58.4 ± 9.7	70.3 ± 10.8	28.5 ± 3.7
	[10-15]	66.2 ± 6.8	81.3 ± 9.7	30.9 ± 3.3
Entropy 2kg	[1-5]	1.74 ± 0.16	1.11 ± 0.15	1.37 ± 0.13
	[10-15]	1.82 ± 0.12	1.06 ± 0.12	1.33 ± 0.11
Entropy 4kg	[1-5]	1.86 ± 0.14	1.12 ± 0.13	1.38 ± 0.12
	[10-15]	1.85 ± 0.13	1.07 ± 0.11	1.32 ± 0.13
SMR 2kg	[1-5]	-30.4 ± 0.15	-29.8 ± 0.23	-30.9 ± 0.33
	[10-15]	-30.5 ± 0.10	-29.9 ± 0.12	-31.0 ± 0.16
SMR 4kg	[1-5]	-30.6 ± 0.17	-29.9 ± 0.14	-31.0 ± 0.27
	[10-15]	-30.6 ± 0.10	-29.9 ± 0.13	-31.1 ± 0.22

Table. 1*. Mean and std values of the traditional parameters for RF (Rectus Femoris), VL (Vastus Lateralis) and BF (Biceps Femoris) muscles. during the first (1-5) and last (10-15) 5 muscle activations of the exercise.*

An increase of RMS and decreasement in bandwidth and sample entropy, between the beginning and the end of the exercises was observed for all muscles pointing out possible muscular fatigue. SMR did not reveal an observable difference between the mean value at the beginning and the end of the exercise. However, a more in-depth analysis of its trend of all the parameters will be carried out.

Table 2. represent the MCC mean and standard deviation of the first and last 5 muscle activations between each pair of muscles for the exercises lifting 2 and 4kg. In this case, there was a decrease of the correlation during the exercise.

Mean ± std values	Activ.	RF-VL	RF-BF	VL-BF
MCC 2kg	[1-5]	0.17 ± 0.04	0.13 ± 0.03	0.13 ± 0.03
	[10-15]	0.15 ± 0.03	0.12 ± 0.03	0.11 ± 0.03
MCC 4kg	[1-5]	0.17 ± 0.04	0.13 ± 0.03	0.13 ± 0.03
	[10-15]	0.15 ± 0.03	0.12 ± 0.03	0.11 ± 0.03

Table. 2. *Mean and std of the cross-correlation value between each pair of muscles during the first (1-5) and last (10-15) 5 muscle activations of each exercise.*

Then, for a more in-depth analysis of the evolution of the parameters, the calculation of their slope was carried out.

Fig. 1. shows the tendencies of the bandwidth evolution throughout the exercises. The slope of every muscle for the 4kg exercise is negative, this means, there was a reduction of the bandwidth throughout the exercise, which, according to the literature, is a sign of muscle fatigue [10]. It has also been noticeable that the agonist muscles exhibit less positive and more negative slopes than the antagonist muscle. This could imply that the agonist muscles point to a higher fatigue than the antagonist muscle.

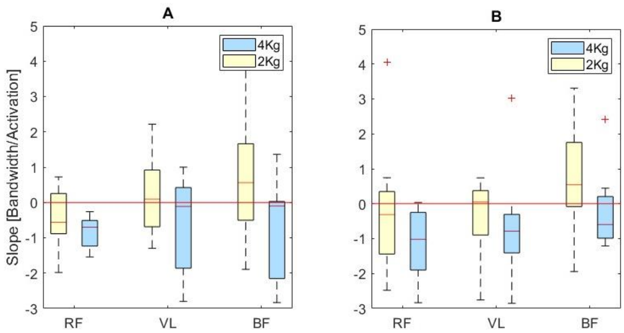

Fig. 1. *Box & Whisker plots of the bandwidth slopes through the 15 repetitions of the dynamic exercise with 2kg (yellow) and 4kg (blue) computed for each muscle. (A) Left leg, (B) Right leg.*

The results display an overall increase of the RMS (positive slope) in all exercises and muscles of both legs (Fig. 2). In this case, according to existing bibliography, the increase of the RMS values indicates muscle fatigue, although this parameter appears controversial due to difficulties in normalisation of the RMS [2,3]. RMS values for 4kg also has a higher slope comparing with 2kg, as occurs in the preview parameter, due to a higher effort and the outcome of a quicker fatigue state. Analysing the differences between agonists and antagonist muscles, the antagonist muscle exhibits less steep slope than the agonists.

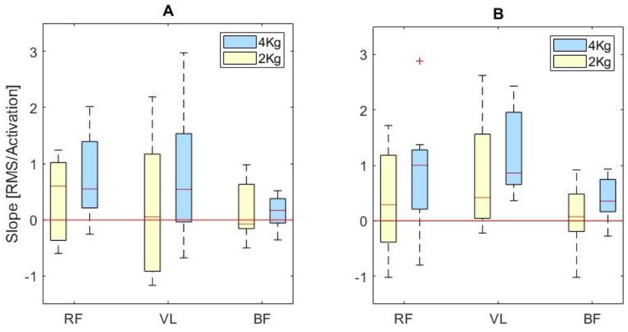

***Fig. 2.** Box & Whisker plots of the RMS slopes through the 15 repetitions of the exercise with 2kg (yellow) and 4kg (blue). (A) Left leg, (B) Right leg.*

Inspecting the slope for the sample entropy during the execution of the exercises, in Fig. 3., it is appreciable generally negative slopes except for the Rectus Femoris muscle in the right leg pointing out muscle fatigue as stated in the literature [11]. The probable cause of this effect is that the Rectus Femoris is the most trained muscle of the leg, and because all subjects are dexterous, and therefore less prone to fatigue. Moreover, the results of this parameter in this study are quite controversial due to various reasons. Firstly, there is no observable difference between the exercise with 2kg and 4kg in most of the cases. Secondly, the agonist muscles use to have similar behaviour in contraposition to the antagonist muscle, which is something that cannot be observed in this instance. According to bibliography, sample entropy is a parameter with low susceptibility to fatigue detection [12].

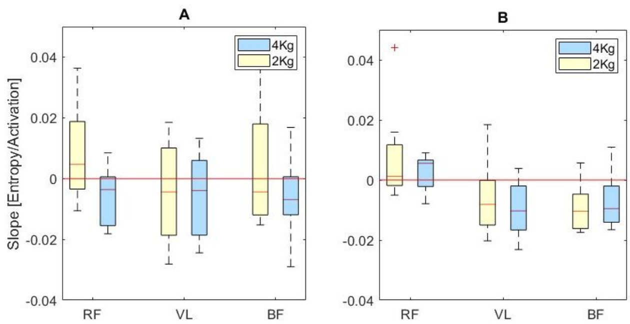

***Fig. 3.** Box & Whisker plots of the sample entropy slopes through the 15 repetitions of the exercise with 2kg (yellow) and 4kg (blue). (A) Left leg, (B) Right leg.*

Regarding the slope of the SMR (see Fig. 4) results show an evident displacement from more negative slopes with 2kg exercises to a more positive slopes with 4kg exercises in all muscles, according with the literature [8]. This increase of the slope is more blatant for agonist muscles (as the slopes reach positive values) than the antagonist muscle (the slopes become less negative, but not yet positive). Agonist muscles of the right leg are showing negative tendencies for 2kg exercises, which could be since the subjects are right-handed, their right leg is more trained leg, which may require more effort to show muscle fatigue. Although it doesn't show a clear tendency for mild fatigue, as the 2kg exercises show both positive and negative slopes, this parameter could lead to a possible discerning factor of mild muscle fatigue, as there are observable differences between 2kg and 4kg exercises.

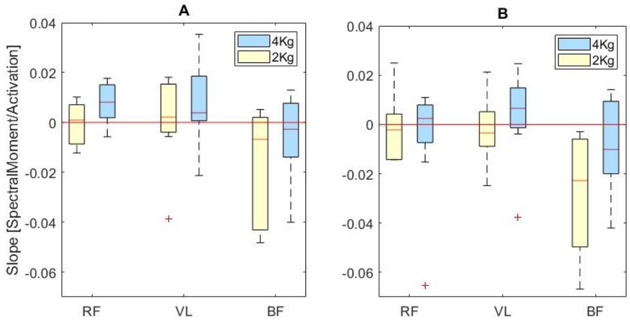

***Fig. 4.** Box & Whisker plots of the SMR slopes through the 15 repetitions of the exercise with 2kg (yellow) and 4kg (blue). (A) Left leg, (B) Right leg.*

The next step for the assessment of mild fatigue has been the analysis of muscle interactions. One of the undercurrent physiological behaviours in muscle fatigue is the slowing of conduction velocity of muscle fibers [13]. Cross-correlation technique is used in experiments to estimate the average muscle fiber conduction velocity during isometric exercises [13, 14]. Fig. 5. shows the box and whisker plots of the slopes of the MCC during the exercise. The results reveal mostly negative slopes for all exercises and pair of muscles. This increase of the delay between signals, leading to a decrease of the correlation may be caused by the reduction of the conduction velocity in the fibers due to muscle fatigue. This muscle impairment could also be associated to the first signs of muscle fatigue.

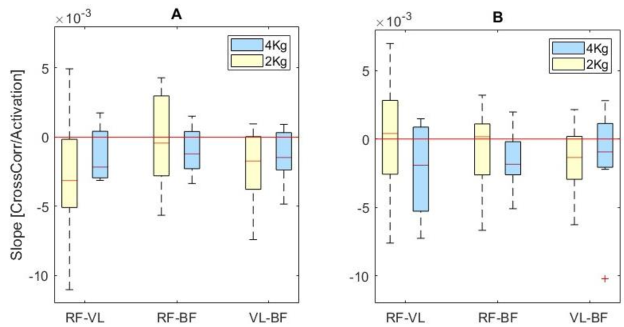

***Fig. 5.** Box & Whisker plots of the Cross-correlation slopes through the 15 repetitions of the exercise with 2kg (yellow) and 4kg (blue) for each muscle. (A) Left leg, (B) Right leg.*

In this study, the final objective has been the determination of mild muscle fatigue during the realisation of a dynamic exercise in healthy subjects. Bandwidth, SMR, RMS and sample entropy parameters show signs of fatigue in line with the state of the art [2,3,8,10-12], due to a specific tendency during the exercise, especially in agonist muscles lifting 4kg. These parameters did not show a specific tendency with the 2kg exercise, which could mean two possibilities, or they are not sensible enough to mild muscle fatigue, or due to the variability in the population, some did not achieve that state. From the rest of the parameters analysed in this study, MCC stands out because the reduction of the value during the exercise means a desynchronization of muscles leading to a mild fatigue. As these results are in accordance with the traditional parameters (temporal, spectral mainly), then, this is a possible feature for the determination of not only muscle fatigue, but other muscular injuries too, regarding muscular interaction and reduction of conduction velocity in muscle fibers.

The principal limitation of this study is the reduced database. For further investigation of these parameters, including a sensibility study, is imperative to increase it. Also, another handicap observed was the lack of a gold standard for the determination of the start of the fatigue state. This, correlated to the variability of the training status of the subjects and the exercise had low limited number of repetitions, then it was very difficult to determinate a state of muscular fatigue. Future studies will be done with higher number of participants and including an extenuating exercise ending with the surrender of the subject.

4. Conclusion

The purpose of this study has been to analyse the behaviour of traditional and novel parameters during a non-extenuating task with the objective of determine new biomarkers for muscular fatigue. The bandwidth, SMR, RMS and sample entropy did not reveal muscle fatigue during the 2kg dynamic exercise. However, the dynamic exercise with 4kg has given the expected results in the tendency of the traditional parameters. Between all these parameters, the SMR exhibited great performance in the early detection of fatigue, then bandwidth and RMS and lastly, sample entropy. The relationship between the reduction of conduction velocity of fibers during muscle fatigue and the muscle impairment seen in MCC values, as well as its accordance with the results of bandwidth, SMR, RMS reveals a potential biomarker for the first signs of muscle fatigue. Further investigations and sensitivity studies with a larger recording database will be done to verify present study.

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