STATE OF THE ART OF THE MUSCLE FATIGUE ASSESSMENT THROUGH SURFACE ELECTROMYOGRAPHY

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Abstract: The muscle fatigue is defined as an insufficiency in the capacity of the muscles for exerting strength with the intensity with that they made it normally, this carries to in the investigation field has become a wide subject of study that searches to benefit to sportsmen and workers. One of the procedures for the data acquisition that has the purpose the estimate of muscle fatigue is the surface electromyography (sEMG), which has been studied widely due to the ergonomic it presents for the study. In the sEMG analysis has been found relations between electromyographic signal changes with fatigue transition and muscle fatigue through the estimation of indices extracted in the time domain, spectral domain, time-frequency domain, and non-linear parameters.

This bibliographic review contextualizes to the reader about the different concepts that have been addressed in the studies of muscle fatigue using a meticulous conceptual framework which defines several aspects related to this subject, besides this work provide an overview of the more important works which have performed in the last years (2012-2018) for the evaluation of muscular fatigue from sEMG, emphasizing the muscles that have been commonly worked, data processing techniques, classification techniques and indices used in the different transformations of the EMG signal for the evaluation of fatigue.

Keywords: **data processing, muscle fatigue, muscular contraction, processing techniques, sEMG.**

I. INTRODUCTION

Muscle fatigue is a reduction in the maximum voluntary force induced by exercise [1], currently considered one of the most important subjects of study in the field of sports physiology, despite this, they conserve multiple questions due to their multifactorial nature [2], such for example the reaction of the muscle to lactic acid, the decrease of glycogen in the motor units, the alterations in the pH, in the temperature, or in the blood flow, the loss of Ca2 + ion homeostasis, muscle injury and oxidative stress. This subject has been addressed by different researchers of the physiology of exercise because the muscle fatigue has a high impact on the performance of athletes and that in turn becomes an important indicator of the risk factors for the occurrence of overload injuries that can be in some cases irreversible [3], [4].

On the other hand, muscle fatigue has also been widely studied in the field of occupational health, since the subject causes numerous injuries in workers of industries that perform mechanically or force work, generally associated with overload efforts [5],[6], in Colombia according to the ,*"Informe ejecutivo de la segunda Encuesta nacional de condiciones de seguridad y salud en el trabajo en el sistema general de Riesgos Laborales de Colombia."* carried out in 2013 [7] is established that 33.09% of the population, works all the time in positions that can produce fatigue or lift heavy loads without mechanical aids, 29.41% always or almost always work with forced efforts and postures inadequate and 38.04% always or almost always manifests fatigue or tiredness. The report also indicates that during the years 2009-2012 according to the reports carried out by the occupational risk insurers, the most trend attentions are to musculoskeletal injuries that represent 87%, 89%, 87% and 90% respectively, of the reports of occupational disease. Taking into account the previous, that is important to carry out researches which allow to the people predict possible muscle problems in order to generate better working conditions and avoid diseases associated with the musculoskeletal system, as has been done in other countries, where the topic has called the attention of the academic field which seeks to deepen into the causes, prevention and physiological phenomena related to muscle fatigue [8]-[13]. The data collection for the estimation of muscle fatigue is done in 2 ways, one of them are invasive techniques where is used: lactate level in the blood, the oxygen level in the blood, muscle pH, needle electromyography and others [14]. On the other hand, there are the non-invasive interventions which include techniques of surface electromyography, mechano-myography, acoustic-myography, ultrasound and infrared spectroscopy [15]-[18]. In addition, new technologies based on biomarkers have also been used in recent years [19].

The most used procedures for the estimation of muscle fatigue have been non-invasive techniques due to their ergonomics and to allow real-time monitoring.

Within the non-invasive study methods, we have surface electromyography or sEMG which has been widely studied, one of the pioneers in this subject was H. Piper who in 1912 noticed a progressive decrease in the sEMG signal, which consisted basically in a change in the spectral components of the EMG signals which are focus in the lowest frequencies [20], similar results have been obtained in others works [14], [21], [22]. The procedure to detect the physiological phenomenon which occurs in muscle fatigue [3], [20], [23]-[29], require analysis techniques in the time domain, domain of frequency and time-frequency domain [8], [30]-[34]. While a physical work is prolonged, these parameters present an increase or decrease behavior according to their properties and those are evaluated when a subject put on physical activity. From these procedures and the extraction of parameters such as those mentioned above, it is possible to detect or predict muscular fatigue though of signal processing methods and classification.

Given the importance of the topic of muscle fatigue in different areas such as sports and work, a bibliographic review was made to know the scientific and technological advances in the different processing methods in the last 6 years and identify possible future works or open research topics.

II. CONCEPTUAL FRAMEWORK

A. *Muscle contractions*

Muscle contractions are the phenomenon in which thin myofilaments or actin slip through the thick myofilaments or myosin towards the center of the sarcomere that is called the M line [35], through this process are generated muscular movements, strength and muscular endurance. The classification of contractions according to [36], [37], can be done in various ways based in the characteristics of the work which you want to perform, in this way we find that the contractions can be classified according to:

- Their direction: they can be classified as concentric (when the muscle length is shortened to overcome a load) or eccentric (when the length of the muscle lengthens because it is defeated by the load).
- Their length: the contraction can be isometric (if the muscle length is not modified independently of the tension) or dynamic (if there is a variation of the muscle length during the contraction).
- Their tension: the contraction may be isotonic (if the muscle tension is constant throughout the movement) or of a hetero-dynamic nature (if the tension is variable throughout the movement).

• Their speed: the contraction can be isokinetic (if the speed is equal during the contraction process) or hetero-kinetic (if the speed varies during the contraction process).

A given exercise can belong to several types of contractions at the same time, that is, is possible to performance exercises that are dynamic-concentric, isometric-isotonic, among others.

B. *Surface electromyography*

Electromyography (EMG) is based on the study of the electrical signals of muscles during an effort, either a movement or a contractile reaction in response to a load, therefore they are measures of the electrical activity generated by a neuron or a Neuronal group on a specific muscle [38]-[41]. The signals that can be obtained in the electromyography are due to the action potentials that travel from the central nervous system to the motor units and causing the depolarization of the membranes of the muscle fibers. In this way potential differences are created, ranging from 50uV to 10mV (peak to peak) [30], [38], [42],[43]. These amplitude values of the sEMG are influenced by the number of activated motor units, their discharge rate, their shape and the speed of propagation of the action potentials [20].

C. *Analysis in the time domain*

It refers to the extraction of characteristics based on the signal coming from sEMG without having previously made any transformation in the domain of the signal. In this signal the amplitude is represented as a function of time and the most used parameters take into account the amplitude characteristics an example of this is the mean absolute value (MAV) [44] or the root mean square (RMS) which has been widely used in research related to muscle fatigue [20],[23], [26],[29].

D. *Analysis in frequency domain*

When we refer to the analysis in the frequency domain we talk about the extraction of characteristics from the signal SEMG when this has been applied a domain transformation which allows us to analyze the signal in the spectral domain. Different researchers have reported changes in the frequency domain when there is a presence of muscle fatigue and "traditional" indexes have been established in the analysis of the signal to detect it, such as the average and median frequency (FM and Fmed) [4], [34],[45].

E. *Analysis in Time-Frequency domain*

During the extensive study that has been developed based on the analysis in the spectral domain, it has been established that the characteristics from this method of analysis works better in isometric contractions and presents complications when working dynamic contractions due to the non-seasonality of the signals during these contractions [46]. Variety of factors such as the positioning and movement of the electrodes, changes in strength, changes in muscle length, and the number of activated motor units contribute to the signal's non-seasonality during dynamic contractions [20], [30], while during isometric contractions the seasonality of the signal is greater. To address this problem that is presented during dynamic contractions, the time-frequency analysis was proposed, which allows analyzing the signals of varying frequencies over time and techniques have been implemented in this field, of which stands out the Short Time

Fourier Transform (STFT) and the Wavelet Transform (WT).

F. *Non-linear parameters*

The use of non-linear parameters is an alternative analysis technique to the previous ones, where it is suggested that myoelectric signals could be better modeled as outputs of a non-linear dynamic system instead of random stochastic signals, this proposal was made by Nieminen & Takala (1996) [20]. Currently the use of non-linear parameters for the analysis of muscle fatigue is gaining strength, especially the use of entropy and fractal analysis.

III. METHODOLOGY

This document establishes the development of a bibliographic review of the estimation of muscle fatigue through the analysis of the sEMG signal, for this purpose more than 70 articles were reviewed in a window of time defined as 2012-2018, the documents were searched through the meta-searcher SCOPUS, and the IEEE, Springer, Elsevier and ScienceDirect databases with the follow search algorithm: ("EMG" & "analysis" & “muscle" & "fatigue"). In order to carry out a detailed analysis of each document, the review focused on: the main objective, the methods used, the groups muscle worked, the type of contraction performed, the most important result and the problems presented or future work. Subsequently, the documents were classified into: time domain analysis, spectral frequency domain, time-frequency domain, non-linear parameter analysis, novel approaches, and related studies. As a result, 57 articles of documentary relevance were selected for the development of the present state of art.

In order to summarize the work done, the analysis was divided into 3 categories where each category is based on the work developed for different muscle groups. It is worth saying that the research that has been undertaken is very varied in the muscles taken, that is why a classification was made where are taken the muscles associated with the lower limbs, the muscles associated with the upper limbs and associated muscles to the torso and the back.

IV. RESULTS AND DISCUSSION

A. *Lower limbs muscles*

The muscles of the lower limbs such as the rectus femoris, the biceps femoris, hamstrings and vastus muscles are frequently analyzed. Generally, these studies are carried out during dynamic contractions [9], [11],[25],[46]-[49] with some exceptions [50]. These muscles are also widely used in research seeking to establish procedures to prevent muscle fatigue by evaluating aspects such as resistance, an example is [9] that through of dynamic-isokinetic contractions establishes that adequate hydration with hydrogen-rich water before of exercise reduces lactate levels in the blood and improves muscle performance.

Among the significant results are the work of [46] which shows that for an analysis of dynamic signals using FFT there are high values of variance that directly influence the standard deviation of the data, which could prevent the detection of representative differences in a given dataset. Therefore, for studies that use a small number of subjects where the variability of the data may compromise statistical comparisons, it is recommended to use WT, in this case, as in [51], the authors highlight the effectiveness in the use of the analysis in the time-frequency domain over the use of the spectral domain during dynamic contractions.

In the same way is possible to find novel approaches and little explored areas as in [47] where the authors sought to analyze the relationship between isokinetic power and electromyography (EMG-P) developing a reliable method for an exercise test standard cycle ergometer and in [52] where the conduction velocity (CV) and the fractal dimension (FD) are studied as reliable indicators of fatigue.

By last a significant and novel approach is considered in [16] since in the study three modes of data acquisition are used: electromyography (EMG), mechano-miography (MMG), and acoustic-myography and in this paper is established that the combination of the 3 myograms is suitable for the classification of fatigue and non-fatigue conditions.

B. Upper limbs muscles

On the other hand, the muscles of the upper limbs are the most explored according to the articles reviewed, and they use advanced signal processing techniques and novel algorithms focused on the classification and prediction of muscle fatigue [8], [44], [30],[53]-[56], it can be said that in these studies there is no specific trend with respect to the type of contraction, since they are managed both isometric and dynamic contractions [57],[44],[58]-[62].

In these muscles the use of the WT is a trend in recent years [5], [56], [63], [64], among the most significant aspects are:
The procedure of [5] in which the energy of the detail coefficients of the multilevel wavelet decomposition shows a promising parameter for the estimation of muscle fatigue when the muscular force decreases since the energy of the levels 3, 4 and 5 of the detail coefficients increases in the development of muscle fatigue. Likewise, the use of the WT has been explored and improved, as shown in [65] that exemplifies the use of feature selection methods such as genetic algorithms (GA) to find the best set of the characteristics of the sEMG signals for the classification process, other case of parameters selection is presented in [44] where the authors make a comparison between two methods of selection GA and Information Gain Based Ranking (IGR), the results show us a superiority of the data set selected with IGR.
Among the most important results is presented in [44] in which the accuracy of the classification procure using the characteristics of multiple time windows (MTW) is compared with the accuracy obtained using time and frequency domain characteristics. The results show a reduction in the mean and median frequency of the signals under fatigue conditions, the outcome agrees with those presented in previous works. It is important to say that the signal characteristics obtained using MTW methods give better accuracy than the time and frequency characteristics, but this can be because the selection of feature is established from a genetic algorithm (GA) and information gain-based ranking (IGR). The authors conclude that the MTW method extracts characteristics over time and does not require a transformation in the domain, therefore it has less computational load than the frequency techniques and that the features found are efficient in the study of non-stationary signals. However, the fatigue induction protocol proposed is based in isometric exercise, therefore is significant to carry out studies of this type during dynamic contractions where the analysis with time-frequency techniques and non-parametric analysis is taking force.
Another significant study is carried out in [8] where new algorithms to determine an overall EMG index for fatigue/strength relation assessment using the integrated mean EMG and the MF were suggested and demonstrated.
Following the line of significant results, a novel approach is established in [14] where the decrease in the mean frequency and the increase of the vibration speed are taken as parameters to determine the muscular fatigue localized during isometric contractions, the results indicate that localized muscle fatigue can be observed effectively with these two parameters combined. The method can apply to dynamic contractions, but, the researchers have not corroborated this information.

Finally, some researchers have bet on the evaluation of fatigue through a combination of sEMG and electro stimulation as proposed in [66], [67] which shows that wavelets can provide reliable indexes of fatigue by elongation of the M wave during an Electro-stimulus, other authors have also analyzed the behavior of the M wave under conditions of muscle fatigue [68].

C. Associated muscles to trunk and back

The analyzes that focus on the muscles of the neck, torso and back are a little scarcer than the previous ones, however they are considered of great importance for the prevention of diseases associated to the musculoskeletal system, generally the analyzes that involve the trapeziums are analyzed in dynamic contractions [58],[64],[65], while those of other muscles of the back and abdominal muscles tend to work isometric contractions. These analyzes generally seek clinical applications, where for example, fatigue estimation can be used as a diagnostic means in the case of [10].

In [64] the results showed less variability in the power values calculated by the DWT algorithm compared to FFT, which again supports the inadequacy of the analysis in the spectral domain for the evaluation of muscle fatigue during dynamic contractions.

D. Developments in the algorithms for detection and prediction of muscle fatigue

During the development of the work, it is possible to identify some indexes for the evaluation of muscular fatigue, which corresponds to the analysis in the time domain and the domain of the frequency. These indices are presented in table I. Is possible to say that the features extraction for the muscle fatigue evaluation is a field widely explored. Currently, many studios focus on the study of different methods for features selection and in the performance evaluation from classifiers.

The methods of analysis in time domain have been widely used due to its low computational complexity and low noise during the tests [30], a significant result with respect to the extraction of parameters is evidenced in [27] where the results show that the IIS index of sEMG had the highest correlation with muscle fatigue and the relationship was statistically significant ($p < 0.01$), similar results are obtained in [44] where the data sets from fatigue and non-fatigue show a statistically significant difference with respect to the parameters extracted of multiple time windows (MTW). In the same way it has been established that the use of characteristics in the spectral domain give good results under isometric contractions, however with the spectral index of Dimitrov has reported good results under dynamic contractions [20],[30].

Subsequently, were identified the methods used for the analysis in the time-frequency domain, the analysis of nonlinear parameters and some indices that were extracted [74], this summary can be observed in table II.

In the extraction of non-linear parameters, the use of entropy as an index stands out, such that the decrease in this parameter associated with muscle fatigue [20], since the frequencies tend to concentrate in the low-frequency bands generating greater attenuation in the high-frequency bands progressively producing a decrease in the entropy since the signal simplified.

In addition to this, it can be established that the use of GA or IGR for the selection of characteristics during the analyzes for maximize the performance of the classifiers, such as the one presented in [70] or [44] is a little-explored research area with great potential to guarantee precision of algorithms for detection and/or prediction of muscle fatigue.

	ÍNDICES	CÁLCULO		ÍNDICES	CÁLCULO
TIEMPO	Root Mean Square (RMS)	$\sqrt{\frac{1}{N}\sum_{n=1}^{N}(x(n)^2)}$	FRECUENCIA	Mean Frecuency (MF)	$F_{mean} = \frac{\sum_{n=1}^{N} n.S_x(n)}{\sum_{n=1}^{N} S_x(n)}$
	Variance of EMG (VAR)	$\frac{1}{N}\sum_{n=1}^{N}(x(n) - mean)^2$		Median Frecuency (Fmed)	$F_{median} = \frac{1}{2}\sum_{n=1}^{N} S_x(n)$
	Mean Absolute Value (MAV)	$\frac{1}{N}\sum_{n=1}^{N}\lvert x(n)\rvert$		Peak frecuency (PKF)	$F_{peak} = \left(arg\left(max(S_x(n))\right)\right)$
	Integrated EMG (IEMG)	$\sum_{n=1}^{N}\lvert x(n)\rvert$		Variance of CentralFrecuency (FC)	$F_{var} = \frac{1}{P_x}\sum_{n=1}^{N} S_x(n)(n - F_{mean})^2$
	Zero Crossing (ZC)	$\{x(n) > 0 \; and \; x(n+1) < 0\}$ $or \; \{x(n) < 0 \; and \; x(n+1) > 0\}$		Dimitrov normalized spectral moment indices (Flnsmk)	$Fl_{nsmk} = \frac{\int_{f1}^{f2} f^{-1}.PS(f).df}{\int_{f1}^{f2} f^{k}.PS(f).df}$ $k = 2, 3, 4 \; or \; 5$
	Slope Sing Changes (SSC)	$\sum_{n=1}^{N}[f\,[(x(n)-x(n-1))x(x(n)-x(n+1)]]$		Mean Power (MP)	$P_{mean} = \frac{\sum_{n=1}^{N} S_x(n)}{M}$
	Waveform Length (WL)	$\sum_{n=1}^{N}\lvert\Delta x(n)\rvert$ $\Delta x(n) = x(n) - x(n-1)$		Total Power (TTP)	$P_X = \sum_{n=1}^{N} S_x(n)$
	Increse in Sycronization Index (IIS)	$\lVert G\rVert = \sqrt{\sum_{i=1}^{N}\sum_{j=1}^{N}\lvert g_{ij}\rvert^2}$		Relationship between isokinetic power and electromyography (EMG-Piso)	N/A

TABLE I Indices of greater relevance in the domain of time and frequency identified in the development of the bibliographic review ([27]; [30];[47];[69];[73]).

ANÁLISIS	TÉCNICAS	ÍNDICES
DOMINIO TIEMPO-FRECUENCIA	Short Time Fourier Transform (STFTT)	Average Instanteneus Frecuency (AIF), Instantaneus Frecuency Variance (Fvar), Root Mean Square (RMS), Wavelet Indices
	Wavelet Transform (DWT and CWT)	
	Choi Williams Distribution (CWD)	
	Wigner-Ville Distribution (WVD)	
PARAMETROS NO LINEALES	Análisis Fractal	Entropy, Percentage of Recurrence (%REC), Percentege of Determinism (%DET), Hurst Exponent (HE)…
	Análisis Multifractal	
	Recurrence Quantification Analysis (RQA)	
	Principal Component Analysis	

TABLE II Identification of techniques and indices most used in the analysis in the time-frequency domain and in the analysis of non-linear parameters

Many researchers have addressed the study of muscle fatigue with time-frequency methods as wavelet transform, which becomes in one the most use transformation for the features extraction from where even they proposed new features, is possible that in future works pose optimization methods for seeking to improve the performance of different classifiers.

E. Statistical analysis and classification algorithms

The statistical analysis is a group of tests that allow us to know if some data sets are statistically different among themselves through the comparison of the parameters, the statistical analysis techniques implemented in the process of detection/prediction of muscle fatigue are varied, among them the variance analysis (ANOVA) and the regression models [13],[27],[46], [75]. An example is given in [27] that shows how a regression analysis was carried out to determine the linearity of the relationship between each characteristic and the force of contraction and then an analysis of variance is performed to determine the statistical significance of the relationship.

Similarly, in the classification area, multiple algorithms have been studied that can provide a high degree of accuracy in the identification of non-fatigue and fatigue states [15], [44],[70] where Support Vector Machine (SVM) has satisfactory results. In [44] the authors compare the mean and variance values in two data sets and show us the difference form behavior of these indices in the 2 sets.

A novel approach is proposed by Al-Mulla in [71] through which a base for the analysis of muscle fatigue is established through three periods, which are presented as non-fatigue, transition to fatigue and fatigue, generated great interest in the academic field that seeks to develop different prediction algorithms and / or detection of muscle fatigue, which explains why it has been adopted by different authors as can be evidenced in [55] in which they explore the detection of muscle fatigue using Deep Learning methods, and in [30] in which they resume the studies carried out by Al-Mulla to make a comparison in the effectiveness between many classifiers.

According to [30] the best classifier in the proposed approach (no fatigue, transition to fatigue and fatigue) is AR which presents an accuracy of 99% in the identification of the states, while in the task of detection of muscular fatigue the SVM classifier Gets a significant 96% accuracy. These accuracy values may vary depending on the features selection as is presented in [15] and [44] where the performance of the classifiers varies according to the type of characteristics.

According to [44] is important the performance evaluation of the classifiers with methods of features selection, in this article the authors work with features in the time domain using MTW and make a comparison with the performance of 4 classifier of the which highlight el kNN with a algorithm of features selection from IGR.

Finally a recent research proposed a bacterial foraging algorithm (BFA)-Gaussian support vector classifier machine (GSVCM) model was proposed to improve the fatigue classification accuracy of electromyography (EMG) signals, this proposal seems to be very promising since it improves the accuracy of the classifier [72].

V. CONCLUSIONS

- The analysis in the time-frequency domain through of wavelet transforms has become a trend in recent years to evaluate muscle fatigue in dynamic contractions, having satisfactory results that surpass the analysis in the spectral domain offered by the Fourier transform.
- Although extensive studies have been conducted regarding the detection of muscle fatigue based on the SEMG, the studies that seek to predict it are poor, therefore fatigue prediction can be considered as an open study subject for future researchers who wish to prevent this physiological phenomenon.
- In recent years, new indices for the estimation of muscle fatigue have been developed that should be explored in depth to corroborate their efficiency and reproducibility in order to know their real impact in the detection and prediction of muscle fatigue.

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- "Solar Mobile Robot". Journal "Colombian Advanced Technologies" ISSN: 1692-7257.
- "Case study of the learning environment generated in an introductory course in robotics". Virtual Journal Universidad Católica Del Norte ISSN: 0124-5821.
- "Analysis and Application of a Displacement CPG-Based Method on Articulated Frames". Advances in Computing. CCC 2017. Communications in Computer and Information Science, vol. 735. Springer.