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Isokinetic Work-to-Surface Electromyographic Signal Energy Ratios as a Muscular Fatigue Indicator

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Abstract—**Efficiency of muscular work is usually measured as the relationship between work load and maximum exercise duration. The present study analyzes the efficiency feature as a ratio between mechanical work (WK) and the energy (E) of the surface electromyographic signal (SEMG). This relation (WK/E_{SEMG}) was compared with the most common electromyographic descriptors and its behavior was observed during muscle fatigue. A total of sixteen healthy men (26.8 ± 4.7 yrs, 175.7 ± 4.7 cm, and 79.2 ± 9.4 kg) performed three sets of ten maximal concentric repetitions of dominant knee extension at 60°/s on an isokinetic dynamometer, with 1 minute of rest interval between the sets. The SEMG signals were recorded during the exercises. With the view to minimize the factors other than fatigue that also influence the SEMG descriptors behavior, the only isokinetic repetition phase considered for measurements was the load range. Statistical analyses showed significant correlations between WK/E_{SEMG} and the traditional electromyographic fatigue indicators.**

I. INTRODUCTION

RESEARCHES of human movement have pointed that there are three main ways of describing mechanical efficiency during exercise [1]: (1) gross efficiency, expressed as the percentage ratio of external work performed to the total production of energy; (2) net efficiency, expressed as the percentage ratio of work performed to the extra energy expenditure during the exercise; (3) delta efficiency, expressed as the percentage ratio of the change in work performed per minute to the change in energy expended per minute. In a physiological aspect, work efficiency represents the product of two phenomena [2]: (1) the efficiency with which the chemical energy of glucose and/or fat is converted to adenosine triphosphate (ATP) through oxidative phosphorylation; and (2) the efficiency with which the chemical energy of ATP hydrolysis is converted to work. Previous studies have focused on the importance of accurately measure mechanical efficiency in order to well know the human movements and the forms of locomotion, what yields, for example, in methods to estimate internal power generated to overcome inertial and gravitational forces related to the movement when external power is delivered [3], [4].

Another important characteristic related to the study of human movement is the muscular fatigue. Although it is not difficult to know when one is fatigued, it is entirely another matter to be able to identify the physiological mechanisms responsible for this condition [5]. In general, fatigue can be defined [6] as “any exercise-induced reduction in the ability of a muscle to generate force or power.” Muscle fatigue can refer to a motor deficit, a perception or a decline in mental function [5]. It can describe the gradual decrease in the force capacity of muscle or the endpoint of a sustained activity, and it can be measured as a reduction in muscle force, a change in electromyographic (EMG) activity or an exhaustion of contractile function [5]. Regarding to EMG signal, fatigue is known to be reflected as an increase of its amplitude and a decrease of its characteristic spectral frequencies [7]. Whereas this assertion may be valid under completely static conditions, its validity is questionable under dynamic conditions [8]. However, some researchers have claimed some success in tracking fatigue with a single myoelectric parameter when contractions yield cyclic changes in muscle length and/or tension [8].

The main goal of this study is to analyze the muscular work efficiency feature as a ratio between isokinetic work (WK) and the energy (E) of the surface electromyographic signal (SEMG), as well as to determine how this relation (WK/E_{SEMG}) is good enough to indicate muscular fatigue on isokinetic exercises. The load range phase of the isokinetic repetition [9] was the only phase used in the analysis to assure similar cyclic conditions. Statistical correlations between WK/E_{SEMG} and the traditional electromyographic descriptors showed significant values.

II. METHODS

A. Subjects

The subjects were sixteen normal healthy adult males, with no history of orthopedic disease, aged 18-37 years (mean and standard deviation 26.8 ± 4.7). Their height and weight were 175.7 ± 4.7 cm and 79.2 ± 9.4 kg, respectively. They signed a written consent form before participating in the experiment voluntarily. The project was approved by the

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B. *Dynamometer setup*

A calibrated Biodex System 3 Pro isokinetic dynamometer (Biodex Corp., Shirley, NY, USA), which has been shown to be a reliable instrument for collecting data and a valid measurement tool of human torque, joint position, and limb velocity [17], [18], [29], [30] was assembled with the knee attachment according to the manufacturer's specifications [19]. The dynamometer shaft was aligned with the assumed axis of rotation (lateral femoral condyle) of the dominant knee (right leg for all the subjects) with the subject in a seated position and the back reclined at approximately 110º. The left thigh was secured with straps as were the waist and thoracic torso [20]. Arms were placed across the chest with hands grasping the straps [21]. The lever arm pad was positioned to place the inferior aspect immediately superior to the medial malleolus. Subjects were passively moved by the dynamometer through a ROM of 90º of flexion to 0º of extension (full extension). The mechanical stops of the ROM were set at 90º and 10º of knee flexion. Gravity compensation analysis was performed by the computer system software provided with Biodex System 3 Pro.

C. *SEMG and biomechanical data acquisition*

An electromiograph (EMG 16, OT Bioelettronica Snc, Italy) connected to a laptop computer with a PCMCIA card was used to acquire the SEMG signals. The optimal SEMG acquisition region of the *vastus lateralis* muscle was mapped with a semi-flexible linear electrode array of 16 electrodes (Ag, 5mm inter-electrode distance, OT Bioelettronica Snc, Italy) during a 5s of a maximum voluntary knee isometric contraction at 60º. After mapping, a flexible linear electrode array of eight electrodes (Ag-AgCl, 1x10mm with 5mm inter-electrode distance, OT Bioelettronica Snc, Italy) was placed over the cleaned skin of the *vastus lateralis* muscle between the enervation zone and the tendon region with conductive gel using single differential configuration, resulting in seven SEMG signals for each acquisition. A reference electrode was placed on the right kneecap. Electromiograph was setup with a sample rate of 2,048 Hz and an analog gain of 2,000 in the single differential configuration.

The Biodex System 3 Pro was built with the feature of record the biomechanical signals with a sample rate of only 100 Hz. Hence, the dynamometer DB-15 female interface [19] had to be used to record biomechanical signals at the same sample rate which the SEMG signals were acquired. This interface provides in real time analog signals of torque, angular velocity, and angular position. An adaptor was built by the authors in order to get the signals from DB-15 interface and send them into three separated BCN connectors of a digitizer board (BCN-2120, National Instruments, TX, USA) which recorded the biomechanical signals at a sample rate of 2,048 Hz, quantized with 12 bits.

With the view to guarantee the posterior synchronization between biomechanical and SEMG signals, a marker of magnetic pulses was developed in the Biomechanical Laboratory of the College of Physical Education. The marker was fixed on the lever arm to register the exact beginning time of each knee extension cycle and the magnetic pulses were sent simultaneously to the electromiograph and the digitizer board.

D. *Isokinetic experimental protocol*

Following equipment setup, subjects were asked to perform 10 gradient sub-maximal reciprocal concentric extension (240º/s) and flexion (300º/s) repetitions for warm-up and familiarization with the equipment. In addition, the subjects performed three sets of ten maximal concentric repetitions of dominant knee extension at 60º/s, with 1 minute of rest interval between the sets. Consistent and standard, moderate (no yelling or screaming) verbal encouragement was given; however, the computer screen was not made accessible for visual feedback [22]-[24].

E. *Signal processing*

A software tool [10] was used to synchronize SEMG and biomechanical (torque, angular velocity, and angular position) signals, as well as to adjust the DB-15 volts quantities of the recorded signals to the real units (N·m, degrees per second, and degrees), following the manufacturer's specifications. A bandpass zero-phase FIR filter was applied to the SEMG signals in order to cut off the frequency components out of the SEMG bandwidth (20 Hz to 500 Hz) [12]. The root mean square (RMS), median frequency (MDF), and mean frequency (MNF) of the SEMG signals were calculated as in [11]. Fiber membrane conduction velocity (CV) was estimated as in [13]. The isokinetic work [9], [25] and the SEMG energy [14] were determined to calculate the WK/E_{SEMG} ratio. All the descriptors were calculated over the load range phase of the isokinetic repetition [9], what was possible because of the features implemented in the software tool [10]. Linear regressions were performed for all descriptors and the fatigue index (FI) – defined by the angular coefficient normalized by the linear coefficient (initial value) [26] – was calculated for comparing the muscular activity between different subjects [27].

F. *Statistical Analysis*

Statistical analysis was made for all descriptors in each of the three isokinetic sets and for a larger set built by a concatenation of the first three sets. Shapiro-Wilk's normality test was applied in all related cases. Pearson's correlation coefficient was calculated for the normally distributed cases and Kendall's tau non-parametric correlation was determined for the non-normal ones [15].

III. RESULTS

Table I shows the FI for all descriptors in each isokinetic set. Table II illustrates the correlation coefficients and their respective significance when $FI_{WK/E_{SEMG}}$ is correlated with the

TABLE I
FATIGUE INDEX OF EMG AND EFFICIENCY DESCRIPTORS IN EACH ISOKINETIC SET
(MEAN ± STANDARD DEVIATION) · 10^{-3}

Set	FI_{RMS}	FI_{MDF}	FI_{MNF}	FI_{CV}	$FI_{WK/E_{SEMG}}$
S_1	12.69 ± 18.84	-16.55 ± 8.84	-15.97 ± 7.16	-11.92 ± 36.96 *	-43.42 ± 31.73 *
S_2	6.68 ± 16.72	-10.02 ± 8.77	-11.56 ± 6.65	-78.36 ± 268.67*	-52.46 ± 13.70
S_3	0.33 ± 13.87	-11.82 ± 8.54	-11.26 ± 6.36	-15.33 ± 28.23 *	-45.68 ± 18.04

* Significantly non-normal ($p < 0.05$)

TABLE II
STATISTICAL CORRELATION BETWEEN $FI_{WK/E_{SEMG}}$ AND THE FI OF EACH EMG DESCRIPTOR IN EACH ISOKINETIC SET

Set	Statistic	RMS	MDF	MNF	CV
S_1	*CC*	-0.81 **	0.46 *	0.53 **	-0.03
	Sig.	<0.01 τ	0.01 τ	<0.01 τ	0.87 τ
S_2	*CC*	-0.89 **	0.29	0.47	0.18
	Sig.	<0.01 *r*	0.25 *r*	0.55 *r*	0.32 τ
S_3	*CC*	-0.89 **	0.06	0.31	0.29
	Sig.	<0.01 *r*	0.82 *r*	0.22 *r*	0.10 τ

CC is the correlation coefficient.
Sig. is the 2-tailed significance.
τ represents the Kendall's tau non-parametric correlation.
r represents the Pearson's parametric correlation.
* Correlation is significant at the 0.05 level.
** Correlation is significant at the 0.01 level.

TABLE III
FATIGUE INDEX OF EMG AND EFFICIENCY DESCRIPTORS FOR THE CONCATENATED ISOKINETIC SET
(MEAN ± STANDARD DEVIATION) · 10^{-3}

Set	FI_{RMS}	FI_{MDF}	FI_{MNF}	FI_{CV}	$FI_{WK/E_{SEMG}}$
S_{123}	7.56 ± 17.02	-13.37 ± 9.05	-13.45 ± 7.17	-15.81 ± 155.35 *	-47.95 ± 21.90 *

* Significantly non-normal ($p < 0.05$)

TABLE IV
STATISTICAL CORRELATION BETWEEN $FI_{WK/E_{SEMG}}$ AND THE FI OF EACH EMG DESCRIPTOR IN THE CONCATENATED ISOKINETIC SET

Set	Statistic	RMS	MDF	MNF	CV
S_{123}	*CC*	-0.68 **	0.21 *	0.32 **	0.12
	Sig.	<0.01 τ	0.03 τ	<0.01 τ	0.24 τ

CC is the correlation coefficient.
Sig. is the 2-tailed significance.
τ represents the Kendall's tau non-parametric correlation.
* Correlation is significant at the 0.05 level.
** Correlation is significant at the 0.01 level.

IF of each electromyographic descriptor in each isokinetic set. Table III is similar to Table I, however the three isokinetic sets were concatenated to generate an only and larger set. This fact also represents the difference between Table II and Table IV since the last establishes the correlations considering the larger set.

IV. DISCUSSION

Conventional electromyographic fatigue indicators are related to amplitude features (RMS), spectral features (MDF and MNF), and CV. Their behavior revealed a progressive state of fatigue after the three isokinetic sets. The proposed efficiency indicator was compared with the classical ones.

The results in Table I showed a behavior consistent with what is expected under fatigue conditions. Increases in RMS values were registered for the three sets, however with decreasing FI values along the sets. This is a consequence of the applied protocol where the subjects were oriented to perform the exercises producing the maximal force. Thus, it is reasonable to think that the most part of muscular motor units (MU) were activated in the first set in order to reach the maximal force. The slope of FI_{RMS} is highly accentuated in the first set, indicating higher amplitudes and E_{SEMG} production. The efficiency indicator $FI_{WK/E_{SEMG}}$ reveals its better performance what means that more work was produced with less energy. In the second set, FI_{RMS} continues its ascendant tendency, with a lower intensity, but still indicating new MU recruitment and a necessity for more quantity of energy. The $FI_{WK/E_{SEMG}}$ in S_2 shows that even the supposed additional MUs recruited were not enough to maintain the same work production of the previous set. This could indicate a fatigue state according to the definition of muscle fatigue [16] as "an exercise-induced reduction in the ability of muscle to produce force or power whether or not the task can be sustained." This fact could justify the little slope of the FI_{RMS} in S_3. However, there is a recuperation of the $FI_{WK/E_{SEMG}}$ in S_3 which could be associated with the ability to continue the task (non- exhausted muscle) at a low level of energy production [5].

For the three sets the spectral indicators (FI_{MDF} and FI_{MNF}) and the CV manifested a decrease what is also related to the fatigue state [7], [28]. Nevertheless, the CV in S_2 has a great standard deviation which could be related to motion artifacts [31].

Table II shows that RMS has a high negative correlation with WK/E_{SEMG} what is easily understandable since RMS is directly proportional to E_{SEMG}. Regarding to spectral indicators, WK/E_{SEMG} is significant correlated with MNF and MDF only in S_1 what is not sufficient to suppose the proposed ratio as a reliable fatigue indicator. Since the MNF has been hailed as the gold standard for muscle fatigue assessment [8], at least under static conditions, we could expect that the WK/E_{SEMG} had some kind of correlation with the MNF.

So, in order to investigate the collected data under another point of view, all the three sets were sequenced and concatenated, what permitted to analyze the isokinetic protocol as a whole. Table III shows the FI of each descriptor for the concatenated set. Their behaviors are still coherent with a muscular fatigue state and the CV presents a high standard deviation influenced by S_2. Table IV shows that for the entire protocol the WK/E_{SEMG} has significant correlations with the spectral descriptors. This may suggest the WK/E_{SEMG} as a possible indicator of fatigue at the same that time it shows how efficient a muscular activity can be performed.

V. CONCLUSION

The SEMG behavior for the dynamic isokinetic contractions performed in the load range phase was similar to that usually related for static contractions. This was possible probably because of the similar cyclic conditions provided by load range phase.

The proposed efficiency indicator showed significant correlations with traditionally recognized fatigue indicators (MNF and MDF) when the isokinetic protocol was seen as a whole. However, further analysis is needed in order to consolidate WK/E_{SEMG} as a reliable fatigue indicator.

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