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Electromyography Linear and Non-Linear Analyzing to Evaluation of the Rest Times Adequacy between 30 Lumbar Extension Tests for Fatigue Prevention

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SUMMARY

Objective. This paper aims to answer the following question: "*Do the endurance and rest times defined in the studies prevent the physiological fatigue and its central and peripheral aspects?*".

Methods. 16 muscles activity are recorded from 14 healthy men (23-29 years) during maximum lumbar isometric extension in different postures (30 trials). The electromyography linear analysis (root-mean-square (RMS) and median-frequency (MDF)) is performed to investigate the physiological fatigue. Non-linear analysis is also used to examine the central (fractal-dimension (FD)) and peripheral (recurrence-quantification-analysis (RQA)) aspects. The relationship between FD and RQA is evaluated through t-tests in each muscle, separately.

Results. The FD in all trials is above 1.9, and RQA average is equal to 0.198 ± 0.057. There is a possibility of fatigue for one muscle in two subjects and its type is peripheral; t-test show a significant difference between FD and RQA in all muscles ($p = 0.000$).

Conclusions. The fatigue possibility increases during consecutive tasks. Thus, we suggest that in the case of consecutive trials, it is better to choose a longer rest time than what suggested in endurance time studies to prevent from physiological fatigue. Besides, the RQA and FD schemes are suitable for investigation of the peripheral and central fatigue, respectively.

KEY WORDS

Electromyography; endurance time; physiological fatigue; relaxation allowance; rest time.

INTRODUCTION

In the biomechanical and functional evaluations of the body segments, the fatigue and its prevention strategies are one of the most important factors because it can affect on the movement behavior by 50% (1) and increase the chance of damage by 60% (2). It has been shown that the muscular fatigue influences the trunk movements, muscles activity and spinal loading (3). The fatigue leads to the changes in muscles activity, performance limitations and efficiency decreasing, which can affect the experimental results. Thuse, understanding the fatigue basic mechanisms and developing methods for its prevention is essential (4).

Fatigue is a psychological-physiological state. The physiological fatigue represents a complex phenomenon that includes various causes, mechanisms, and manifestations (5, 6). Electromyography (EMG) is an important non-invasive measurement method to evaluate the physiological fatigue (7). The simultaneous investigation of the amplitude and frequency of EMG can show the changes in muscle activity caused by fatigue (6, 8, 9). Briefly, if the EMG amplitude increases and its frequency decreases, this indicates the muscle fatigue (6). There are many studies in the field of fatigue detection based on EMG amplitude and frequency (7, 10, 11). According to its origin, the physiological fatigue can be divided into two parts: central (inappropriate central activation during contraction (12)) and peripheral (peripheral mechanisms damage from stimulation to contraction (13)) fatigue (13). It is suggested that the fatigue myoelectric manifestations can be better described if the central/peripheral aspects are measured separately instead of a single fatigue index (14). In this context, the nonlinear EMG analysis methods are used which are based on the neural networks (13) such as recurrence quantification analysis (RQA) and fractal analysis (or fractal dimension, FD) methods. The RQA is based on a graphical method to detect specific structures in signals that repeat during contraction (13). The FD is an indicator based on the hypothesis that the normal EMG interference pattern has fractal properties (15).

To investigate the central and peripheral fatigue separately, Mesin *et al.* (14) compared the FD with the other indices of muscle fatigue. They found that FD is the index that is least affected by conduction velocity changes (a strong indicator of peripheral fatigue (4)) and fat layer thickness, and it has the highest correlation with synchronization level. The other studies confirm the relationship between the FD and central fatigue (4, 16). It is suggested that the RQA method can indicate the increase of the deterministic structures during a fatigue contraction (13). Thus, it is a diagnostic tool to investigate the peripheral fatigue (17, 18).

To prevent the fatigue during activity, two concepts of maximum endurance time (ET) and relaxation allowance are used. ET refers to the maximum time that a static muscle load can be maintained, and it is related to the static muscle work (19). This factor is useful to determine the differences between genders and anthropometric variables (20). El ahrache *et al.* summarized the ET models and presented a model for calculating ET in the lower and upper limbs separately (19). Using this model, in our previous study, we used two-minute rest periods between 5-second duration trials to prevent fatigue (21). Usually, the number of trials is not taken into account in the ET and relaxation allowance models. Considering the large number of trials in our study and the effect of fatigue on the experimental results, the aim of this study is to answer this question: "*Do the defined ET and relaxation allowance times prevent from the occurrence of physiological fatigue and its central and peripheral aspects in consecutive trials?*".

METHODS

Study design and participants

14 male volunteers between the ages of 23-29 participated. None of them had a history of low back pain or injuries in the past year. Mean of weight and height of them were 74 kg and 177 cm, respectively. All subjects were informed about the study design and signed an informed consent. The participants information was kept confidential and they could withdraw from the tests at any time. The study was reviewed by Tabriz University of Medical Sciences Committee (Tabriz, Iran). It was approved by IR.TBZMED.REC.1400.312 ethics code on April 24, 2021.

The tests were designed to obtain how the maximum lumbar extension torque and muscle activity change with respect to the change of the trunk position in three anatomical planes. To record muscle activity, surface EMG electrodes were placed on the external oblique (EO), rectus abdominis (RA), internal oblique (IO), erector spinae (ES), iliocostalis lumborum at the distances of the 3 and 6 cm (IL3 and IL6), latissimus dorsi (LD) and multifidus (MF) in both sides (22). The test was performed in two steps: 1) maximum voluntary contraction (MVC) in six main directions in upright standing posture with two repetitions (12 tests), and 2) maximum voluntary isometric extension at different angles of three motion planes (30 tests). Each test consisted of 5-seconds of activity with two-minute intervals between tests (more information regarding the data recording method (21)).

Data analysis

EMG signal processing was used to investigate the possibility of general physiological fatigue and its peripheral and central aspects. To this end, a steady 3-seconds of torque (3-seconds with the least standard deviation (SD)) and its equivalent EMG was selected. After noise cancellation, linear factors including the median frequency (MDF) and root mean square (RMS), and the nonlinear factors of the fractal dimension (FD) and recurrence quantification analysis (RQA) were calculated. The RMS was calculated using a 200 ms window and its maximum value was extracted (**figure 1A**). The Fourier transform was used to calculate the MDF (**figure 1B**). About FD, the box counting method, which is one of the common fractal analysis methods, was used (13, 15) (**figure 1C**). In order to find RQA, early embedding dimensions (D) and time delays (τ) were calculated using false nearest neighbor (FNN) (**figure 1E**) and mutual information (MI) (**figure 1F**) methods, respectively. Then, the recurrence plots were created using the Euclidean distance and the threshold of 0.10 of the maximum distance. Finally, the percentage of determinism (%DET) was calculated by measuring the diagonal lines with a length of more than 2 points (**figure 1D**).

After calculating the mentioned factors, the possibility of the general physiological fatigue (increase of RMS simultaneous with MDF shift towards low frequencies) as well as its central (decrease in FD) and peripheral (increase in %DET) aspects were evaluated for 30 trials (step 2). Considering the subjects placement in different positions and the possibility of the resultant differences in the factors, the mean and SD were calculated from the 12 initial trials (step 1) for all of the 4 factors in each muscle,

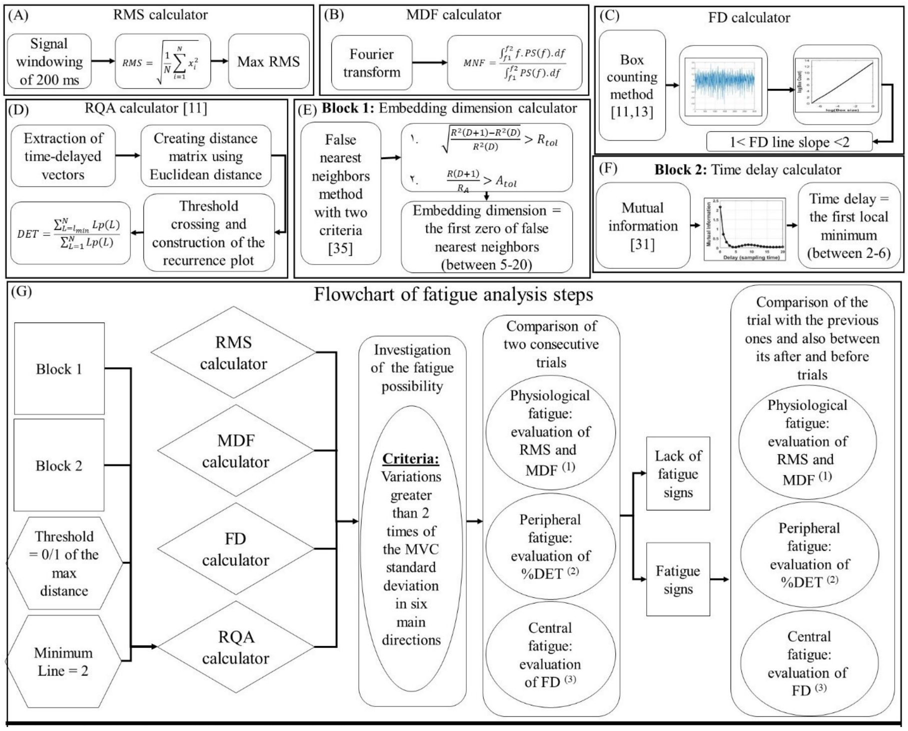

Figure 1. Calculating methods of **(A)** RMS, **(B)** MDF, **(C)** FD, **(D)** RQA, **(E)** D, **(F)** τ and **(G)** the steps taken to investigate the possibility of physiological fatigue and its central and peripheral aspects.

(1) Increase of RMS simultaneous with decrease of MDF (5, 7-9); (2) Increase of %DET (15-17); (3) Decrease of FD (4, 12).

separately. Hence, if the variation of each factor was more than 2 times of its SD, it was considered as a manifestation of fatigue. In the first step, the changes of the RMS, MDF, FD and %DET were evaluated in each trial compared to the previous one. After that, the trials by fatigue manifestation were evaluated in two other stages. These investigations were done with this fact that if fatigue has occurred, it must be displayable in the trial in question compared to the previous ones, and also between the previous and preceding trials. Therefore, the fatigue manifestation factors were compared between the trial in question with the previous trials as well as between its previous and following trials. **Figure 1G** shows the flowchart of the steps taken to assess the fatigue probability.

Also, the relationship between FD and RQA was evaluated through t-test for each of the muscles.

RESULTS

In total, RMS, MDF, FD, %DET, D and **τ** values are calculated for 14 subjects in 42 trials. The FD value for all muscles in all subjects is between 1.903-1.911. **Table I** shows the mean of %DET for each muscle in all subjects.

The values of embedding dimension and **τ** are between 5-20 and 2-6, respectively.

The simultaneous evaluation of MDF and RMS shows that the increase of RMS simultaneously with the decrease of MDF exceeds the threshold in one muscle of two subjects. The ES muscle of subject 8 in the 20th trial onwards and the IL6 muscle of the subject 12 in the 17th trial onwards show fatigue manifestation. The investigation of the %DET for these cases shows its increase greater than the threshold (twice the SD). The FD values for these cases as well as all of the subjects in all of the trials are very high (above 1.9) and the reduction of FD by more than the threshold is not observed in any of the subjects and muscles.

The t-test results for the muscles separately show that there is a significant difference between FD and RQA (%DET) in all of the muscles (p = 0.000). The **table II** shows the results of these tests.

DISCUSSION

The studies show that the fatigue can increase the risk of back injuries by affecting the motor behavior and muscular activity (1-3). Two concepts of ET and relaxation allowance are

Table I. The mean value of %DET for 16 abdominal and lumbar muscles in all subjects.

Muscle	Mean	(SD)
REO	0.16	0.19
RRA	0.15	0.26
RIO	0.23	0.29
RMF	0.2	0.16
RES	0.2	0.17
RIL3	0.2	0.16
RIL6	0.2	0.23
RLD	0.27	0.27
LEO	0.14	0.22
LRA	0.12	0.23
LIO	0.22	0.26
LMF	0.22	0.2
LES	0.22	0.21
LIL3	0.29	0.25
LIL6	0.072	0.13
LLD	0.28	0.25

used to prevent fatigue in the experimental tests (19). Recent investigations seek to increase the endurance time in order to enhance the subjects' efficiency, especially in the sports fields using different methods (such as the use of caffeine) (8). Therefore, considering the importance of fatigue and its effect on the experimental results, this study was conducted with the aim of evaluating the physiological fatigue possibility and its central/peripheral aspects during consecutive trials with ET and relaxation allowance suggested in the studies.

An increase in the amplitude simultaneous with a decrease in the mean and median frequencies is a common pattern that has been reported as a fatigue manifestation in the lumbar muscles EMG signals (22, 23). In the present study, the possibility of the physiological fatigue, despite having the rest periods between trials, was evaluated using linear analysis of EMG. In order to consider the effect of the changes in muscle activity due to the different positions in 30 trials, 12 primary tests were used. For this purpose, the SD of each factor in first 12 trials (MVC in 6 main directions) were calculated and its double was considered as the permissible limit of change due to the position (doubling is due to the possibility of positive and negative changes). Finally, the simultaneous increase of RMS along with the decrease of MDF exceeding the threshold was considered as a sign of fatigue. If this sign is observed, comparison of all trials in addition to the consecutive ones was used (**figure 1G**). It should be noted that the rest time is not enough for recovering, so if

Table II. The results of t-test to evaluate the difference between FD and RQA in 16 muscles.

Muscle	T	df	P-value
REO	218.667	587	0.000
RRA	161.392	587	0.000
RIO	141.691	587	0.000
RMF	265.358	587	0.000
RES	243.425	587	0.000
RIL3	251.198	587	0.000
RIL6	181.684	587	0.000
RLD	149.428	587	0.000
LEO	200.147	587	0.000
LRA	191.761	587	0.000
LIO	161.522	587	0.000
LMF	208.296	587	0.000
LES	195.612	587	0.000
LIL3	157.087	587	0.000
LIL6	357.567	587	0.000
LLD	158.905	587	0.000

a muscle is fatigued in one trial, this fatigue is also present in the next ones. Taking this fact, the physiological fatigue possibility occurred only for one muscle of two subjects and complete fatigue is not observed in any of them.

The separate examination of fatigue central/peripheral aspects using EMG non-linear analysis methods (RQA and FD) is a matter of great interest recently (4, 14, 17, 18). We used the box counting method to calculate FD (13, 15). In this method, the EMG signal is gridded with a specific box size (initially one box with the length of the signal) and the number of boxes that contain the signal is counted. This manner is repeated with different box size and the curve of the inverse box sizes logarithm with the number of counted box logarithm is drawn. The slope of this curve gives the FD value of the desired signal. FD is between 1 (for smooth signals) and 2 (stochastic or deterministic signals filling the whole space) for a continuous signal (14). In the present study, FD are above 1.9 in all muscles and trials that indicate the stochastic nature of the signal. Also, the reduction of FD by more than the threshold is not observed for any of the subjects, which shows that none of them suffered from central fatigue.

To investigate the peripheral fatigue, RQA method was used which is based on embedding EMG signal in an N-dimensional Euclidean space (13, 24). In this method, the time-delayed D-dimensional vectors are extracted from the EMG signal, and the distance matrix is created by calculating Euclidean distance between vectors. Then, the reoccurrence plot will be created by replacing each element of matrix with black (less than threshold) and white (greater than threshold) (17, 24). Due to the fact that these plots contain patterns that are very difficult to detect by visual inspection, some quantitative descriptors have been developed (6, 13). %DET measures the ratio of recurrence points forming diagonals of length l_{min} to all recurrence points (17). Uncorrelated random time series either do not produce any diagonal or produce very short ones (17). According to **table I**, %DET has a low value for all muscles. Also, an increase of %DET more than threshold is observed for the two mentioned fatigue manifestations. This indicates that the type of these physiological fatigues was of a peripheral.

In connection with the RQA factors, it should be noted that two methods of the first zero of autocorrelation function (13, 18) and MI (25, 26) are used to determine τ. The comparison of these methods shows that MI is superior in estimating the optimal τ (25) and it is used in this study. In the case of D, choosing a very small D (less than 5) makes underestimating the number of main variables, and a very large D (greater than 20) makes it possible to increase the effect of noise (18). FNN method is used to select D (17, 26). In the present study, D values for all muscles are between 5-20, which is equal to the accepted value in the literature. Several estimation methods have been proposed to choose the threshold value: the percentage of maximum distance (between 5 and 33%) or the average ones (in distance matrix) (14, 17), or a value that ensure the recurrence point density of approximately 1% (27). Comparison of different values shows that a small percentage of maximum distance is an efficient and valid method (27). Thus, we used this method. Also, to increase the accuracy, the percentage of r was set to 0.1.

In connection with the mechanisms of two mentioned methods, studies suggest that FD depends on the motor units synchronization (14) and its reduction is considered as an indicator of the progress of motor units synchronization (4, 16). On the other hand, RQA indicates the mechanisms involved in peripheral fatigue, *i.e.*, from neuromuscular junction to excitation-contraction coupling (17). In this study, to answer the question whether FD and RQA can show different aspects of fatigue, the significant differences between two factors were evaluated using t-test. The results show that there is a significant difference in all muscles. Therefore, it seems that each of two factors can show different aspects of fatigue, which is consistent with the previous findings (4, 14, 17, 18).

As mentioned, we used 2-minutes rest periods between 5-secounds MVC trials (21). Using ET (according to %MVC) and relaxation allowance models, ET for 100% MVC was estimated to be about 6-seconds and required rest time was estimated about 26-seconds (19). Thus, due to the large number of tests and to ensure the fatigue absence, the exertion and rest time were set to 5-seconds and 2-minutes, respectively. Although this condition has prevented the occurrence of general fatigue, fatigue signs can be observed in some muscles (described above), which is most likely due to the large number of trials. Therefore, we suggest to use a longer rest time than the value obtained from the mentioned models to prevent physiological fatigue in consecutive trials. Also, presenting ET and relaxation allowance models in relation with the trials number can help in better choosing these two times to prevent fatigue and more accuracy of the findings.

Limitations of the study

This study was conducted on healthy young people. Due to the close relationship between fatigue with low back disorders and aging, it is recommended to perform a similar test on people with low back pain as well as different age groups. Also, the present study investigated the isometric extension activity. Similar tests can be carried out for different activities in dynamic mode. The findings can be useful in providing a comprehensive model for endurance and rest times as a function of age, health status, type of activity and number of trials. Such a model can provide a more complete insight and increase accuracy of experimental tests.

CONCLUSIONS

In conclusion, we suggest that in case of consecutive trials, it is better to choose a longer rest time than that suggested in ET studies to prevent physiological fatigue and more validity of experimental data. According to the findings of the present study, it seems that having 2-minutes rest period between 5-seconds isometric maximum consecutive activities and the subjects' declaration of not fatigue feeling is sufficient to prevent the physiological fatigue. Also, the EMG linear and non-linear (RQA and FD) analysis methods are effective methods to investigate the physiological fatigue and its peripheral and central aspects, respectively.

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None.

DATA AVAILABILITY

Data are available under reasonable request to the corresponding author.

CONTRIBUTIONS

All authors contributed equally to this work.

CONFLICT OF INTERESTS

The authors declare that they have no conflict of interests.

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