COBEM 2023
27TH INTERNATIONAL CONGRESS OF MECHANICAL ENGENEERING

ABCM
Brazilian Society of Mechanical Sciences and Engineering
27th ABCM International Congress of Mechanical Engineering
December 04-08, 2023, Florianópolis-SC, Brazil

COBEM2023-1958
ASSESSMENT OF NEUROMUSCULAR FATIGUE, TORQUE REDUCTION, AND VELOCITY PERFORMACE FOLLOWING FES INTERVENTION

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Abstract. *Muscle fatigue is a widely recognized phenomenon that occurs when the body is faced with intense muscular effort or when performing physical activity that exceeds a person's fitness level. Despite being a normal and expected effect in sports training and physical activity, the excessive accumulation of residual muscle fatigue can evolve into a condition known as chronic fatigue. This chronic fatigue, characterized by a persistent feeling of weakness and exhaustion, can have a significant and negative impact on both physical performance and overall health.*
Understanding the various types of fatigue and their influence on muscle work capacity is of utmost importance. Although the phenomenon of muscle fatigue has been extensively researched, there are still gaps in our knowledge about how it affects different population groups. This is due in part to individual variability in response to fatigue and the lack of accurate and effective tools to study the effects of muscle fatigue on various muscle structures.
In this article, we present research that focuses on the study of muscle fatigue in individuals with different muscular constitutions. To carry out this study, we used Functional Electrical Stimulation (FES) as a controlled fatigue device. FES allows us to induce muscle fatigue in a precise and controlled manner, which facilitates the evaluation of its effects on specific muscles and in different population groups.
The results obtained from this research reveal interesting findings. In particular, muscle fatigue was observed to differentially affect people with different fitness levels and muscular constitutions. This suggests that the response to fatigue is not uniform and that individual factors play a crucial role in how fatigue is experienced and overcome.
The use of FES as a tool to study muscle fatigue opens new perspectives in the research of muscle physiology and its practical implications. The results obtained in this study not only contribute to a deeper understanding of muscle fatigue and its effects, but also have important practical implications. These findings can inform the design of training programs and personalized rehabilitation strategies, tailored to the specific needs and characteristics of each individual. Furthermore, they provide a solid foundation for future research in the field of muscle physiology and improvement of physical performance.

Keywords: *Functional Electrical Stimulation (FES), Muscle fatigue, Bioengineering.*

1. INTRODUCTION

Muscle fatigue is a widely recognized phenomenon in the field of physical activity and sports training. This phenomenon manifests itself as a result of intense muscular effort or physical activity that exceeds a person's physical fitness level Enoka and Duchateau (2017). Although fatigue is a normal and expected effect of sports training, it is important to note that excessive accumulation of fatigue can lead to chronic fatigue, a state that can have a significant negative impact on both physical performance and general health. Dos Santos *et al.* (2022). Therefore, understanding in depth the different types of fatigue and their influence on muscle work capacity becomes a crucial aspect to address both sports performance and musculoskeletal health.

Despite the extensive research on muscle fatigue, notable gaps remain in our knowledge about how this phenomenon affects various population groups. Furthermore, the need to develop more precise and effective research tools that allow us to explore in greater detail the effects of muscle fatigue on different muscle structures Hu *et al.* (2011) becomes evident.

In this article, we present research that focuses on the study of muscle fatigue in people with various muscular constitutions, using the functional electrical stimulator (FES) as a device to induce controlled fatigue. The results obtained through this research reveal that fatigue affects individuals with different levels of physical fitness significantly differently, suggesting the presence of notable individual variations in the response to muscle fatigue **?**. Likewise, the usefulness of the FES is highlighted as a valuable tool to explore the effects of muscle fatigue in various population groups Huo *et al.* (2018).

By addressing these issues comprehensively, our research aims to advance the understanding of muscle fatigue, which, in turn, may contribute to the improvement of sports training programs and the promotion of muscle health across a wide range of people. variety of populations Dumitru (2019). This study represents a step forward in the research of muscle fatigue and lays the foundation for future research aimed at optimizing the prevention and management of this phenomenon in different contexts and profiles of individuals Sandhu (2018).

In summary, this article focuses on the study of muscle fatigue in individuals with different muscular constitutions, using the functional electrical stimulator (FES) as a controlled fatigue device SA (2013). Our central objective is to examine in detail the effect of electrical stimulation-induced fatigue on motor control and electromechanical delay in the quadriceps muscle group. Through this research, we seek to shed light on the complex interplay between muscle fatigue and motor function, which can have a significant impact on optimizing physical performance and musculoskeletal health.

2. METHODS

In this study, a rigorous analysis was carried out focusing on the quadriceps muscle group through the application of electrical stimulation. The primary objective was to investigate two fundamental aspects: electromechanical delay and the effectiveness of motor control in response to fatigue induced by the Functional Electrical Stimulation (FES) device.

To ensure the accuracy and integrity of our results, a carefully structured experimental protocol was designed, consisting of a set of four sequential tests. Before starting these tests, a calibration process, detailed in the Moreno *et al.* (2022) study, was carried out to accurately determine the current stimulation amplitude (40 mA), the stimulation frequency (30 Hz) and the pulse width (250 μ). Additionally, as part of the baseline of our study, participants were asked to perform maximal voluntary extension movements without intervention from the FES system during testing conducted on the first two days of the experiment.

Within the test sequence scheme, a pulse width pattern was designed that not only allowed repeated measurements throughout the tests, but also induced muscle fatigue in a controlled manner. Each test sequence had a total duration of 3 minutes, allowing the effects of fatigue to be assessed over time. In the first sequence, which corresponds to test 1, the FES system was activated for 3 minutes and then turned off for 1 minute. In the second sequence, which corresponds to test 2, the same pattern of activation and deactivation of the FES system was repeated. Additionally, a 48-hour recovery period was established between tests to evaluate muscle recovery and motor control over time.

This experimental approach allowed us to thoroughly analyze the effect of electrical stimulation-induced muscle fatigue on the quadriceps muscle group. The results obtained in this study have a potential significant impact, since they can provide crucial information about the response of the neuromuscular system to the fatigue generated by the FES device and its influence on motor performance. Additionally, our findings may help inform and improve rehabilitation and training strategies, especially for those individuals who rely on electrical stimulation as part of their process of recovery or improvement of motor function.

This extended version of the text provides a more detailed description of the experimental protocol and highlights the relevance of the results obtained in the context of rehabilitation and motor performance.

2.1 Subjects

Two subjects were recruited, with no known neurological or biomechanical conditions, one 26 years old, height 171 cm and weight 73 kg and another 21 years old, height 173 cm and weight 71 kg, to apply the protocol proposed by the Department of Mechanical Engineering of the São Carlos School of Engineering. The experimental protocol was approved by the Ethics Committee of the University of São Paulo, Ribeirão Preto School of Physical Education and Sports, of Ribeirão Preto, EEFERP-USP, CAAE N^o 41150620.7.0000.5659 Decision Statement (approval) N^o 4.579.836.

2.2 Experimental Setup

All tests were performed using the experimental setup shown in Figure 1, which consists of the following devices:

- a current-controlled 4-channel stimulator RehaMove 3;
- a microcontroller board based on AT Mega 2560;
- a personal computer running Matlab and RerobApp Moreno *et al.* (2022);
- a passive knee orthosis with analog encoder qp-2hc;
- an ADB232 EMG sensor;
- electrodes (Hasomed FES 00200 RehaTrode and Monserrat COD-9359);

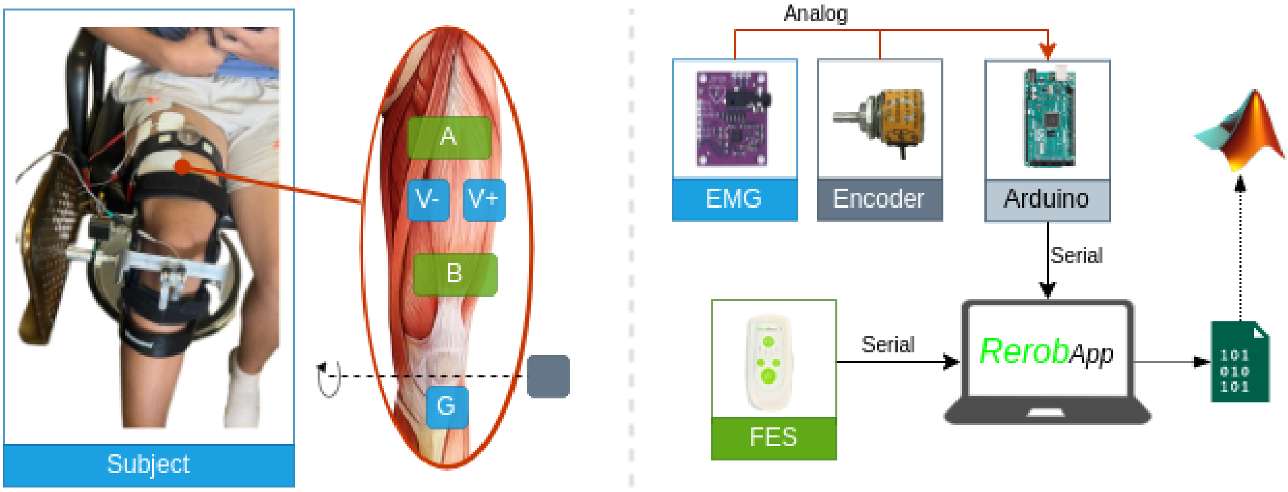

Figure 1: Experimental setup for the proposed study. The graphs illustrate (left) the configuration of sensors and actuators and (right) the data processing and communication protocol. In this configuration A and B are FES electrodes, V^-, V^+ are the potential difference and G is the ground of EMG sensors.

In the context of our study, electrical stimulation was carried out using a pair of electrodes with a rectangular shape that had dimensions of 5 x 9 cm. The strategic location of these electrodes was of vital importance, and in accordance with the guidelines established in reference Dos Santos *et al.* (2022), one of the electrodes was placed between the vastus lateralis and vastus medialis muscles. The second electrode was carefully positioned between the rectus femoris and vastus medialis. This arrangement guaranteed precise and effective electrical stimulation of the quadriceps muscle, allowing accurate assessment of its response to fatigue.

On the other hand, the electromyography (EMG) system we used consisted of three electrodes, each with dimensions of 5 $\times$ 5 cm. Two of these electrodes, identified as V^+ and V^-, were strategically placed between the vastus lateralis and the vastus medialis to capture the electromyographic signals with maximum precision. The third electrode was placed between the rectus femoris and vastus medialis, which provided a complete view of the electrical activity in the quadriceps muscle.

An important aspect to take into account was the choice of the ball joint as the ground connection point (G) in the circuit. This strategic decision allowed not only to monitor the electrical activity of the quadriceps, but also to clearly identify the beginning and end of muscle activation associated with this muscle group.

To ensure accurate data collection and recording during our testing, we rely on the RerobApp platform. This tool, combined with a real-time testing environment, gave us the ability to acquire data efficiently and reliably.

Subsequently, to carry out a comprehensive analysis of the collected data, we used the Matlab tool. This allowed us to examine in detail the responses of the quadriceps muscle to electrical stimulation and evaluate how they varied over time and in response to different levels of fatigue. Taken together, this comprehensive approach to stimulation, data acquisition, and analysis provided us with valuable information on the behavior of the quadriceps muscle in situations of electrical stimulation-induced fatigue.

2.3 Mathematical equations

For each trial, we recorded time evolution from the following variables:

- **Angle (θ):** Angle position was smoothed using a digital low-pass filter with a cut-off frequency of 10+ Hz and the maximum voluntary joint extension value into account for normalization, i.e., $\{min(\theta), max(\theta)\}$ is adjusted to the range $\{0, 100\}$ using Equation 1. The normalization of the entire set of $\{\theta\}$ is called percent extension $\bar{\phi}$. Angle velocity $\dot{\theta}$ was calculated using the central finite difference method using three points and then fitted to a straight line using a matrix method to get slope and bias.

$$Z(\theta) = \frac{-100 * \cdot(\theta - MIN(\theta))}{MAX(\theta) - MIN(\theta)} + 100 \tag{1}$$

- **Delay (δ):** Delay is the time it takes a muscle to reach maximum angular velocity when it is stimulated by the FES pulse.

- **Fatigue index (Ψ):** Fatigue was determined in two ways. First, it is the ratio between the maximum extension of the first excitation with respect to $15°$. According to Vergara-Amador and Román-Chalarca (2011), only the Vastus Medialis muscle is active in this range, Equation 2. Therefore, this situation was considered maximum fatigue. On the other hand, fatigue was also quantified with the maximum angular velocity of the knee, Equation 3. In this sense, we use the maximum peak on the first test as the reference and 0 as fully fatigued.

$$\Psi_k^{\bar{\phi}} = 100 - \frac{\bar{\phi}_k - Z(15°)}{MAX\left(\bar{\phi}\right)} * 100 \tag{2}$$

$$\Psi_k^{\dot{\theta}} = 100 - \frac{\dot{\theta}_k}{MAX\left(\dot{\theta}\right)} * 100\% \tag{3}$$

3. RESULTS

This chapter shows the results obtained after performing the procedures indicated above.

In the following experiments, we examined the behavior of the quadriceps muscles when stimulated with electrical impulses. We performed two tests with the two subjects, with an interval of 48 hours between each one. During the experiments, we used kinematic measurements (angle and speed) to normalize the remaining data. As a result, we found that the minimum and maximum extension angles of the knee joint were $\phi = 8°, 86°$, respectively. Furthermore, we observe that the range of motion of the knee joint is 78 degrees, with a value of $Z(15°) = 14\%$.

In the tests on day 1, image a corresponds to the position and image b to the speed, both associated with an FES excitation of 250 mA pulse width. A total of 3 minutes were allocated for these tests. Figure 2 shows the observed temporal responses. It is important to highlight the constant loss in range of motion, which varies between the two subjects. The active subject shows a loss rate of 0.55 % per second, with a decrease in movement efficiency of approximately 55%, while the non-athletic subject shows a loss rate of 0.93 % per second, with a decrease in movement efficiency. approximately 93 %. The maximum reference speed is $\dot{\theta} = 208°/s$, and at the end of this test, it is reduced to $129°/s$. The estimated fatigue is 62% for $\Psi^{\bar{\phi}}$ and 55% for $\Psi^{\dot{\theta}}$, while for the subject who does not practice sports at the end of this test , the active level is reduced to $203°/s$. The estimated fatigue is 97% for $\Psi^{\bar{\phi}}$ and 90% for $\Psi^{\dot{\theta}}$. These were the first tests, and further tests were subsequently carried out after 48 hours, the results of which are detailed below.

In the tests performed on the second day (referred to as image tests c and d), electrical excitation with a pulse width of 250 mA was applied using the FES system. These tests had a total duration of 3 minutes, during which position and speed data were recorded that were essential for our analysis. Figure 1 shows the temporal responses obtained in these tests.

It is crucial to highlight the constant loss in range of motion observed in both subjects, but with notable differences. In the case of the active subject, a decrease in the range of motion was evident at a rate of 0.55% per second, which translated into a considerable loss of 55% in movement efficiency. On the other hand, the non-athletic active subject experienced a decrease in range of motion at a rate of 0.88 per second, which represented a staggering 88% loss in movement efficiency.

It is relevant to mention that the maximum reference speed for these tests was $\dot{\theta} = 208°/s$, however, at the end of the evaluation, the active subject reduced it significantly to $129°/s$. This fatigue phenomenon translated into fatigue estimates of $\Psi^{\bar{\phi}} = 65\%$ and $\Psi^{\dot{\theta}} = 58\%$ for this particular subject.

In the case of the non-sports subject, at the end of these tests, his activity level also experienced a considerable decrease in maximum speed, reducing to $128°/s$. The fatigue estimates in this case were even more notable, reaching $\Psi^{\bar{\phi}} = 87\%$ and $\Psi^{\dot{\theta}} = 80\%$. These results underscore the importance of understanding how fatigue differentially affects individuals with different levels of physical activity.

This analysis reveals not only the influence of fatigue on movement efficiency, but also the significant variability in responses between subjects with different fitness levels. These observations highlight the importance of considering individuality in the response to fatigue and underline the need to adapt training and rehabilitation strategies based on the specific characteristics of each individual.

As a result of our analyses, valuable conclusions can be drawn about the influence of fatigue on subjects' performance at different testing times as shown in Figure2.

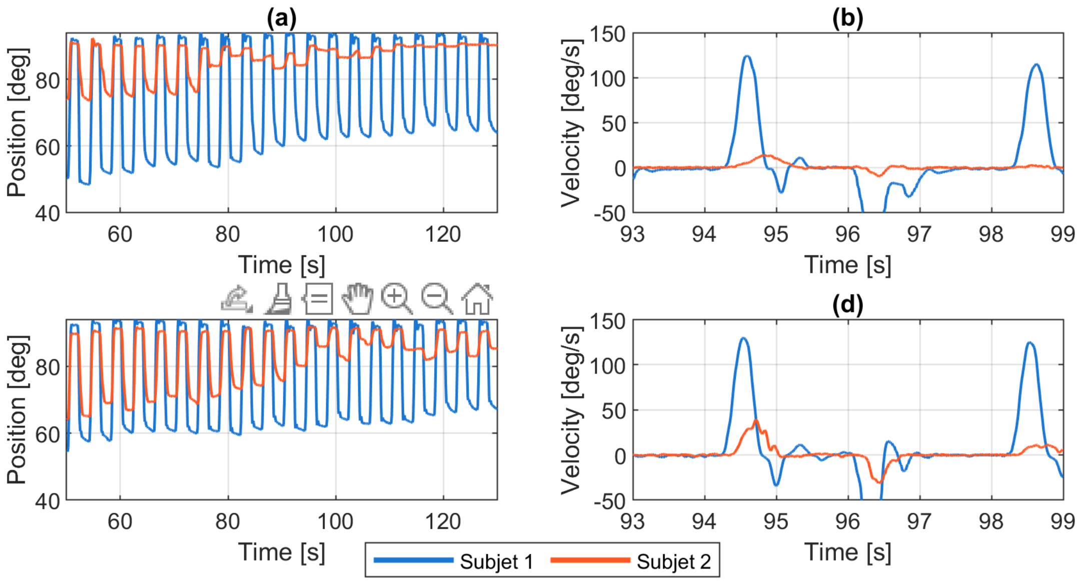

Figure 2: Extension response in the first minutes of electrical excitation. The blue waves represent the active subject and the orange ones the sports passive, the images a and c represent the angle results and the b and d the speed.

On day 1 of our tests, we observed an interesting pattern in behavior. of the subjects. The non-athletic subject experienced a greater loss in angle of movement compared to the active subject. Furthermore, movement speed was also significantly higher in the non-athletic subject. These findings suggest that fatigue initially affected non-athletic subjects more pronouncedly in terms of their ability to maintain range of motion and execution speed.

However, the scenario changed noticeably after 48 hours. The non-athletic subject, although still showing notable differences from the active subject, showed signs of improvement before subsequent testing. At this point, we observed an increase in muscle activation of the non-athletic subject, both in terms of angle and speed. This phenomenon is of particular interest as it suggests an ability to adapt and recover in response to fatigue.

These results highlight the complex interaction between fatigue, recovery time and individual adaptive capacity. They not only confirm the differential influence of fatigue in subjects with different levels of physical activity, but also highlight the importance of considering the temporal factor in the evaluation of human performance. These findings may have significant implications in planning training and rehabilitation programs, where understanding how individuals recover from fatigue can lead to more effective and personalized strategies."

4. CONCLUSIONS

In summary, this study represents a first step in the investigation of muscle fatigue, focusing on two individuals with contrasting levels of physical fitness. The findings obtained offer an initial vision of how fatigue can manifest differently depending on the physical state of people, and raise the possibility of using Functional Electrical Stimulation (FES) as a valuable tool in the exploration of this phenomenon.

However, it is essential to recognize the inherent limitations of this study, such as the small sample size. Consequently, these results should be considered as a starting point for future research in this evolving field. The implications related to the optimization of sports training and the promotion of muscle health in diverse populations must be interpreted with caution, as they require a more solid foundation supported by broader and more varied research.

Furthermore, it is important to highlight that this study highlights the need to take a personalized approach in the assessment of muscle fatigue and its management. Given that individual responses can vary significantly, it is important to consider the uniqueness of each individual when designing training and rehabilitation strategies. Understanding how different people recover from and adapt to fatigue is an essential research topic that can provide valuable information for decision-making in the field of fitness and muscle health.

Ultimately, this study not only contributes to current knowledge about muscle fatigue, but also lays the foundation for future research that delves deeper into this rich and diverse phenomenon. The potential implications for improving the quality of life of diverse populations, from high-performance athletes to sedentary people, make this area of study highly relevant in the search for more effective and personalized strategies for the management of muscle fatigue.

5. ACKNOWLEDGMENTS

This work is supported by Pro-Rectory of Research of University of São Paulo, Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) - Finance Code 001, PGPTA, under grant 3457/2014, and São Paulo Research Foundation (FAPESP) under grant 2019/05937-7 and 2022/06634-0.

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7. RESPONSIBILITY NOTICE

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