PROPOSAL FOR A PROTOCOL TO MUSCLE FATIGUE ANALYSIS DURING GAIT IN DIFFERENT SPEEDS

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Abstract — Stroke is a leading cause of motor disability in the world. New technologies have been developed to increase the efficiency and decrease costs of rehabilitation of stroke patients. Exoskeletons are an alternative, because they may increase the efficiency and intensity of rehabilitation sessions. However, the use of a robotic device can increase the chances of having muscle fatigue. When the patient has fatigue, it is necessary a break in the rehabilitation session until the patient recovers, and then he/she can continue the training. The goal of this work is to identify changes in mean frequency of sEMG signals during gait in different speeds. Three healthy volunteers walked at 3km/h and 5km/h in different days; the analyzed muscles were Rectus femoris, Biceps femoris and Gastrocnemius medialis. The myoelectric signals were analyzed in frequency domain and the mean frequency was used to identify muscle fatigue. It was observed changes in the mean frequencies in a same speed, which is believed to be caused by fatigue. Comparing both speeds, we can see difference between them, but it was not possible to relate the increase of fatigue with the increase of speed.

Keywords — Muscle Fatigue; Stroke; Exoskeleton.

1 Introduction

A limiting factor post-stroke is the muscle fatigue. It can interfere in the life quality and in the rehabilitation process. The fatigue prevalence in stroke patients ranges from 16% to 70% (Lewis et al., 2011).

A high degree of muscle fatigue limits some daily activities and can interfere in his/her ambulation ability, even for small distances (Hesse, 2006). The subject, when has muscle fatigue, feels lack of energy, tiredness and difficulty to make strength in addition to a decrease in the ability of performing physical activities (Lewis et al., 2011).

Muscle fatigue can be measured through reduction of muscle strength, changes in electromyographic activation or debility of contracting function (Enoka; Duchateau, 2008). Using sEMG, muscle fatigue can be identified through analysis of frequency domain.

It is important to highlight that muscle fatigue occurs gradually, according to the imposed motion. Thus, the muscle has its maximum strength decreased, due to the available power reduction to perform the task. However, it is possible the subject has muscle fatigue and even so keeps the motor task (Enoka; Duchateau, 2008). Nonetheless, if the fatigue is neglected and the movement is going on, it may happen an accumulation of problems, because the muscle does not have enough time to recover itself.

In stroke individuals, the fatigue occurs earlier than in healthy individuals. Therefore, muscle fatigue can be a limiting factor during the rehabilitation process. When the patient has fatigue, the training session must be interrupted in order to allow the patient to recover and, then, the session can continue. However, depending on the duration of each session, the recovery may not be carried out, and the patient cannot complete it. Furthermore, fatigue may cause pain, fear to continue the treatment, and may lead the patient to make wrong movements (Xu; Chu; Rogers, 2014).

On the other hand, using devices that enhance the motion amplitude, speed and intensity may increase the possibility of having fatigue easier.

New technologies towards gait rehabilitation of post-stroke hemiparetic subjects are being developed in order to increase training efficiency and cost reduction. Robotic devices, such as an exoskeleton may be useful for this application, due to the fact of providing high efficiency, more precise movements and greater repeatability in the rehabilitation tasks.

In the Intelligent Automation Laboratory (LAI) at the Federal University of Espirito Santo (UFES), a robotic rehabilitation system composed of robotic walkers (Cifuentes et al, 2014 and Valadão et al, 2014) and knee active exoskeleton is being developed. The exoskeleton will be controlled by myoelectric (sEMG), which will provide information about the movement intention of the user. Then, the controller will send the data to the actuator of the exoskeleton in order to execute the indicated task (Villa-Parra et al, 2014).

Gait rehabilitation using this robotic device can result in muscle fatigue in these patients. Due to that, in this research we intend to characterize the muscle fatigue pattern of users in order to identify differences in muscle fatigue in two distinct speeds for futures applications in the exoskeleton.
2 Methodology

2.1 Volunteers

Three healthy individuals (two male, age average 28 ± 4.6 years) participated of the experiments. The inclusion criteria for the study were: the subject should have healthy gait; be available to participate of three test sections in two different days; do not have done strong physical exercise in the test days. The study has approval of the UFES’s Ethic Committee.

2.2 Experimental Protocol

For muscle fatigue analysis, three surface Electromyography (sEMG) channels were used. The analyzed muscle (Figure 1) and their functions were, respectively:

- Rectus femoris (RF): knee extension;
- Biceps femoris (BF): knee flexion;
- Gastrocnemius medialis (GM): Flexion of the ankle joint and assist in flexion of the knee joint.

The electrodes position was identified following the SENIAM recommendations (Hermens et al., 1999). To obtain a better contact between electrode and skin, the region was shaved and cleaned with 70% alcohol solution. The inter-electrode distance was 25 mm. A reference electrode was placed on the lateral malleolus. In both volunteers, the right lower limb was analyzed.

The experiments sequence was done in two days (Figure 2). In the first one, three sessions were conducted, with the subject walking for five minutes at 3km/h and resting for one minute, before the next session. In the second day, the same protocol was followed, but the subjects walked at 5km/h.

![Figure 1. Analyzed muscles during the experiments.](image)

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![Figure 2. Experiments sequence.](image)

2.3 Borg’s Scale

After the third section of each day, the volunteer answered the modified Borg’s Scale, in which he/she indicates his/her own perception of effort. This scale ranges from 0 (no effort) to 10 (maximum effort) (Kendrick, 2000). They also reported some physiologic changes during gait: sweating; heart and respiratory rate changes and lower limbs pain.

2.4 sEMG Analysis

The myoelectric signals were captured through the device EMG System do Brasil®, which is an equipment with analog/digital conversion of 16-bit resolution. EMG amplifier with total gain of 2000, bipolar electrodes with preamp gain of 20 times, common mode rejection greater than 100 dB and impedance of 10⁷ Ohms. The sampling rate was 1 kHz.

Myoelectric signals were filtered using a fourth order Butterworth band-pass filter that allowed frequencies from 20 to 500Hz to pass. For the fatigue analysis, it was used the frequency domain analysis (especially the mean frequency of the signal).

According to Phinyomark et al. (2012), the frequency domain shows better results in muscle fatigue analysis than other domains of the signal. Mean (MNF) and median frequency are considered the gold standard for muscle fatigue analysis.

The mean frequency can be calculated using the Equation 1:

\[ MNF = \sum_{j=i}^{M} f_j P_j \sum_{j=i}^{M} P_j \]  \hspace{1cm} (1)

where \( f_j \) is the frequency value of EMG power spectrum at the frequency bin \( j \), \( P_j \) is the EMG power spectrum at the frequency bin \( j \), and \( M \) is the length of frequency bin (Phinyomark et al., 2012).

As fatigue accumulate, the activation energy becomes lower. Therefore, it is expected that the mean frequency of EMG reduces after gait (Kim, 2013).
2.5 Statistical analysis

For statistical analysis, ANOVA and the Friedman tests were used to compare three mean frequencies obtained at 3km/h and 5km/h for each muscle in an individual to detect differences in treatments across multiple test attempts. ANOVA for one criterion was used when sample had equal variances, and Friedman test is a non-parametric test used when the variances were different.

3 Preliminary Results

The volunteers are 28 ± 4.6 years and Body Mass Index (BMI) = 24.4 ± 3 kg/m². All of them are sedentary and no smokers.

In the gait at 3km/h, the Borg Scale scored mean was 2 (light), and at 5km/h was 4 (somewhat heavy). Only in the gait at 5km/h all volunteers related, subjectively, heart rate changes and only volunteer 3 felt pain in his lower limbs.

3.1 EMG results

The total signal obtained during 5 minutes of gait at 3km/h was analyzed in frequency domain and its mean frequency was identified. To exemplify, Figure 3 shows three graphics with its mean frequency, respectively, for the volunteer 3. The aforementioned graphic depicts the signals of the RF muscle. In this graphic can be seen the reduction of Power Spectrum Density (PSD), which indicates a muscle fatigue accumulation. In the Experiment 1, the mean frequency is bigger than the second one, and the last experiment has a shorter mean than the first one.

The same method was used to analyze gait at 5km/h and the graphic is showed in Figure 4.

For rectus femoris (RF) (Figures 5, 6 and 7), only the volunteer 3 showed difference significant (p = 0.03), however the higher reduction in the mean
frequency was seen during gait at 3km/h. During this gait, the volunteer had a great reduction in the mean frequency ($S = -9.00$), but in the gait at 5km/h there was a oscillation in the second repetition, which changed the curve shape.

Both volunteers 2 and 3 showed differences significant in mean frequency of biceps femoris (BF) ($p = 0.03$ and $p < 0.01$, respectively). The gait that had more reduction of mean frequency was at 5km/h which was expected (Figures 9 and 10). For volunteer 1, there was changes during gait at 5km/h, but in gait at 3km/h the curve was stable (Figure 8).

Finally, gastrocnemius medialis (GM), volunteers 1 and 3 (Figure 11 and 13) did not have significant differences, however, in both cases, one curve had a common pattern while the other one did not change. For volunteer 2 (Figure 12), in all muscles there were significant changes, but the GM had more reduction of mean frequency during gait at 3km/h. 

![Figure 7. Comparison between gaits for the volunteer 3 rectus femoris. S (3km/h) = - 15.18; S (5km/h) = - 10.71. ANOVA p = 0.03.](image)

![Figure 8. Comparison between gaits for the volunteer 1 biceps femoris. S (3km/h) = - 0.47; S (5km/h) = - 4.13. Friedman test P-value = 0.08.](image)

![Figure 9 . Comparison between gaits for the volunteer 2 biceps femoris. S (3km/h) = - 2.38; S (5km/h) = - 2.80. ANOVA p= 0.03.](image)

![Figure 10. Comparison between gaits for the volunteer 3 biceps femoris. S (3km/h) = - 1.45; S (5km/h) = - 7.11. ANOVA p < 0.01.](image)

![Figure 11. Comparison between gaits for the volunteer 1 gastrocnemius medialis. S (3km/h) = - 3.37; S (5km/h) = - 0.47. Friedman test P-value = 0.08.](image)

![Figure 12 . Comparison between gaits for the volunteer 2 gastrocnemius medialis. S (3km/h) = - 3.98; S (5km/h) = - 2.27. ANOVA p < 0.01.](image)
In stroke patients, a higher level of muscle fatigue was found in hamstring muscles (including BF), however the protocol showed the subjects had fatigue caused by gait and submaximal contractions using 30% of maximal load (Rybar et al., 2014). This method can induce a more uniform level of fatigue in healthy subjects. However, gait rehabilitation process using the Exoskeleton and Robotic Walker there is no extra load that have to be supported by the patient. Because of this, it is necessary to conduct experiments with stroke patients, with gait tests in order to describe the natural muscle fatigue caused in them.

It is important to highlight that spasticity in lower limb extensor muscles can cause fatigue, even when there is no movement. Therefore, this is a factor that must be considering for the development of protocols for this purpose.

5 Conclusion and Future Works

In different speeds of gait, it was possible to see some changes in the mean frequency of the analyzed myoelectric signals. However, it was expected greater changes in higher speeds, but in some muscles it was found a greater reduction during low speeds.

In future works, we will intend to perform tests with stroke patients and larger control groups to try to identify a pattern in the muscle fatigue during the gait.

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