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Effect of the fatigue in the equilibrium training

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ABSTRACT

Maintaining an equilibrium of the human body in an upright position is crucial for the majority of motor activities. Numerous studies of physiologists, clinicians, scientific researchers show that the equilibrium function is very complex. In this work, we conducted an experiment involving equilibrium maintaining on a balance board to research different aspects of this process. The purpose of this study was to assess the dynamics of the movement of the platform movement associated with the equilibrium during the experiment and how muscle fatigue effects it. With the help of the statistical analysis we determine which muscles were affected by the fatigue more.

Keywords: signal analysis, fatigue, electromyograms, EMG, equilibrium, balance

1. INTRODUCTION

In everyday life, we are constantly dealing with tasks related to motor activity. Therefore, in neuroscience the interest in the study of motor tasks has always been of great interest.[1–4] This is related both to the need to understand the processes of sensorimotor integration when performing movements in order to solve neurorehabilitation[5,6] and disease diagnosis[7,8] tasks, and to the tasks of neurotechnology, namely, creating brain-computer interfaces.[9] In the latter case, of particular interest is the study of motor imagination[10–12] for the formation of commands for BCIs.[13] However, in such tasks, motor movements of limbs are most often analyzed.[14,15] There are far fewer works analyzing the neurophysiological aspects of whole-body movement. One such example is the task of maintaining and controling balance.[16]

To examine balance control, researchers have examined various features of postural response with different support surfaces positioned underneath foot. Some works has been reported that the efficiency of postural control system depends mostly on the afferent activity from plantar cutaneous mechanoreceptors[17,18] located in the glabrous skin of human foot sole that is activated only in the presence of pressure, load, vibration.[19–21] Experiment in the work[22] involved release of a load coupled to a cable affixed to a harness. The work[23] involved the use of electrically induced vestibular perturbation. The problem of a clear understanding of the control strategies and mechanisms that are used by the central nervous system of humans to stabilize the unstable posture robustly while maintaining flexibility remains unsolved. Investigation of factors of training and fatigue can help to undercover some features of this process.

A generally accepted idea is that the central nervous system might simplify the production of movement by activating muscles in common patterns.[24,25] Instead of activating each muscle individually, a motor output is formed by combining small sets of time-dependent commands and time-independent motor modules that create patterns in muscles.[25] It has been proposed that synergies may be specific to each task.[26] This task-related control could allow for fast reconfigurations when the task demands change.[27] During walking and running, although the general modular organization remains unaltered in the presence of perturbations, a modification of the temporal components of the muscle activity, characterized by a widening of the motor primitives, has been reported.[28,29] The main focus of the experimental works involving humans is pointed to the evaluation of the response to the disturbances given from the outside.[22,23,30–32] The key difference between the current

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work and majority of studies where subjects passively responded on the balance disturbances aimed towards perturbation-evoked responses induced by the subject itself in a long-time continuous interaction rather than a multi-week training manner.

Muscle fatigue is characterized by a decrease in the production of maximum strength or muscle power.[33] Muscle fatigue is gradually developing shortly after the start of sustainable physical activity, such as when a subject performs an interrupting exercise in the submaximal effort, and cannot maintain the intensity of exercises, reducing the ability to generate the required strength. Consequently, muscle fatigue can reduce performance at work and in everyday activity, which leads to a decrease in productivity, as well as leading to errors in activities that require good static or dynamic postural controls,[34] increasing the number of falls.[35] Understanding the consequences of muscle fatigue could bring new insights into how motor strategies are used by the motor system after perturbation, such as changes in joint strategy or increased asymmetry during postural control.[36]

The current work has the main aim to determine if the training of muscles most involved to the most efficient management of the balance platform, will get fatigued more during the experiment. To achieve that we need to assess the dynamics of the movement of the platform movement associated with the equilibrium during the experiment and investigate how muscle fatigue effects it.

2. METHODS

We conducted a series of experiments involving the placement of subjects on the originally designed balance platform as shown on Fig. 1. The number of volunteer subjects was 20 (15 male, 5 female) aged from 25 to 42 years. We instructed all volunteers before conducting the research to observe the regime of full night rest for three days. The experimental procedure was performed following the Helsinki's Declaration and approved by the local Research Ethics Committee of the Innopolis University.

We conducted the experimental study in the morning and afternoon periods (9 AM – 1 PM) 2 hours after a healthy meal with limited consumption caffeine and (or) other stimulating additives to food. While recording signals, subjects were standing on a balance platform. The design of the experiment included three 10-minute sessions with two rest breaks between them (Fig. 1c). We performed preliminary registration of the background activity of the quietly standing subject for five minutes. We instructed all subjects to maintain and keep equilibrium as long as they can during their attempts. Subjects were not able to train their ability to maintain balance before the experiment, and thus we conducted the study with untrained volunteers. This is important because some studies have shown differences in the distribution of spectral activity between trained and untrained people. It should be noted that the balance of the human body is not indefinitely stable due to the small radius determined by the contours of the feet and the space between them, and in addition to the high location of the general center of mass of the body. Therefore, even some small-scale internal or external influences can affect the balance and bring the body out of a stable state.

During the experimental session, we were recoding EMG, angle and velocity of the balance platform signals simultaneously. Such criteria as the center of gravity position were not available for the recordings. As shown on the scheme in Fig. 1, arrangement included next muscles: Tibialis Anterior (Left — LTA, Right — RTA), Gastrocnemius (LGC, RGC), Rectus Femoris (LRF, RRF), Semitendinosus (LST, RST). Immediately before the experiments started, we performed all necessary procedures to increase skin conductivity and reduce its resistance using the abrasive "NuPrep" gel (Weaver and Company, Colorado, USA). The impedance was monitored after the electrodes were installed and measured throughout the experiments. Usually, the impedance values varied within a 2–5 kΩ interval.[?] The electroencephalograph "Encephalan-EEG-1926" (Medicom MTD company, Taganrog, Russian Federation) with multiple EMG channels. This device possessed the registration certificate of the Federal Service for Supervision in Health Care No. FCP 200700124 of 07.11.2014 and the European Certificate CE 538571 of the British Standards Institute. Given 10-min time-series of the balance board angle variation $\theta(t_i)$ in sessions $s = 1, 2, 3$, we first numerically evaluated the angular velocity $\omega(t_i)$ as the first derivative of the angle:

$$\omega_s(t_i) = \dot{\theta}_s(t_i) = \frac{\theta_s(t_i) - \theta_s(t_{i-1})}{\Delta t}, \quad s = 1, 2, 3, \quad i = 2, ..., T \tag{1}$$

where $\Delta t =$ ...s a time resolution of the balance board angle recordings. Due to inter-subject variability of the angular velocity, this quantity was standardized across the participants analogously to the z-score. In each

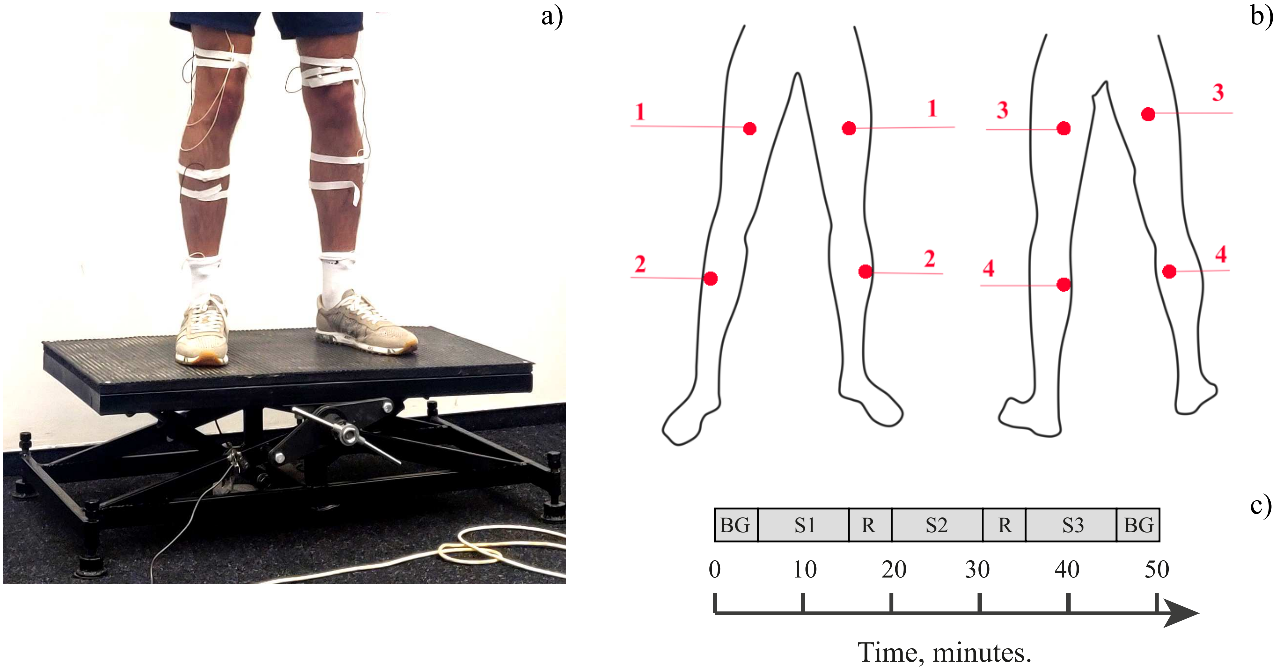

Figure 1. a) Photo of an experimental setup; b) EMG electrodes placing scheme (1 — Rectus Femoris, 2 — Tibialis Anterior, 3 — Semitendinosus, 4 — Gastrocnemius); c) timeline of the experiment, S here denotes session, R denotes rest between sessions, BG denotes backround activity.

session, we standardized angular velocity by dividing each value $\omega_s(t_i)$ of the time-series by the standard deviation of angular velocity in the first session $\sigma(\omega_1)$:

$$\omega'_s(t_i) = \omega_s(t_i)/\sigma(\omega_1), \tag{2}$$

EMG data. We filtered raw EMG signals with a band-pass filter with cut-off frequencies at 1 Hz (LP) and 10 Hz (HP). If it is wanted to analyze the recruitment of muscle fibers during a contraction, estimators of EMG amplitude would be more appropriate An estimate of EMG amplitude can be done with many processing techniques, but Root Mean Square (RMS) is the most common. The RMS value has been used to quantify the electric signal, it is a linear variable used to evaluate the excitability and activation of muscles.[37,38]

To estimate the muscle fatigue we used a method proposed in the work.[39] Then Wigner-Ville transform was performed on the raw EMG data and Wigner-Ville Distribution obtained. These time–frequency features account for the nonstationarity of the EMG signals. Selecting an appropriate type for time-frequency distribution is most important and it decides the amount of cross-term rejection and time–frequency resolution. From Wigner-Ville Distribution Instanteneous Median Frequency (IMDF) can be calculated. Lower values of IMDF correspond to the stronger muscle fatigue.[39]

3. RESULTS

For the dynamics inside sessions, and total equilibrium duration was calculated. The percentage of successful attempts significantly increases during the session that demonstrates the process of successful learning during the exercise. A significant difference was observed for the different parts of sessions $\xi(2) = 3.942$, p = 0.041. The post hoc analysis based on the Wilcoxon signed rank test revealed the insignificant increase for the 2nd part when compared with the 1st part (Z =–1.381, p = 0.166), for the 3rd when compared with the 2nd (Z = –0.971, p = 0.332), but significant for the 3rd when compared with the 1st (Z = –2.613, p = 0.009). RM ANOVA revealed a significant change of mean angular velocity between the sessions (F_2 = 21.49, p¡0.001, η^2 = 0.59).

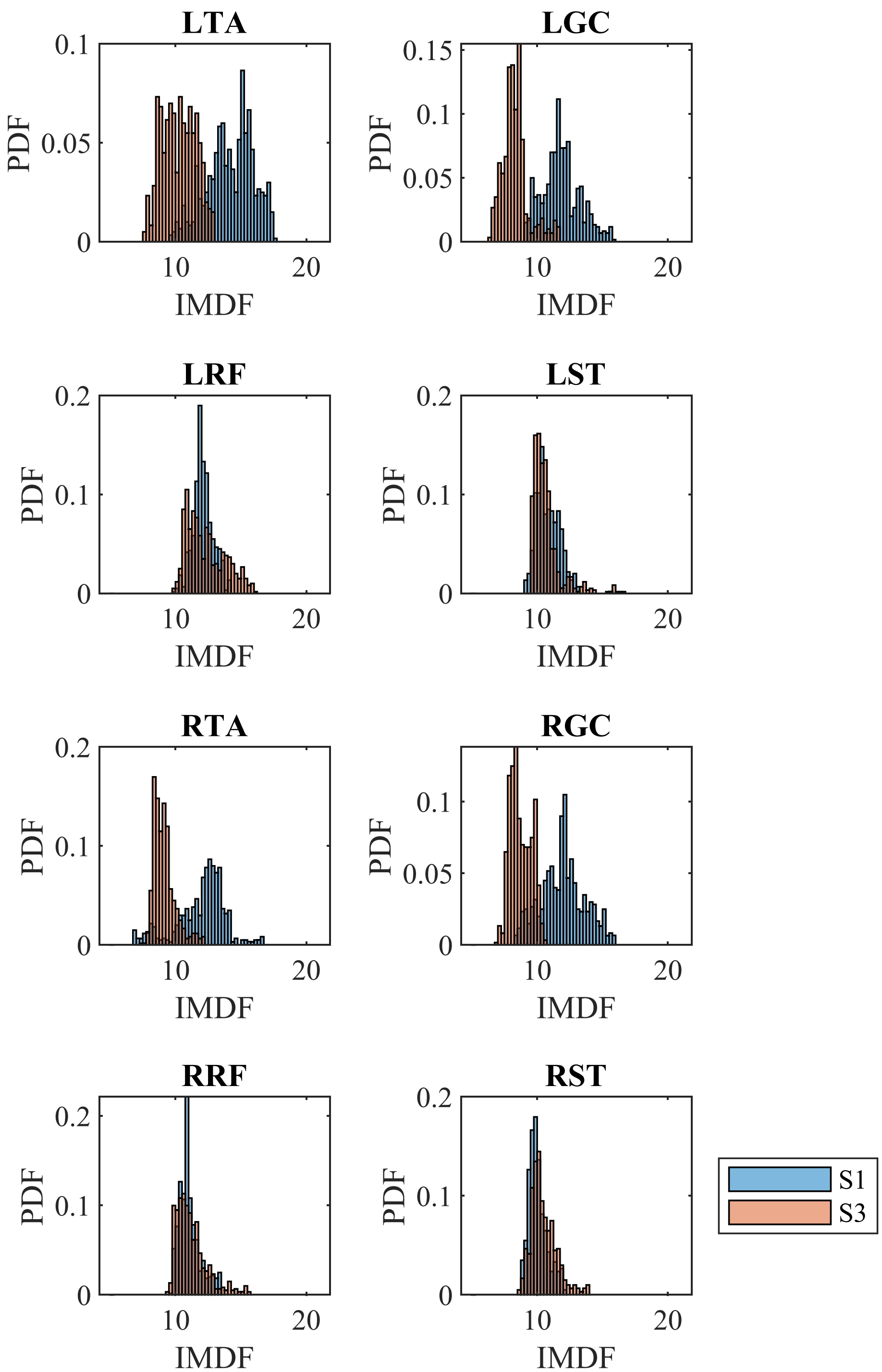

Figure 2. Changes in the distribution of IMDF between first and third sessions for different muscles.

Changes in the distribution of IMDF between first and third sessions for different muscles can be seen in Fig. 2. The shape and positions of the maxima for the muscles demonstrate shifts towards lower frequencies. Especially explicit changes can be seen for the shin muscles. RM ANOVA revealed a significant change of IMDF between the sessions ($F_2 = 6.304$, p=0.019, $\eta^2 = 0.869$). Statistical analyses were run using statistical packages IBM SPSS and JASP. Decrement of the angular velocity showed that participants improved their performance. In other words, learning to maintain an unstable balance cannot be understood as a simplification of the performed movements. The group-level correlation between the observed changes in the equilibrium attempt duration and corresponding muscular IMDF was quantified via the repeated measures correlation, RM CORR[40] with the statistical package Pingouin.[41] Repeated measurements correlation between IMDF and equilibrium attempt duration ($R = -0.6416$, $p = 0.00002$).

4. CONCLUSIONS

Our findings regarding fatigue supports the conclusion of the work[36] stating that ankle and hip muscle fatigue increased body sway, but the strategy to mitigate the muscle fatigue effects on postural control was not muscle fatigue joint-dependent, as the ankle strategy was used in both fatigue conditions to control posture. Also, the effect fits well with the work[42] idea showing that control of upright stance operates in a less stochastic and more antipersistent manner when fatigue is present. Altogether, the present results suggest that, compared with the no-fatigue conditions, fatigue places higher demands on the postural control system by increasing the frequency of actions needed to regulate the upright stance. Higher fatigue effect on the Tibialis Anterior shows the greater contribution of these muscles for the task regulation and control.

In conclusion, the results obtained can be used to isolate the phases of planned movement and allow you to advance in understanding the principles of functioning of the equilibrium keeping strategies, and contribute to solving a number of applied tasks related to improving the quality of life of people.

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