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# The effects of fatigue on synergy of selected lower limb muscles during running

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**Abstract**

The purpose of this study was to investigate the effect of fatigue on selected lower extremity muscles synergy during running using non-negative matrix factorization algorithm method. Sixteen male recreational runners participated in this study. The surface electromyographic activity of rectus femoris (RF), vastus lateralis (VL), vastus medialis (VM), biceps femoris (BF), semitendinosus, gastrocnemius medialis (GM), soleus (SO) and tibialis anterior (TA) were recorded on treadmill at 3.3 $m.s^{-1}$ before and after the fatigue protocol. Synergy pattern and relative muscle weight were calculated by non-negative matrix factorization (NNMF) algorithm method. The results showed that using the VAF method, five muscle synergies were extracted from the emg data during running. After the fatigue, the number of muscular synergies did not show a change, but relative weight of the muscles changed. Fatigue did not have any effect on the structure of muscular synergy, but changed the relative weight of muscles. These changes could be the strategy of the central nervous system to maintain optimal function of the motor system.

**Key Words: Fatigue, Running, Muscle synergy, Non-negative matrix factorization algorithm**

## Introduction

Running is one of the most common forms of human locomotion. Running is progressively growing in population and many people continue to choose it as their exercise of choice (Thordarson, 1997). The motor control of running required a coordination between a combination of skeletal and neuromuscular systems. Disturbing these systems or their harmony leads to some changes in running biomechanics and human's motor control (Koblbauer et al., 2014). Also, running on an uneven surface could alter neuromuscular control characteristics of movement (Santuz et al., 2018). Running exposes the body to some degrees of fatigue because of its cyclic nature. Running in fatigue changes the mechanics of running. For instance, exhausting running changes the cadence, step length, lower limb kinematics (Gerlach et al., 2005), planter pressure distribution (Anbarian & Esmaeili., 2016) and kinetics (Kadono et al., 2013). Such deviations are the consequences of changes in muscular activity patterns due to fatigue (Kellis et al., 2011; Mizrahi et al., 2000) and can expose the body to various injuries (Mizrahi et al., 2001). A possible strategy for dealing the consequences of fatigue is to modify muscular coordination defined as the distribution of muscular activity or the power among distinct muscles for making a combination of joint torques (Smale et al., 2016). More obviously, fatigue may lead to redistribution of muscular activity among various muscles or change the profile of muscular activity (Mizrahi et al., 1997).

Running as locomotion is considered as a natural motor behavior, in which the central nervous system acts by controlling the groups of muscles related to the mechanical demands (D'Avella & Bizzi, 2005). Recently, an issue has been developed that considers the central nervous system as a model to control the motor performance. The mentioned model decreases the degrees of freedom of the central

nervous system in controlling the muscular groups and movements, and lets the muscular groups be activated as a unit. This model presents the muscular groups as the module or synergy to control movements (Mussa-Ivaldi et al., 1994; Tresch, et al., 1999; D'Avella et al., 2003; Chvatal & Ting, 2013). It has been shown that, running also follows synergistic control (Cappellini et al., 2006; Hagio et al., 2015). These synergies are activated by the stimulations made by the central pattern generators and cause particular motor behaviors (Lacquaniti et al., 2012a).

Non-negative Matrix Factorization Algorithm (NNMF) approach was applied to extract muscular synergies from Electromyographic data (Clark et al., 2010; Oliveira et al., 2014; Serrancolí et al., 2016). This method is capable of extracting the synergies and remaking the data with the least rate of error (Barimani at al., 2014), and allows each muscle to act in more than one synergy. Moreover, considering the fact that no negative command is sent to muscles, all commands are positive in this approach.

Saito et al. used NNMF algorithm method to analyze electromyographic signals and discover the number of muscular synergies of the body during walking, and revealed 4-synergy model (Saito et al., 2018b). Cappellini et al. also used the NNMF algorithm to extract muscular synergies during running and walking (Cappellini et al., 2006). The authors found five synergies that controlled walking and running. The researchers pointed out that a maximum of five muscular synergies are directed from the central nervous system to control muscular groups for walking and running (Cappellini et al., 2006). Serrancoli et al. studied muscular synergies in patients with ACL rupture and showed that muscular synergy has remained unchanged (Serrancoli et al., 2010). Rozumalski et al. studied the muscular synergy in various speeds and different slope conditions on treadmill, and pointed out that in spite of several changes in movement kinematics, the synergy of the muscles remained constant

(Rozumalski et al., 2017). Also, Saito et al. showed that muscular synergies are similar during running in different speeds and slopes (Saito et al., 2018).

Given the fact that fatigue affects the mechanics of running and synergy can reflect the body's motor control ability, the previous studies have not addressed the effect of fatigue on synergy as the function of body's motor control system during running. Studying muscular synergies can provide a more comprehensive perception of the central nervous system in fatigue after running and brings a new perspective about motor control after fatigue by the central nervous system. Therefore, the purpose of the present paper is to examine the effects of running-induced fatigue on the selected muscular synergy of the lower limb.

## 1. Methods

### 2.1 Participants

Sixteen healthy recreational runners (male and female) (age: 23.76±2.14 years), (mass: 78.45±2.54 kg, height: 179.82±2.32 cm) familiar with running on treadmill participated in this study voluntarily. Participants had at least six months of recreational running experience. The inclusion criteria for participation included being physically and mentally healthy and having no disorder or injury in the lower limb during the last six months. The subjects' disorders were examined via New York Rating Chart. New York Rating Chart is a postural assessment method that is commonly used for clinical postural evaluation (McRoberts et al., 2013). As the experiment was conducted on a treadmill, the criterion for excluding the subjects from the study was feeling any kind of pain in the back and lower limbs while running on treadmill.

### 2.2 Electromyography

2.3 After entering the laboratory, the participants were informed about the testing procedure. Then, their skin was well prepared for attaching adhesive surface electrodes of Ag-Agcl by shaving redundant hair with blade and cleaning the skin

with alcohol pad. The electrodes were adhesive enough not to be removed and moved during perfoming the test and fatiguing protocol. In order to avoid movement-induced artefacts and fixation of wires, the wires connected to the electrodes were well secured with an adhesive band. Based on the SENIAM protocol, surface electrodes were attached on Rectus Femoris (RF), Vastus Medialis (VM), Vastus Lateralis (VL), Semi Tendinosus (ST), Biceps Femoris (BF), Gastrocnemius Medialis (GM), Soleus (So), and Tibialis Anterior (TA) muscles (Hermens, 2000). The distance between electrodes was 20 mm and the ground electrode was placed on tibia tuberosity. In order to record a successful stride while running, two footswitches; one on the most posterior plantar region of the heel and the other under the first metatarsophalangeal joint were used under the shoes. For recording the muscles' activity synchronously with footswitch information, a ME-6000- T16 bio monitor device (Mega Electronics Ltd. Finland) with sampling frequency of 2000Hz, band width of 10-500Hz/3dB and common mode rejection ratio of 110 dB in differential amplifier was used.

2.4 Fatigue Protocol

This protocol was started with running on a treadmill (American Horizon Fitness treadmill, Omega GT), and required the participants to run at 6 km/h followed by 1-km/h speed increase every 2 min during the protocol. The participants were asked to rate the 15-score Borg scale (6 out of 20) every one minute, and simultaneously the individuals' heart rate was observed and controlled through a Polar Heart Rate transmitter (Model RS100, NY). The individuals were not allowed to see their running speed and heart rate on the treadmill monitor. The speed increase continued until the participants reported the score of 13 on the Borg scale. After reaching this score, they continued running at that fixed speed to achieve the score of 17 or 80% of their maximum heart rate (age-220) (Pescatello et al., 2014), and in that moment they continued running for two additional minutes. Then the fatigue protocol stopped

(Koblbauer et al., 2014; Dierks et al., 2010). Following that, the participants tried to cool down with self-selected running speed for two minutes. In this state, the participants were ready to perform the post-fatigue session. This protocol lasted 18-32 minutes. All the participants used the same neutral shoes (ASICS Gel nimbus 11) during treadmill running.

## 2.5 Data Analysis

Participants were asked to run at 3.3 $m.s^{-1}$ on a treadmill before and after fatigue (Willems et al., 2012) and Electromyographic data were recorded concurrently. Six complete cycles were collected from each participant before and after the fatigue (after the cool-down session) protocol. Six cycles were selected because it has been shown that the amount of step cycles and its pre-processing procedure do not impact the synergies structure (estimated dimensionality) (Oliveira et al., 2014). Running cycles were extracted using footswitches data. In order to recognize each running stride, the time period between a foot strike and the next touch of the same foot was set.

Running stride was divided into two phases of 1) Stance (when the footswitches had contact with the ground) and 2) Swing (when the footswitches did not have contact with the ground) based on Lohman et al. (2011). The stance phase was further divided into absorption and generation ones in which the first 50% was considered as absorption and the rest of it was regarded as the generation phase (Lohman et al., 2011) The swing phase was divided into three phases of initial-swing (from the beginning of swing to 50% of the cycle), mid-swing (50- 85% of the cycle) and late-swing (the final 15% of the cycle) (Lohman et al., 2011).

Electromyographic data were filtered through Band-Pass Filter 10-500 Hz. To perform linear envelope, the EMG data were full-wave rectified and low pass filtered

at a cut frequency of 10Hz through 4th order Butterworth filter with no phase lag. The data were normalized using submaximal method, in which, first, the maximum activity of the muscles was calculated in each cycle and, then, each data point was divided into the maximum amount of each cycle to gain the muscles' activity based on the percentage of maximum activity of muscles in each cycle. At the end, each step was time-normalized through cubic interpolation and divided into 101 points. All analyses were carried out through MATLAB (v2.9, 2016a).

Non-Negative Matrix Factorization Algorithm:

Electromyographic analyzed signals were factorized for obtaining the muscular synergy components including 1) NCs (neural commands) and 2) SVs (synergy vectors). Factorization includes analyzing and decomposing the matrix of all electromyographic signals (number of frames* muscles) into 1) NCs, showing activation time of each synergy (number of frames*synergies) and 2) SVs, showing the weight of each muscle during each synergy (number of synergies*number of muscles). The mentioned factorization provides more positive numbers for neural commands and synergy vectors and leads to more physiological commentaries (Lee & Seung, 2001). To correspond and match the reconstructed matrix with the experimental matrixes, variance accounted for (VAF) value was used in which reconstructed Electromyographic signal $EMG_t^{rec}$ and the original Electromyographic signal $EMG_t^{exp}$ were in "t" frame (Muceli et al., 2010). The analysis for each subject began by assuming that only one synergy was needed for Electromyographic reconstruction. If VAF was ≥0.9 for each of the eight muscles, it was concluded that additional synergies were not needed (Clark et al.,2010; Serrancolí et al., 2016)

$$VAF = 1 - \frac{\sum_{t=1}^{101} EMG_t^{rec} - EMG_t^{exp}}{\sum_{t=1}^{101} EMG_t^{exp}}$$

### 2.5. Statistical analysis

For testing the normality of data distribution, Shapiro-Wilk test was used. In order to assess the similarity of synergy patterns, Pearson correlation coefficient was used. If the correlation in each synergy is close to 1, it reflects the similarity of muscular synergy patterns (0.0-0.29: small similarity, 0.3-0.69: moderate similarity, 0.7-1 is high similarity) (Mukaka, 2012). For comparing synergy vectors, time to peak of synergy and VAF values, before and after the fatigue, paired-samples t-test was used. SPSS 22 (V22.0, IBM, USA) statistical package was used with level of significance of $\alpha = 0.05$.

## 2. Results

The results showed that in the first synergy, the correlation between the synergy patterns, before and after fatigue, was r=0.95, which reflects a high similarity between the two patterns (Fig.1). In this synergy, before fatigue (solid line) the peak was in absorption and late-swing phases, but it remained unchanged (Fig. 2) after fatigue (dotted line). This synergy is responsible for using RF, VL, VM, GM, SO and TA muscles, but after fatigue, BF muscle is also involved. In the first synergy, after fatigue, the relative weight of BF (p=0.003) and TA (p=0.002) muscles significantly increased.

In the second synergy, correlation between-synergy patterns of before and after fatigue was r=0.84, which suggests a great similarity between the two patterns. Before fatigue, synergy peak occurred during the absorption phase and, after that (dotted line), the amount of peak decreased significantly (Fig. 2). This synergy is responsible for applying and involving Quadriceps, Gastrocnemius, Soleus and Tibialis Anterior muscles, and BF muscle is also involved after fatigue. In the second

synergy, after fatigue, the relative weight of Biceps Femoris (p= 0.025) and TA (p= 0.01) increased significantly.

In the third synergy, the correlation between the pre and post-fatigue synergy pattern was r=0.58, suggesting a moderate similarity between the two patterns. Before fatigue, the synergy peaks (solid line) occurred in the first 10% of absorption, generation, mid swing and pre-activation phases, whereas, after fatigue (dotted line) synergy peak altered in all parts of the pattern, especially in the initial swing phase (p=0.001) (Fig. 2) in which it significantly decreased. This synergy involves BF, ST and TA, and after fatigue GM muscles are also involved. In the third synergy, after fatigue, GM was relatively heavier (p=0.012) and relative weight of TA (p= 0.024) significantly increased in comparison with the pre-fatigue phase.

During the fourth synergy, the correlation between synergy model, before and after fatigue, was r=0.27, which suggested a very small similarity between the two patterns. Synergy peak before fatigue (solid line) was under the late-swing phase and after fatigue, it was significantly different and under the generation phase (p=0.001) (Fig. 2). This synergy involves Hamstring and Tibialis Anterior and also after fatigue Gastrocnemius and Sloeus muscles. In the fourth synergy, after fatigue, the relative weight of Gastrocnemius (p=0.041) and Sloeus (p=0.004) significantly decreased.

In the fifth synergy, the correlation between synergy patterns was r=0.48 suggesting a low-moderate similarity between pre and post-fatigue. In the pre-fatigue, the synergy peak occurred in the generation phase and after that, it occurred in the absorption phase (p=0.001) (Fig. 2). This synergy involves mainly RF, GM and TA muscles. Also, other muscles also had a great role in this synergy. In the fifth synergy and after fatigue, the relative weight of VM (p= 0.001) and VL (p= 0.032) muscles showed a significant decrease.

Mean and standard deviation of VAF for models with 4 and 5 synergies-are shown in Fig 3 and Fig 4. VAF findings for muscles, before and after fatigue, suggested that using five synergies for reconstructing the original signal was appropriate and all muscles had more than 0.9 VAF but considering 4 synergies, the amount of VAF in most muscles was less than 0.9. There was also no significant statistical difference in the amounts of VAF before and after muscular fatigue during 4 and 5 synergies.

**Discussion**

The present study was aimed at investigation of the effect of running-induced fatigue on synergy of the selected muscles in the lower limb while running. The findings suggested that after running-induced fatigue, synergy model and relative weight of muscles in runners changed during running. In muscular synergy levels, after fatigue and considering the amount of VAF, the number of muscular synergies did not change, which means that the number of muscular synergies remained constant after fatigue in the runners. The results also indicated that the tendency of the synergy model (synergy activation time) and muscles' relative weight changed. These findings correspond with those of other studies such as Smale et al. pointing to no differences in synergy structure because of fatigue. Smale et al. showed that after muscular fatigue, the number of synergies is fixed; meanwhile, its activation occurs in different parts of the movement cycle and the partial weight of the muscles changes (Smale et al., 2016). The authors concluded that muscular fatigue with changes in neuro-muscular features would lead to a change in the tendency of muscular synergies and relative weight of the muscles. As a result, such synergies can alter the movement pattern through changing the tendency of the muscular synergies and their activation in different points of the movement cycle (Smale et al., 2016). This change in movement patterns has been observed during the post-fatigue condition in running kinematics (Kim et al., 2018). Turpin et al. also pointed out that after fatigue, synergies' structures are stable and some changes merely

happen in the activity of muscles, which shows the consistency of the synergy structure after fatigue (Turpin et al. 2011). Ortega-Auriol et al. also showed that the synergies' structures remains consistent during fatigue (Ortega-Auriol et al., 2018). Furthermore, Shaharudin et al. explained that after six-minute maximal paddling, some changes occur in muscular synergies, but their structures will be consistent (Shaharudin et al., 2014). The authors pointed out that during fatigue, CNS distributes activities in the muscles differently in order to decrease the risk of muscular injuries, thus CNS constantly creates some regulations for selecting optimal muscular synergies that are suitable for continuing the movement (Shaharudin et al., 2014). Apart from optimization of synergies for continuing the movement, these changes fulfill other purposes such as compensating for muscles force. Stuizing and Sibert pointed out that in the fatigue condition, the nervous system changes the activity weight of the muscles to compensate for the lost force of the muscles (Stutzig & Siebert, 2015). It seems that changes in muscle activity weight in fatigue conditions are a strategy to compensating for muscular force output.

Various conditions could create different kinematic and kinetic patterns for running. It has been shown that running in different levels (level and uphill) can change running kinematics (Gottschall & Kram., 2005). Dugan and Bhat also showed that running at different speeds can change running kinematics (Dugan & Bhat., 2005). Despite that, Saito et al. showed that during running at different speeds and slopes, muscular synergies are similar (Saito et al., 2018). Riley et al. (2008) and Schanche et al. (2001) showed that running on a treadmill creates a different kinematics in the lower limbs compared to running on the ground; nevertheless, Oliveira et al. found that running on a treadmill and on the ground follow the same muscular synergies (Oliveira et al., 2014). Considering the above-mentioned evidence, it seems that in spite of some differences in kinematics and movement patterns in various running

environments, conditions of the environment does not affect muscular synergies structure but change the synergy patterns. Fatigue can also cause various kinematics and kinetic patterns (Kim et al., 2018). Rozumalski et al. (2017) showed that changes in locomotion kinematics and kinetics do not affect the number of synergies required for movement (Rozumalski et al., 2017). Consequently, it can be concluded that fatigue that is associated with some kinematic and kinetic changes, does not affect the structure of muscular synergies and merely causes some changes in synergy tendency and their activation in different time points.

Dierks et al. (2010) found that fatigue does not influence joint timing and after fatigue, the time for reaching the maximum joint angles does not change. Hamill & Bates (1992) suggested that changing in joint timing while running is one of the mechanisms of injuries in knee joint (Hamill & Bates., 1992). As a result, preserving the structure of synergies and changes created in the relative weight of the muscles could be seemingly a strategy for keeping joint timing to avoid the risk of suffering from injuries due to fatigue.

The present study was constrained by some limitations including not collecting kinematic and kinetic data simultaneously with Electromyographic data for more accurate interpretation of the results and phase separating. However, in this study the phases were separated based on Lohman et al. (2011) having approx accurarcy for temporal representation for gait-cycle characteristics (Lohman et al., 2011). Another limitation was concerned with incapability of recording the activities of the deep muscles involved in running and their effect on synergy. Evaluating more muscles could help us to better reveal muscle synergies and provide a better interpretation of the results. However, Cappellini et al, used 32 muscles to extract muscular synergies for running and walking (Cappellini et al., 2006). In line with our findings, they found that five synergies account for 32 muscles' control. Analyzing the frequency content of EMG signal in synergies analysis and showing

fatigue is one of the greatest components, which was not considered in the present study. More research is needed to study the effect of fatigue on frequency components.

## Conclusion

Based on the findings of the present study, it can be concluded that running-induced fatigue does not have any effect on the structure of muscular synergy but changes the relative weight of the muscles. It seems that these changes are a strategy by the nervous system to avoid injuries in fatigue conditions.

## Conflict of interest statement

The authors declare that they have no conflict of interest about the publication of this article.

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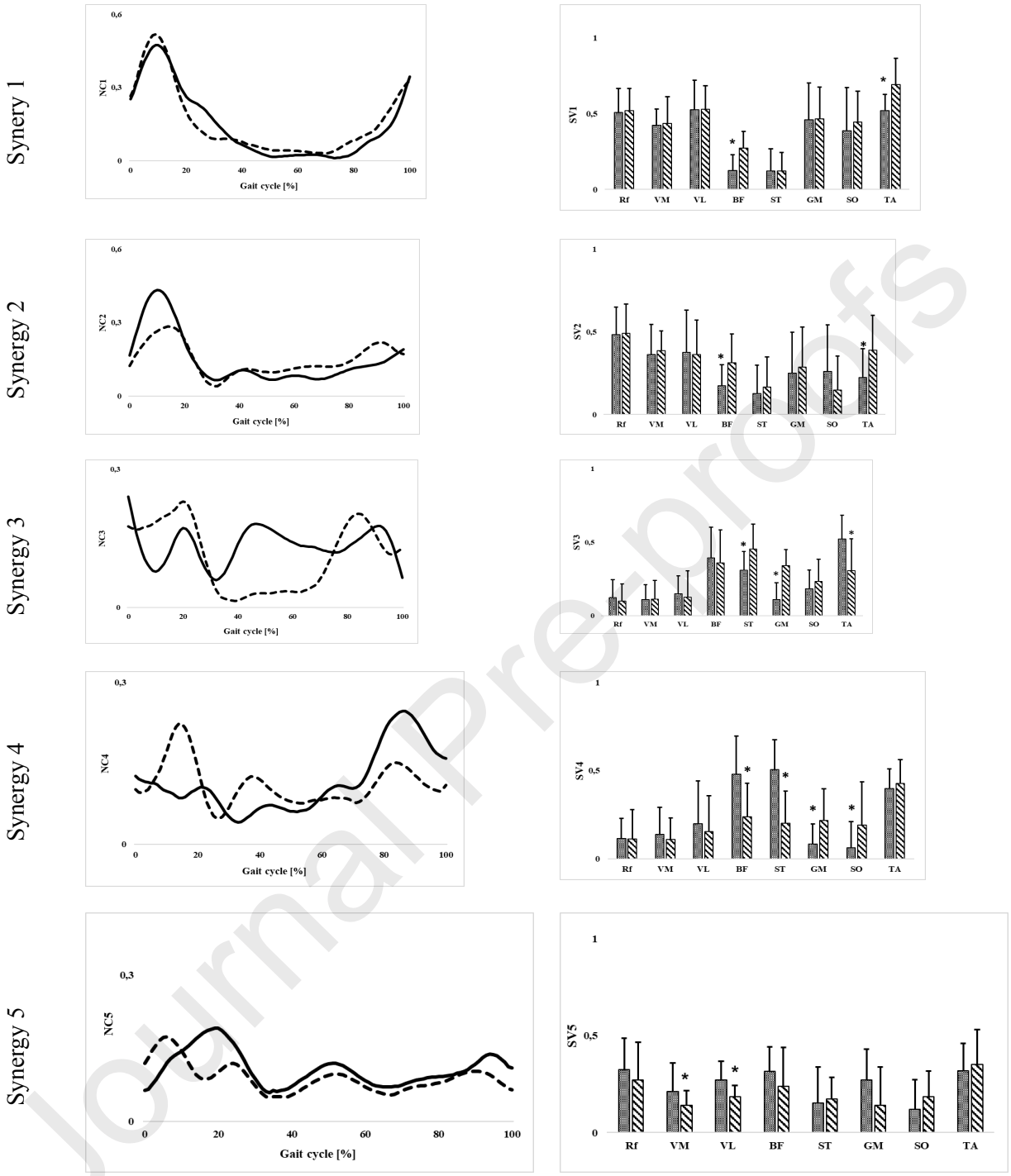


Fig1. Right: Mean synergy components of decomposing EMG signals in 5 modules in pre and post fatigue. Left: mean values of SVs with Standard deviations before and after fatigue. (* represents significant difference at $p \leq 0.05$)

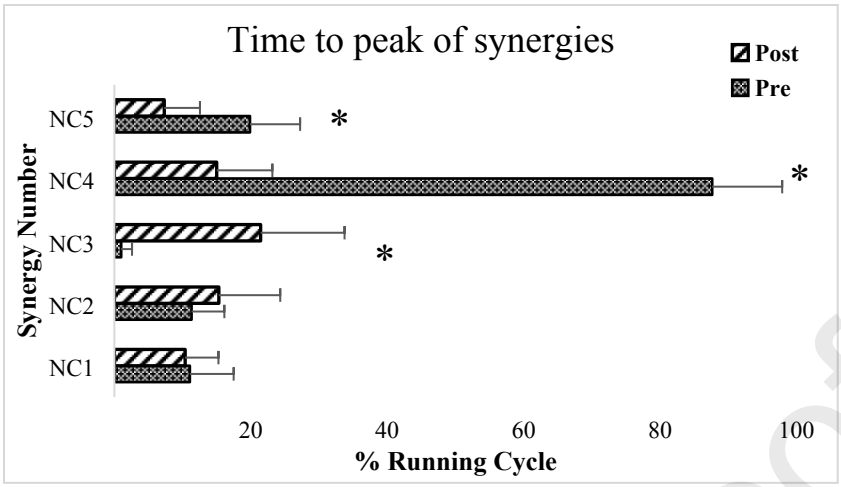


Fig 2. Comparison of time to peak of each synergy before and after fatigue (∗ indicates significant difference).

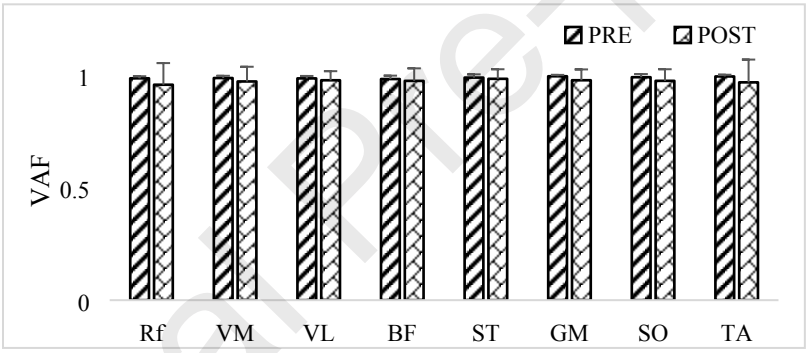


Fig3.Mean and standard deviation of variation accounted for (VAF**)** values of all muscles using 5 modules before (in black) and after (four rooms) fatigue

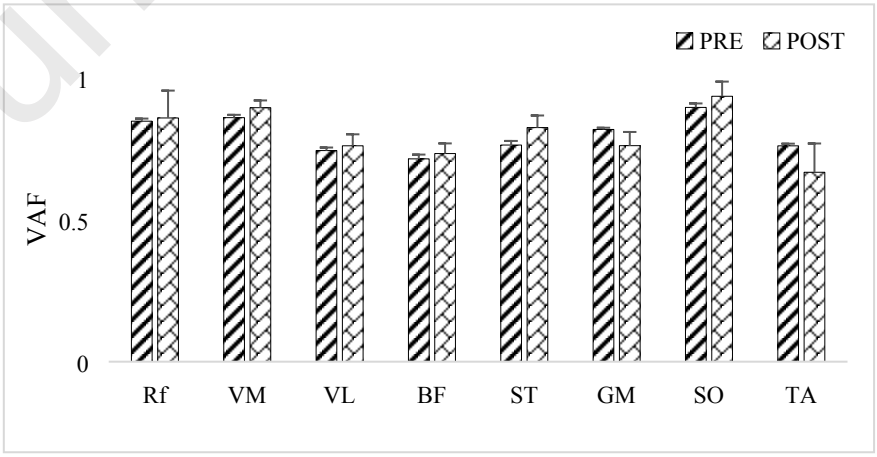


Fig4. Mean and standard deviation of variation accounted for (VAF**)** values of all muscles using 4 modules before (in black) and after (four rooms) fatigue