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Proceeding Paper

Muscle Networks Dynamic in Demanding Postural Tasks and Visual Feedback Privation: A Preliminary Study †

Ana Lía Albarracín [1,*], Fernando Daniel Farfán [1,2], Leonardo Ariel Cano [1], Juan D. Romero-Ante [3], Juan S. Montenegro-Bravo [3] and Eduardo Fernandez-Jover [2,4]

1 Neuroscience and Applied Technologies Laboratory (LINTEC), Bioengineering Department, Faculty of Exact Sciences and Technology (FACET), National University of Tucuman, Superior Institute of Biological Research (INSIBIO), National Scientific and Technical Research Council (CONICET), Av. Independencia 1800, San Miguel de Tucumán 4000, Argentina; ffarfan@herrera.unt.edu.ar (F.D.F.); lcano@herrera.unt.edu.ar (L.A.C.)
2 Bioengineering Institute, University Miguel Hernández, 03202 Elche, Spain; e.fernandez@umh.es
3 Unidad de Investigación en Robótica Médica, Instituto de Bioingeniería, Universidad Miguel Hernández, Avenida de la Universidad, s/n, 03202 Elche, Spain; j.romero@umh.es (J.D.R.-A.); juan.montenegro@goumh.umh.es (J.S.M.-B.)
4 Research Networking Center in Bioengineering, Biomaterials and Nanomedicine (CIBER-BBN), 28029 Madrid, Spain
* Correspondence: aalbarracin@herrera.unt.edu.ar
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Abstract: Postural stability relies on the effective interaction between sensory feedback integration and muscle modulation. This study investigates the dynamics of muscle networks generated during challenging postures and examines the impact of visual feedback deprivation on balance. The postural conditions included three tasks selected from the Berg Balance Scale: standing feet apart, standing feet together, and tandem stance. Additionally, these postures were performed with both open and closed eyes. Electromyographic (EMG) signals were collected bilaterally from six leg and hip muscles. Intermuscular coherence (IMC) was calculated across the twelve muscles within the beta frequency band to identify the muscle networks activated under different postural conditions. The findings revealed a decrease in the number of connections across the sequence of postures, alongside the strengthening of specific muscle connections unique to each individual. These shared patterns and individualized muscle networks may reflect adaptive strategies employed to maintain stability during challenging postural tasks.

Keywords: electromyography; intermuscular coherence; muscle networks dynamic; postural control

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1. Introduction

Postural control requires the efficient functioning of sensorimotor mechanisms and the ability to coordinate movement strategies to stabilize the body's center of mass during stability disturbances. Information from the environment is captured by sensory system receptors and then processed by the central nervous system (CNS), which is responsible for generating a motor response to correct potential body alignment disorders [1,2].

Numerous studies have provided evidence that the CNS employs a modular organization by combining multiple muscle synergies to produce movement [3,4]. Muscle synergy has been defined as low-dimensional modules formed by muscles activated in synchrony and used by the nervous system for constructing motor output patterns during both locomotor and postural tasks [5].

In recent years, the interaction between cortical motor areas and muscles has been extensively studied using functional connectivity measures [6], enabling the establishment of quantitative parameters for motor control. In this context, coherence analysis represents a useful technique to characterize the functional association between muscles involved in a motor task [7]. Thus, intermuscular coherence (IMC) calculated from surface EMG signals can provide an estimate of synaptic input shared by motor neurons that innervate the muscles [8]. Also, coherence in each frequency band quantifies the common oscillatory inputs to the motor neurons [9].

Several studies in the last few years have used the coherence analytical method to address postural stability during standing tasks in humans. The approach used most is to estimate the coherence of muscle pairs across different frequency bands. During quiet standing, numerous studies have shown significant coherence between bilateral and unilateral plantar flexor muscles [10–12] and between agonist–antagonist muscles [13–15]. These authors also reported significant coherence in beta-band in standing tasks. It is thought that coherence in the beta frequency band is strongly associated with corticospinal drive [16–18].

On the other hand, Walker et al. [12] recently examined the impact of resistance training in coherence between muscle pairs in open- and closed-eye standing positions. They found training-induced changes in coherence magnitude between soleus and tibialis anterior pairs for the beta-band during the closed-eye standing task. There is also evidence that coherence between muscle pairs differs between young and elderly adults during the standing task [19–22]. Recently, it has been reported that during bipedal standing, significant coherence in alfa-band has been observed in bilateral and unilateral plantar flexor pairs in the elderly group, whereas significant coherence was below 4 Hz in the young group [23]. In addition, coherence was demonstrated to be a useful tool for examining changes in muscle connectivity in patients with CNS disorders [24]. However, to our knowledge, there are no reports in the literature describing changes in the connectivity of multi-muscles involved in postural tasks of increasing difficulty and considering visual information.

In this preliminary study, we estimated functional connectivity from six muscles of both legs and hips to identify the muscle networks involved in postures of different difficulty and with visual condition changes. The aim of this study was to explore the existence of muscle network patterns that may be modulated under specific conditions of postural instability. Our findings indicate that while certain patterns are consistently observed across the individuals evaluated, distinct individual-specific characteristics were also identified.

2. Materials and Methods

2.1. Experimental Protocol

Three healthy participants (one female and two males), all young adults (21–31 years old), with no neurological or muscular disorders, voluntarily took part in this study after providing informed consent. The participants were instructed to stand upright and perform three different postures selected from the Berg Balance Scale and administered in increasing difficulty: standing feet apart (SFA), standing feet together (SFT), and tandem stance (T) (the heel of dominant foot in front of the toes of the non-dominant foot) (Figure 1A). Additionally, these postures were performed both with eyes open (EO) and with eyes closed (EC). This approach allowed for the evaluation of the ability to maintain posture with and without visual feedback. The sequence of postures was carried out continuously, alternating returns to the initial position with eyes open (SFA-EO). This procedure enabled the establishment of more stable posture as a control (the initial SFA-EO posture between challenging postures). Participants needed to remain in each postural condition for 30 s while maintaining the balance and with their gaze fixated on the wall approximately 2 m in front of them.

Electromyographic signals (EMG) were collected from specific muscles of the legs and hips on both sides (Figure 2). Skin surface preparation and electrode placement were performed according to SENIAM guidelines [25]. After cleaning the skin, 30 mm Ag/AgCl surface adhesive round electrodes (Lessa, Madrid, Spain) were applied in bipolar configuration on the following muscles: Tibialis Anterior (TA), Gastrocnemius Medialis

(GM), Vastus Medialis (VM), Rectus Femoris (RF), Biceps Femoris (BF), and Tensor Fascia Latae (TFL) (Figure 1B). The reference electrodes were placed over both knees. The signals were acquired, amplified, and digitized using an acquisition system RHD2132 (Intan Technologies, Los Angeles, CA, USA) with 32-channel amplifiers (Figure 2). The sampling frequency was 5000 Hz.

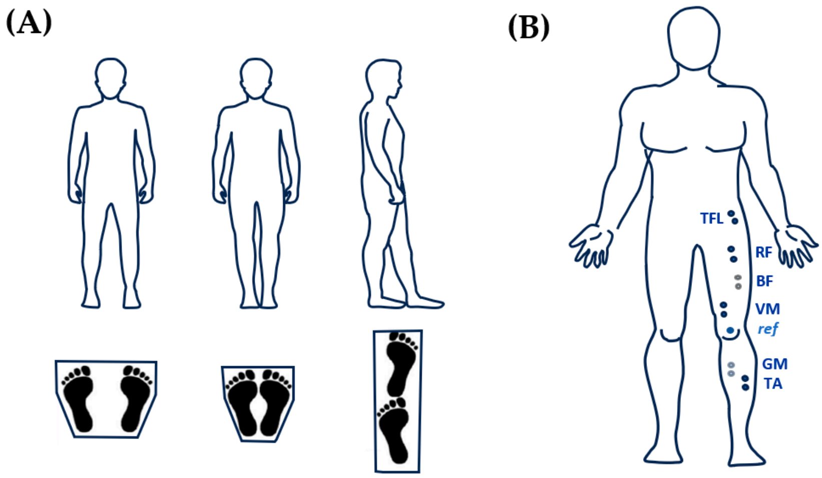

Figure 1. Experimental protocol. (**A**) Schematic representation of the three postures evaluated and the corresponding base of support. From left to right: standing feet apart (SFA), standing feet together (SFT), and tandem stance (T). (**B**) EMG electrodes in bipolar configuration were situated over 6 muscles (both sides): tibialis anterior (TA), gastrocnemius medialis (GM), vastus medialis (VM), rectus femoris (RF), biceps femoris (BF), and tensor fasciae latae (TFL). Note that GM, BF, and ESP are located at the back of the subjects' legs. Reference electrodes (ref) were situated over the heel (both sides).

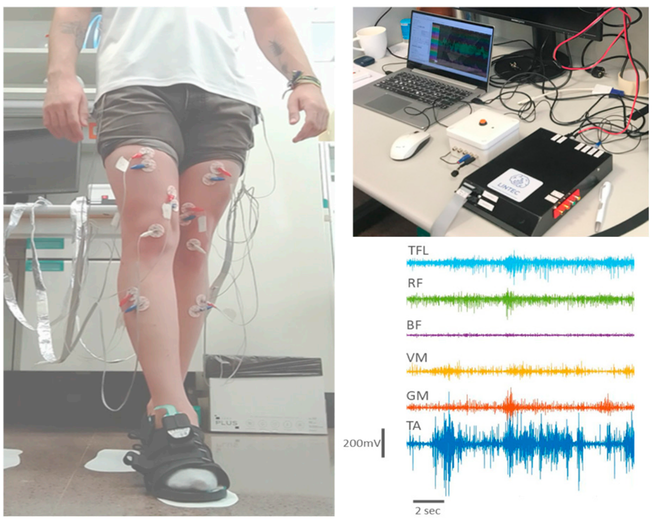

Figure 2. Equipment and EMG signals. Images of the equipment used for the experimental protocol and an example of the signals obtained.

2.2. Pre-Processing

MATLAB version 2020a was used for all data processing (MathWorks Inc., Natick, MA, USA). In order to remove movement artifacts and high-frequency noise, individual EMG signals were filtered using a 5th-order Butterworth filter (band-pass 10–100 Hz, bandstop 49–51 Hz) [26].

To avoid dynamic adjustments associated with weight transfer [27] and any declines in force capacity during the task, 5 s from the beginning and 5 s from the end of each posture were excluded from the analysis.

Intermuscular coherence (IMC) was calculated between all muscle pairs following the method presented by Bigot et al. [28]. This method involves a five-step procedure as follows: auto-spectrum for each muscle signal using continuous wavelet transform; cross-correlation between each pair of muscle signals; mean autospectrum and mean cross-correlation across all muscle signals; magnitude-squared-coherence between the two auto-spectrums; and magnitude-squared-coherence values from regions where the cross-correlation is statistically significant (Figure 3).

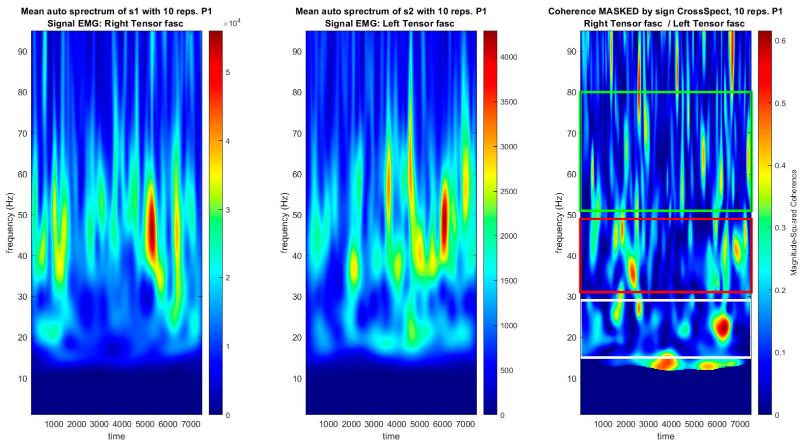

Figure 3. Intermuscular coherence procedure. **Left** and **Middle** panels: mean auto-spectrum of TFL muscles. **Right** panel: cross-spectrum and frequency bands delimited. In white: beta frequency band.

A total of 144 comparisons were obtained from the 12 muscles and delimited in the beta frequency band (15–29 Hz). The IMC was computed as the average value of all measurements in that frequency band. Finaly, connectivity matrices were constructed by assigning the IMC values of each muscle pair to their corresponding positions in the matrix (Figure 4).

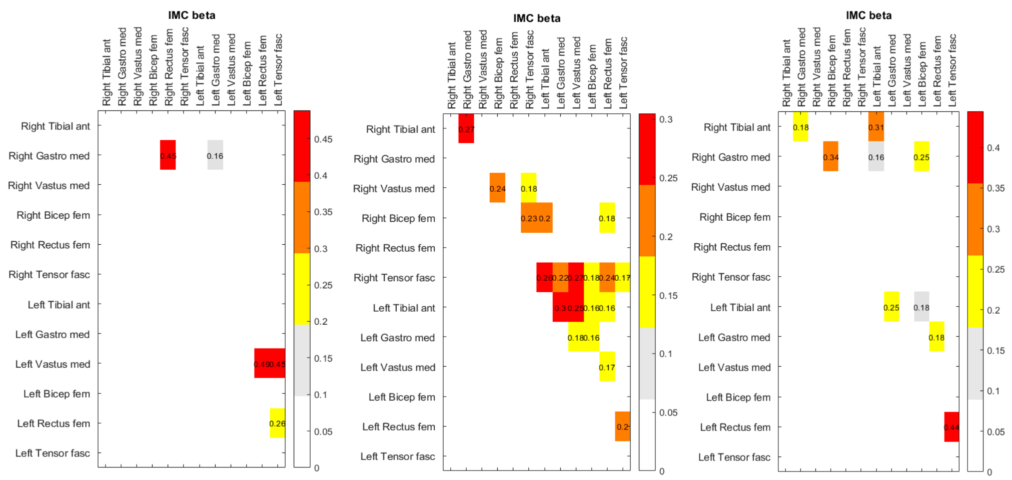

Figure 4. Connectivity matrix obtained for the 3 participants in beta frequency band. The values inside the colored boxes are IMC corresponding to T-EC posture. The colored scale on the right indicates the connectivity strength between two muscles under this postural condition. From left to right: subjects 1 to 3.

2.3. Muscle Networks Analysis

A muscle network was created using Graph Theory for each postural condition. Then, 6 muscle networks were obtained for each participant. Each node (circle) in the network represents a muscle, and the line between nodes represents the connectivity between muscles. The strength or weight of the connection is indicated by the width and color of the line: thicker and darker lines represent stronger connections. In addition, the number of connections a muscle receives is represented by the size of the node, with a greater number of connections corresponding to a larger size.

3. Results

In this study, we performed a connectivity analysis of surface EMG obtained from twelve muscles to extract the muscle networks while the participants were standing upright in three different postures of increasing difficulty with or without visual feedback.

The protocol includes a sequence of three progressively challenging postures, with the effect of visual information deprivation assessed for each. All three postures were performed in a standing position (Figure 1A). The first posture involves standing with feet apart, the second with feet together (bringing the right foot closer to the left), and the third posture (tandem) requires placing the right leg forward, positioning the right heel directly in front of the left foot (Figure 1A). Successfully completing this sequence of movements highlights human neuromuscular flexibility, enabling the modulation of muscle networks to maintain stability across different postures. The postures were denominated as follows: posture 1, standing with feet apart and eyes open (SFA-EO); posture 2, standing with feet apart and eyes closed (SFA-EC); posture 3, standing with feet together and eyes open (SFT-EO); posture 4, standing with feet together and eyes closed (SFT-EC); posture 5, tandem eyes closed (T-EO); and posture 6, tandem with eyes closed (T-EC).

IMC analysis was performed to define the muscle networks involved in postural stability (Figure 5). The results revealed that no consistent muscle network pattern characterizes each evaluated posture. Instead, the simplification of the initially activated networks and the strengthening of specific muscle connections in the tandem stance was observed. These reinforced connections involve pre-existing muscle linkages that already demonstrate a notable degree of prominence in each subject. Therefore, it is possible to speculate that each subject exhibits a distinct pattern or individual signature. This personal signature is characterized by the prominence of specific muscles and connections that become more robust in more demanding postures to achieve body balance, such as tandem stance and the different postures in the eyes-closed condition. Thus, in subject 1, a progression toward strengthening the unilateral RF-GM connectivity can be observed (Figure 5, top). This is particularly evident in both tandem conditions, with and without visual feedback. This individual pattern tends to reinforce the stability of the right knee position (RF) and the right foot (GM). However, for the stability of the left side of the body, the activation of muscles in the upper leg and hip region—TFL, VM, and RF—plays a critical role. The calculated connectivity between these muscles yielded high values, such as RF-VM = 0.49 and TFL-RF = 0.45 (Figure 4, left).

In contrast, for subject 2, the connections between homologous TFL muscles and other muscles, both unilaterally and bilaterally, gained prominence (Figure 5, middle). Furthermore, under more challenging conditions (tandem), bilateral connections between TFL and GM, VM, and TA were reinforced, as well as unilateral connections where the TFL again plays a key role. This is reflected in the IMC values obtained for these connections (Figure 4, middle). In the tandem posture with visual feedback, TFL-RF connectivity showed a value of 0.35, and for TFL-GM the value was 0.42.

Subject #3, instead, exhibited a pattern of strong unilateral and bilateral connections between antagonist muscles of the lower leg (TA and GM) throughout the entire sequence of postures (Figure 5, bottom). Additionally, in postures 1 to 4, strong unilateral connections could be observed in the right leg in RF-BF-VM, which disappear in the tandem postures where TFL-RF connectivity strengthens, providing stability to the left leg with an IMC value of 0.44 (Figure 4, right).

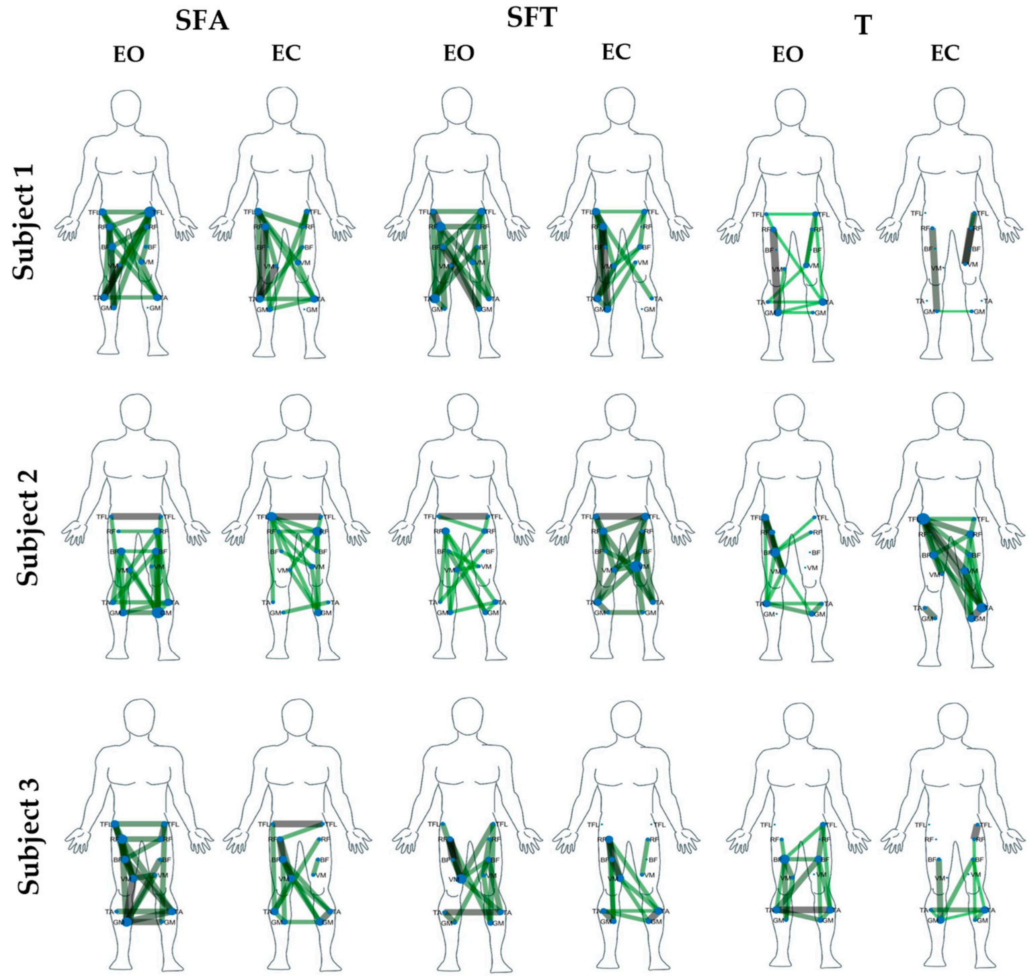

Figure 5. IMC analysis in beta band. Muscle networks generated during different conditions to stabilize the posture. The human figures were standardized in one posture (SFA) to clearly show the connections. SFA: Standing with feet apart. SFT: Standing with feet together. EO: Eyes open. EC: Eyes closed. Thicker and darker lines represent stronger connections and greater number of connections corresponds to larger size of the nodes (circles).

Finaly, it is important to highlight that under visual feedback privation (SFA-EC, SFT-EC, T-EC), the number of significant connections decreases compared to the same postures with visual information.

4. Discussion and Conclusions

This experimental approach enabled the characterization of muscle network dynamics under varying postural conditions, both with and without visual feedback. Functional connectivity was estimated to identify the muscle networks activated under these distinct postural and visual conditions.

Intermuscular coherence has previously been used to investigate oscillatory common inputs of cortical or peripheral origin to different muscle groups [9]. Specifically, in the assessment of postural control, studies have focused on estimating the connectivity between muscle pairs, with a particular emphasis on the foot flexors and across different frequency bands. It has been stated that coherence is significant in bilateral homologous and unilateral plantar flexor pairs in the delta-band and alpha frequencies [11,20–22]. Also, recent studies have shown that coherence in delta and alpha bands between antagonistic lower leg muscles increased with increasing standing difficulty [13,14], such as when standing on one leg. In our study, we have focused on the beta frequency band to consider the most direct information pathways to the muscles (corticospinal). On the other hand, we estimate multiple muscle IMC to extract the muscle network generated during each postural condition. Unlike previous studies, we have also included the tensor fasciae latae muscle in the connectivity analysis. This muscle is involved in hip flexion and rotation, which are crucial for lateral body stabilization, as well as in knee extension by tensing the fascia lata. Our results reveal consistent connections between the TFL muscles on both sides across most postures. Furthermore, in the most destabilizing postures, these connections become significantly stronger, as reflected in the high IMC values observed (Figures 4 and 5).

The results suggest that as postural difficulty increases, the complexity of muscle networks is reduced and specific muscle connections—a "personal signature"—become more prominent and reinforced. Therefore, it is plausible to suggest that a shared muscle network behavior, combined with an individual signature, may represent the strategy employed to respond to postural imbalance situations.

5. Future Work

This preliminary study provides results about the postural control strategies of three healthy subjects. To validate the trends identified in this preliminary study, it will be essential to both expand the sample size and conduct repeated evaluations with the same participants. Additionally, different measures will be employed to quantitatively characterize the observations outlined in this study, including those previously established for evaluating structural and functional integration and segregation [28]. Finally, inertial (IMU) and plantar sensor data will be included in the upcoming analysis to explore possible changes in the spatial orientation and pressure distribution associated with muscle connectivity changes during postural stabilization.

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Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki and approved by the institutional review board of the National University of Tucuman (RES-HCS 356-2023).

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data presented in this study are available upon request from the corresponding author. The data are not publicly available due to data protection policies practiced at our institution, as they contain information that could compromise the privacy of research participants.

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