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Modular control of mediolateral postural sway

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Abstract— **Is voluntary motor control of mediolateral rhythmic sway ruled by modular organization? Answering this question has potential implications in diagnosis and rehabilitation of neurologically impairments. Superficial EMG and computerized dynamic posturography has been used in this study to investigate modular control of six healthy subjects. Postural movements have been performed at three different frequencies to also test the influence of speed on the composition of synergies and activations. Results showed that two synergies account for more than 75% of EMG variance and are shared by all subjects across all frequency conditions. These evidences, together with a functional interpretation of computed muscle synergies, support the existence of consistent modular control across healthy subjects during mediolateral voluntary movements.**

I. Introduction

Postural control is the ability to maintain equilibrium in a gravitational field by keeping or returning the center of body mass over its base of support [1]. Stable postural control requires complex interaction of several neural mechanisms involving musculoskeletal, visual, vestibular, and somatosensory systems [2]. Impairment of one or more of these systems, due to aging or diseases, can reduce the stability of posture and thus affect quality of life [3]. Analysis of posture is essential in the clinical practice to assess the pathologic neural mechanisms as well as to design specific treatments.

The hypothesis of modular organization of CNS has been increasingly supported by several experimental studies over the last 15 years [4,5,6]. According to this hypothesis, spatiotemporal activations of muscles can be explained by the combination of a low dimensional set of muscle synergies. The neural origin of this 'synergistic behavior' is still object of intense debate [7, 8]. Anyhow, the analysis of synergies has been proposed as a potential tool to reveal abnormal neuromotor activity in neurologically impaired people [9]. To deal with this hypothesis, some authors have recently started to explore correlations between motor dysfunctions and muscle synergies [10,11,12,13]. In this context, time is ripe to extend such kind of analysis to new experimental conditions, to give clinicians multiple solutions for the assessment of pathologic behavior under the point of view of synergies. To this aim, this work proposes a different scenario for the study of modular control that can be easily repeated in clinical environment on neurologically impaired people. The method is based on the assessment of voluntary mediolateral sway by means of EMG in conjunction with computerized dynamic posturography (CDP). CDP is considered as the Gold Standard for postural control assessment. Recently, the American Medical Association (AMA) has included the CDP as one of the methods for impairments evaluation and the American Academy of Neurology considers the CDP as a useful clinical tool for human balance analysis. CDP is based on the use of dynamometric platforms measuring the displacement of the Center of Gravity (COG). Typical CDP procedure is to analyze postural behavior in presence of unexpected perturbations, modified sensory inputs, or voluntary movements. Additionally, voluntary postural movements are used clinically to promote motor recovery in stroke population [14].

Study of muscle synergies during postural tasks has been performed over a wide range of experimental conditions. Most of the studies investigate responses to external perturbation, such as those induced by platform translations. In this scenario, experiments on cats [15] and humans [16,17] showed that composition and temporal activation of most of the muscle synergies are similar across subjects and consistent among difference biomechanical conditions and directions of perturbation. Moreover, several studies support the hypothesis that muscle synergies are correlated with task-level variables such as CoP position [18,19,17]. Concerning voluntary postural movements, some studies showed that anteroposterior (AP) rhythmic movements can be described by a few synergistic patterns, called M-modes, consistent across subjects and sway frequencies [20,21]. To the best of authors' knowledge, synergies in mediolateral (ML) voluntary movements have not been previously studied. This work presents a preliminary study on healthy subjects during rhythmic postural movements in the ML direction. The objectives targeted by this work are: i) verifying if similar synergies and activations are shared by healthy subjects during voluntary postural movements, ii) to detect if modular control is affected by speed of movement.

II. Material and Methods

A. Subjects

Six healthy subjects (3 male and 3 female) participated at the experiment. Subjects′ mean age was 46.9 years (±3.0 SD). The research was carried out in the Movement Analysis, Biomechanics, Ergonomic and Motor Control Laboratory (LAMBECOM), Faculty of Health Sciences at the Rey Juan Carlos University (Madrid, Spain). The investigation

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took place between November, 2011 and February, 2012. The study has been approved by local Human Ethics Committee and informed consent was obtained from all participants.

B. *Experimental protocol*

The CDP system NeuroCom Smart Equitest system® (Oregon, USA) has been used for measuring CoP displacement as well as for guiding the patient in the exercise by means of computer-based visual feedback (see figure 1). Participants were asked to step onto the platform base where they faced the visual surround. Each foot was positioned on one force plate such that the medial malleolus and lateral aspect of the calcaneus were aligned with the appropriate markers according to the manufacturer's instructions. Participants were instructed to stand upright, leaving arms at their side throughout the entire test. Arms are not restrained to allow for better comparison to future studies on stroke population, where arms will be let unconstrained. All participants wore a safety harness to prevent falling. The tests were conducted in a peaceful atmosphere and with the removal of alcohol, smoke and psychotropic drugs in the previous 24 hours. The participant's data were entered (age, mass and body height) into the NeuroCom software. The Rhytmic Weight Shift (RWS) test was selected in order to measure rhythmic postural movements in the ML plane. RWS test quantifies movement characteristics associated with the patient's ability to voluntarily move their COG or "sway" from left-to-right (ML plane) rhythmically. Three sway frequencies have been chosen, i.e. 0.167Hz (sway period T=6s), 0.250Hz (T=4s), and 0.5Hz (T=2s) respectively. Visual feedback of COG trajectory together with a reference oscillating at the given frequency is provided to the subject, in order to ensure movement synchronization (Figure 1, right). Also anteroposterior (AP) movements have been performed, in order to define maximum muscle activation values to be used for EMG normalization. In fact, most of the registered muscles do not reach high activation during mediolateral movements. This procedure is used to avoid maximum voluntary contraction (MVC), which is considered excessively burdensome in clinical applications.

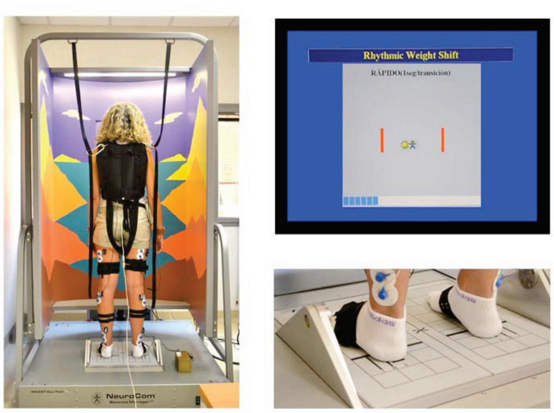

Figure 1. Left: Instrumented patient on the NeuroCom Smart Equitest system® (Oregon, USA). Right-up: user visual interface to ensure synchronization of patient CoP (human icon) to a reference (sun icon) performing sinuisoidal shifts at three different frequencies. Right-down: dynamometric platoform to measure CoP displacements.

At each frequency, subjects were given 1 minute prior to data recording to familiarize with the exercise and synchronize their movement with visual reference. RWS during three complete cycles have been recorded, for each frequency, for a total of 6 trials (3 frequencies, 2 directions of movements). Duration of trials was 18, 8 and 4s for the low, medium and high frequency conditions respectively. Superficial EMG signal have been recorded from 8 lower limb muscles, and synchronized with force data recorded by NeuroCom platform. Electrodes were placed according to the SENIAM recommendations [22] on the following muscles: gluteus maximus (Gmax), gluteus medius (Gmed), tensor fascia latae (TF), rectus femoris (RF), biceps femoris (BF), gastrocnemius lateral (GAS), soleus (SOL), and tibialis anterior (TA).

C. *Data analysis*

EMG signals were sampled at 2000 Hz, demeaned, rectified, and processed by a RMS with a centered window of 200 points (100ms). Than, an *ad-hoc* low pass filtered (Butterworth, 5th order) has been used with cut frequency f_{cut}>2*f (where f is the frequency of sway) to achieve the maximum smoothing without loosing important frequency content. Chosen f_{cut} was 0.5Hz, 1Hz, and 1.5Hz for low, medium high frequency sway respectively. To facilitate intra-subject comparison of muscle activity amplitudes, resulting EMG envelope of each individual muscle has been normalized to the peak value of the same muscle during all the trials (including AP movements), and then resampled at 1% of the sway cycle. For each subject, muscle weightings (synergies W) and time-varying activation coefficients (H) of each individual exercise have been extracted by nonnegative matrix factorization (NNMF) [23]. To reduce the problem of non-uniqueness of solutions, synergies have been initialized with equally distributed weights along all the muscles, whereas activations have been initialized with a zero value matrix. Reconstruction of EMG has been obtained multiplying matrix W by H. Reconstruction quality was expressed as the value accounted for (VAF) value, which is defined as VAF = 1- SSE/SST, where SSE is the sum of squared errors SST is the total variation error between original and reconstructed EMG [11]. In order to estimate the optimal number of synergies, an iterative procedure has been performed, varying the number of synergies from 1 to 4. At each iteration loop, VAF has been calculated. The optimal number of synergies is defined as the lowest value to which i) VAF>85% or ii) the increment with respect to VAF of previous iteration was <5% [11]. Similarities between i) synergy vectors (W) and ii) activation coefficients (H) have been analyzed by calculating the cross-correlation factor (*r*) across subjects and conditions.

III. PRELIMINARY RESULTS

A. *Kinematic performance*

Subjects performed sway movements synchronously across all the required frequencies, as shown in figure 2 (top). In particular, slow, medium and fast movements have been performed at 0.169 ± 0.005 Hz, 0.248 ± 0.003Hz and 0.444 ± 0.073Hz respectively. Shapes and peak-to-peak amplitudes were very similar across low and medium frequencies, whereas at high frequencies more variation in amplitude has been observed. After the process of segmentation by sway cycles and time rescaling from 0-100% of each gait cycle, profiles showed high similarities across subjects (figure 2, bottom), respectively of 0.96 ± 0.03, 0.96 ± 0.05 and 0.94 ± 0.09 for slow, medium and fast conditions.

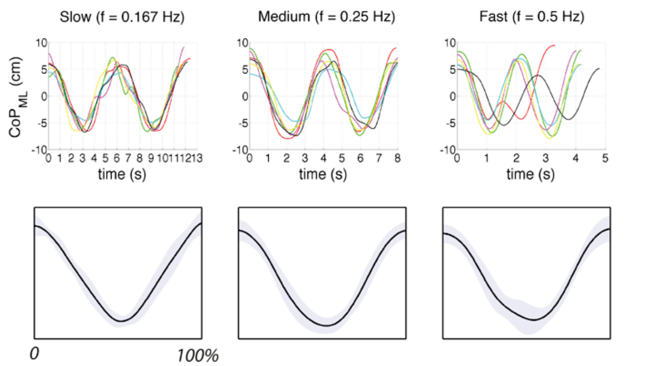

Figure 2. Time course of CoP displacements. Top) Individual CoP displacements over two consecutive sway cycles. Bottom) Mean and std of resampled CoP at each 1% of the sway cycle.

B. Muscle synergies and activations

Analysis of dimensionality showed that two synergies accounted for more than 75% of the variance variability (VAF), for all subjects in all conditions. In particular, calculated VAF were 75.1 ± 4.5 % for low frequency, 77.9 ± 6.3 % for medium and 82.0 ± 5.9 % for high frequency sway condition (see figure 3). Despite the fact that adding a third module still improve considerably VAF (>6%), the calculated r for H and W across subjects dropped drastically (r< 0.15). This high inter-subject variability in presence of the third module, led us considering only the first two modules.

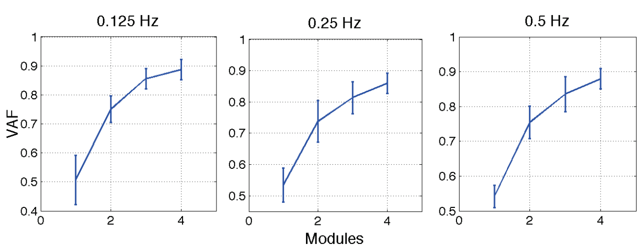

Figure 3. Variance accounted for (VAF) as a function of number of modules. Two modules accounted for more than 75% in all conditions.

Similarity of muscle synergies (W) across subjects was 0.52 ± 0,37 for low sway frequency (0.167Hz), 0.61 ± 0.28 for medium frequency (0.250Hz) and 0.51 ± 0.43 for high frequency (0.5Hz). Activation coefficients (H) show a similarity across all subjects of respectively 0.82 ± 0.21; 0.81 ± 0.14; and 0.62 ± 0.40 for low, medium and high frequency conditions. Similarities across subjects can be also visually inspected in figure 4, where mean values/time-profiles and standard deviations are depicted. High consistency of modular composition across different sway frequencies has been also been observed (0.88 ± 0.02, 0.79 ± 0.07, and 0.85 ± 0.04 for the three conditions). Synergy 1 is characterized by a major activation of TA, SOL, GAS, GMax and GMed, and weaker activation of RF and TF. Synergy 2 is mainly concerned with strong activation of BF and minor activation of TF and RF. A consderable activation of Gmax is also observed in medium and fast exercises. Time course of activation coefficients (H) presents a pseudo-sinusoidal shape, at the same frequency of CoP displacements. First module is most activated (H_1) at the beginning and at the end of the cycle, when the subject is at the maximum lateral inclination and the leg is in its maximum loading conditions. The second module is activated (H_2) in the central part of the cycle, when the subject is leaning on the opposite side. This behavior is shared across the three sway conditions, as shown by the similarity values (0.89 ± 0.05, 0.88 ± 0.05 and 0.56 ± 0.21.

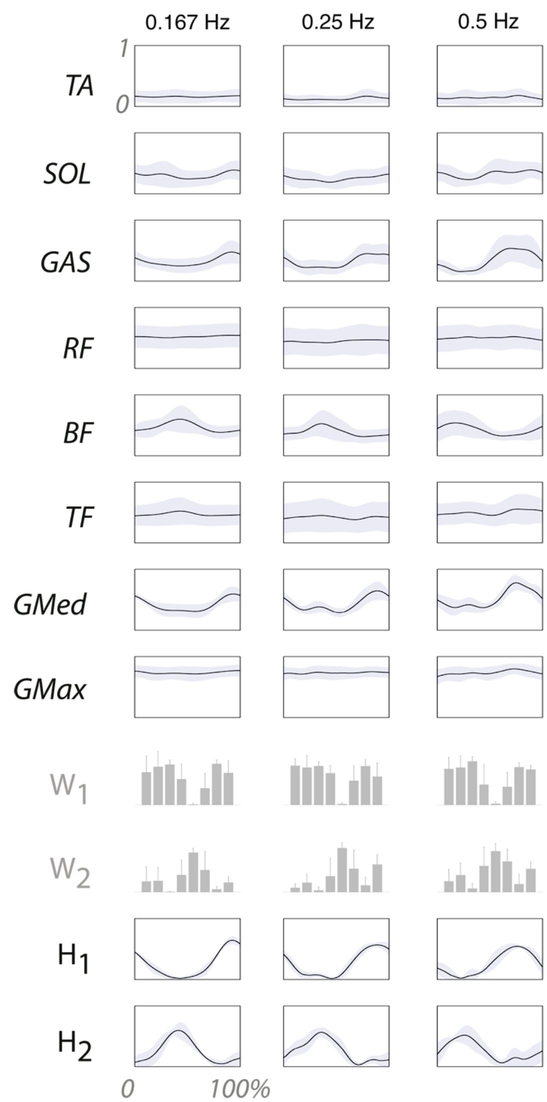

Figure 4. EMG, synergies (W) and time varying activations (H). All the graphics represent mean values (bold line, or gray hystograms) ± standard deviations (shaded area or vertical segments) across subject. The x axis of EMG and activations represents the percentage of a complete sway cycle. Each column referes to a frquency condition. Synergies weights are in the same order as upper EMG representation (the first column of each histogram refers to TA muscle).

IV. DISCUSSION

This study provides evidences supporting the existence of consistent modular control across healthy subjects during lateral voluntary movements. Similarities can be observed in terms of number of modules, composition of synergies, and time-varying activations. Two modules account for most of the variability of the EMG of all subjects. Values of muscle weightings are similar across sway frequencies, meaning that muscle coordination is not particularly influenced by speed of movement. Some slight variations in activations can be observed across conditions, that we interpret as due to different ability of the subject to coordinating with the visual reference (the sun icon moving on the screen). Differences in this ability increase with the sway frequency, as it can be seen in figure 2. Compared to the variability of CoP displacement of AP movements (not shown here), ML condition show higher similarity across subjects. This may be due to the morphology of human musculo-skeletal structure, which permits better stability in ML than AP direction. A functional interpretation of the observed modular organization can also be given. Module 1 is predominantly activated at the end of lateral movement toward the instrumented leg. In such condition, the three agonist-antagonist muscles around ankle joint (TA, SOL, GAS) are co-activated, ensuring higher ankle stiffness during leg loading. Similarly and concurrently, hip joint is maintained stable by co-contraction of rectus femoris (RF) and glutei (GMax and Gmed). Module 2 is instead activated when the body leans on the opposite side (50% of the cycle). In this condition, leg is not loaded, and BF and RF activation stabilize knee joint preventing it from flexing.

V. CONCLUSIONS AND FUTURE WORK

To the author's knowledge, this is the first work in which voluntary ML movements are studied under the point of view of modular control. Previously, Torres-Oviedo et al. [15,16] extensively studied modular control in posture for different biomechanical constraints, including ML movements, but limited to perturbed scenario (platform translations). The present work can be seen as complementary approach to a previous study [21] that provided evidences of modular organization of voluntary AP sway. Our results are encouraging and support the hypothesis that human neuromuscular system applies strategies of motor reduction, which are shared among healthy subjects. Nevertheless, many questions remain unsolved and need to be explored by future experimental analysis. Among these, we are particularly concerned with the use of the analysis of modular organization as a tool for the assessment of neurological injury. As further step, stroke patients will be analyzed following with the same experimental protocol here proposed, in order to investigate if modular postural control of neurological impaired people is different from that of healthy subjects. In this respect, a larger group of subjects and a larger data set should be considered to achieve sound and statistical significant results. Moreover, a detailed analysis on the correlation between CoP changes and differences in synergies shall be faced, to deepen the functional meaning of modular behavior, i.e. its relation with task-level variables. Comparison with AP synergies will be also performed to compare if different directions of movement may share common modules.

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