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Inter-joint coordination of posture on a seesaw device

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ABSTRACT

Even though specific adjustments of the multi-joint control of posture have been observed when posture is challenged, multi-joint coordination on a seesaw device has never been accurately assessed. The current study was conducted in order to investigate the multi-joint coordination when subjects were standing on either a seesaw device or on a stable surface, with the eyes open or closed. Eighteen healthy active subjects were recruited. A principal component analysis and a Self-Organizing Maps analysis were performed on the joint angles in order to detect and characterize dominant coordination patterns. Intermuscular EMG coherence was analysed in order to assess the neurophysiological mechanisms associated with these coordination patterns. The results illustrated a multi-joint organization of posture on both stable ground and on the seesaw, with a higher variability among the individual postural responses observed when standing on the seesaw. These findings challenge the classical assumption of ankle mechanisms as dominating control on seesaw devices and confirm that inter-joint coordination in postural control is strongly modulated by stance conditions. When standing on the seesaw without vision, a decrease in intermuscular coherence was observed without any impact on the joint coordination patterns, likely due to an increase dependence on proprioceptive information.

1. Introduction

Seesaws are widely used as rehabilitation or training devices in order to restore or improve the postural function of various types of subjects by challenging the postural control system. While reducing the ground surface contact and raising-up the feet surface contact, seesaw devices challenge both sensory and motor components of the postural control system (Rougier et al., 2011). Indeed, standing on a seesaw requires the centre of mass (COM) to be projected onto the seesaw's point of contact with the floor thus increasing postural sway when compared to stable ground (Cimadoro et al., 2013). From a control point of view, subjects must shift the seesaw's point of contact with the floor to keep it aligned with the vertical projection of the COM (Ivanenko et al., 1997). When compared to standing still on a stable ground, standing on a seesaw increases the participation of the ankle joint in balance maintenance (Almeida et al., 2006; Cimadoro et al., 2013), with larger movements at the ankle joint (Ivanenko et al., 1997) and a higher electromyographic (EMG) activity of the muscles acting at this joint (Cimadoro et al., 2013). Hence authors have assumed that subjects adopted the so-called "ankle strategy" by freezing the knee and hip joints when standing on both stable ground and on seesaw devices (Ivanenko et al., 1997; Almeida et al., 2006; Cimadoro et al., 2013). Nevertheless, the multi-joint coordination and the associated muscle activation patterns on a seesaw device has never been accurately assessed even though specific adjustments of the multi-joint control of posture have been observed when posture is challenged with modifications of stance and surface conditions (Buchanan and Horak, 1999; Kilby et al., 2015).

It has also been widely demonstrated that removal of vision on its own led to an increase in postural variability and body sway (Hsu et al., 2007; Krishnamoorthy et al., 2005). The effects of vision suppression on multi-joint coordination patterns have been mainly investigated in quiet bipedal stances and results displayed unchanged multi-joint coordination patterns due to vision removal (Hsu et al., 2007; Yang et al., 2015). When focus was given to patterns of muscle activation, results were less consistent since either significant increase (Boonstra et al., 2008) or decrease (Danna-Dos-Santos et al., 2015) in intermuscular coherence were reported when the eyes were closed. With challenging postural tasks (e.g. narrow or unipodal stance) which are known to be affected greater by vision removal than quiet standing tasks, results remain poorly documented (e.g. Krishnamoorthy et al., 2005; Wang et al., 2014)

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and rather demonstrate that the withdrawal of visual information leads to changes in the multi-joint coordination patterns used to maintain balance (Wang et al., 2014). Hence one can postulate that the absence of vision in combination with standing on a seesaw which challenges postural balance can lead to potential changes in the postural coordination pattern.

Therefore, the aim of the present study was to investigate and compare the multi-joint coordination of posture when healthy subjects had to maintain balance while standing on either a seesaw generating instability in the sagittal plane or on a stable surface, with eyes open and closed. Inter-joint coordination was analysed using a principal component analysis (PCA) that was performed on the ankle, knee and hip joint angles in order to detect dominant coordination patterns (Daffertshofer et al., 2004). A subsequent Self-Organizing Maps analysis (Peiró-Velert et al., 2014) was performed in order to characterize the different coordination patterns used by subjects. Assessment of neurophysiological mechanisms associated with the multi-joint coordination patterns was then performed by estimating intermuscular coherence between muscle pairs (Danna-Dos-Santos et al., 2014). Since previous studies have demonstrated that all joints became more actively involved in the postural coordination system with increasingly challenging task constraints (Buchanan and Horak, 1999; Kilby et al., 2015) especially when visual cues were removed (Wang et al., 2014), we hypothesized that keeping balance on a seesaw device is rather performed with a complex multi-joint organization of posture than with the so-called ankle strategy and that the withdrawal of visual information has a greater impact on the postural coordination patterns when standing on the seesaw than when standing on stable floor.

2. Material and methods

2.1. Subjects

Eighteen young active subjects (8 males and 10 females) [20.3 (3.3) years, 172.3 (8.0) cm, 64.2 (9.9) kg; mean (SD)] participated voluntarily in this study. All the subjects were students in sports and physical education. Exclusion criteria were: known balance disorders and/or neuromuscular impairments in the past 2 years, ankle, knee or hip sprains history and medication that might influence balance. Subjects were asked to avoid strenuous activity and the ingestion of alcohol or/and exciting substances 24 h before the experimental session. They signed voluntarily an informed consent form before starting the experiment, which was approved by the local ethics commission and was in accordance with the Helsinki Declaration.

2.2. Kinematic measurement

The acquisition of kinematic data was performed with a Codamotion system (Charnwood Dynamics Ltd, Leicestershire, UK) at a 200 Hz sampling frequency. Two Coda CX1 measurement units, which were perpendicularly placed one from each other in the laboratory, were tracking a set of miniature infra-red light emitting diodes (LED) positioned on the subjects' left side (due to experimental constraints). Two cluster-markers sets with a fixed rectangular configuration of 4 infrared LED were fastened on the shank and the thigh in order to establish measurement frames for thigh and leg segment for subsequent digitalization procedure of accurate anatomical landmarks (Liu et al., 2012). Subjects were asked to stand in the anatomical position while the following bony landmarks were pointed with a digitizing probe and characterized by virtual markers: greater trochanter, tip of the lateral and medial femoral epicondyle, lateral and medial malleolus. Since it was difficult to fix a cluster-markers set on the back and on the foot of the subjects, real markers were used for the acromion and the fifth metatarsal head anatomical landmarks.

2.3. EMG measurement

Surface EMG signals were amplified by 1000 (0.5–1000 Hz band-pass analog filter) with a g.BSamp biosignal amplifier (g.tec, Schiedlberg, Austria) and then digitized using a 16-bit A/D converter (PowerLab 16/35, ADInstruments, Castle Hill, Australia) with a sampling frequency of 1000 Hz (CMMR > 100 dB; input impedance 1 MΩ). Pre-gelled self-adhesive disc bipolar Ag/AgCl surface (10-mm recording diameter) electrodes (Kendall Meditrace 100, Covidien, Mansfield, USA) were placed at an interelectrode distance of 20 mm according to SENIAM's recommendations after appropriate skin preparation (www.seniam.org) on the following muscles (left side): soleus (SOL), gastrocnemius medialis (GM), tibialis anterior (TA), vastus medialis (VM), biceps femoris (BF), Gluteus Medius (GLU) Erector Spinae (ES), Rectus Abdominis (RA). These muscles were chosen because of their contribution in the formation of synergistic muscle modules that are used to maintain the balance in an upright stance (Danna-Dos-Santos et al., 2015; García-Massó et al., 2016).

2.4. Procedure

Two bipedal postural tasks of a similar duration of 25 s were considered: a quiet standing task where subjects had to stand as still as possible on stable ground (STA condition) and a dynamic task where they had to maintain as horizontal as possible a Plexiglas seesaw device (Techno Concept©, Mane, France; radius: 55 cm, height: 6 cm) which generated instability in the antero-posterior direction (AP condition). Both tasks had to be performed with the eyes open (EO) and closed (EC), while standing barefoot with similar 20 cm parallel spacing feet positioning and having the arms crossed in front the chest.

2.5. Data analysis

Data were analysed in Matlab (Mathworks, Natick, USA). The ankle, knee, and hip joint angles were computed in the sagittal plane after having filtered the raw kinematic data with a zero lag fourth-order Butterwoth low-pass filter (5 Hz cut off frequency). A PCA was then performed on the joint angle signals to reveal how joint angles were interrelated and to detect dominant coordination patterns. The eigenvector and eigenvalues of the covariance matrix were obtained and the principal components (PC) were computed as the product of eigenvectors and joint angle signals. In order to determine the importance of each PC, the eigenvalues were used to calculate the percentage of the total variance explained by each PC, as illustrated in Eq. (1), where *PCi* is the *i*-th principal component and *λ_i* is the *i*-th eigenvalue

$$PC_i \ Explained \ Variance = \frac{\lambda_i}{\lambda_1 + \lambda_2 + \lambda_3} \quad (1)$$

A given multi-joint coordination pattern could be represented by the first, second or third principal component depending on the variance associated with this coordination pattern for each subject and condition.

The eigenvector values of the principal component that explained 90% of the variance were then used as inputs in a Self-Organizing Maps (SOM) analysis. The Matlab SOM toolbox was used (Mathworks, Natick, USA). This analysis is a competitive non-supervised neuronal network algorithm (Peiró-Velert et al., 2014) which enables to characterize the different coordination patterns used by subjects. Due to the reduced sample size and the