Journal of Electromyography and Kinesiology 24 (2014) 607–613

Contents lists available at ScienceDirect

Journal of Electromyography and Kinesiology

journal homepage: www.elsevier.com/locate/jelekin

Use of wavelet coherence to assess two-joint coordination during quiet upright stance

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ARTICLE INFO

Article history:
Received 6 January 2014
Received in revised form 29 June 2014
Accepted 2 July 2014

Keywords:
Postural control
Coordination
Wavelet
Coherence

ABSTRACT

Joint coordination plays a critical role in maintaining postural stability, yet there is limited existing work describing joint coordination patterns in the time–frequency domain. Here, two-joint coordination was examined during quiet upright stance. A wavelet coherence method was applied to quantify the coherence between ankle–trunk and ankle–head angles in the sagittal and frontal planes. Wavelet coherence results indicated intermittent joint coordination particularly for frequencies of 2.5–4.0 Hz. Coherence results were further processed to estimate mean time intervals between coherence instances, coherence burst frequency, and the ratio of in-phase versus anti-phase behaviors. Time intervals between intermittent coherence were 1.3–1.5 sec, coherence burst frequency was ~0.4 Hz, and phase ratios were ~1.0. Intermittent "bursting" of postural muscles may account for the finding of intermittent coherence in the noted frequency band. Some age and/or gender differences in coherence were found, and may be related to comparable differences in postural control ability or strategies. Results from application of this new method support earlier evidence that kinematic coordination is achieved intermittently rather than continuously during quiet upright stance. This method may provide richer information regarding such coordination, and could be a useful approach in future studies.

1. Introduction

Controlling the various motions associated with human upright stance is essential for maintaining balance. However, upright stance is an inherently unstable position due to gravitational torque and internal disturbances such as hemodynamic and neuromuscular noise. Moreover, complex sensorimotor controls are involved, which rely on visual, vestibular and proprioceptive feedback (Maurer et al., 2006; Peterka, 2000; Qu et al., 2009) as well as feedforward mechanisms (Fitzpatrick et al., 1996). Several joints are involved in this process, and contribute to balance maintenance (Kiemel et al., 2008; Pinter et al., 2008), and these joints may be controlled synergistically. For example, Hsu et al. (2007) identified a non-random pattern of phase coordination between the ankle and hip joints, and proposed that both ankle- and hip-centered motor control pathways exist for maintaining upright stance (Hsu et al., 2007). An earlier study similarly suggested that motor variability is "channeled" through both the ankle and hip joints (Krishnamoorthy et al., 2005). However, unlike the mechanisms associated with the ankle, hip-centered motor control may use a task-level feedback controller that varies depending on the specific task (Welch and Ting, 2008).

In addition to the ankle and hip, other joints such as the trunk and neck also appear to be involved in the coordination process (Keshner, 2003; Patel et al., 2010). With respect to ankle–hip and truck–neck coordination, muscle synergies are likely activated, thereby controlling a network of muscles simultaneously, as opposed to controlling individual muscles separately, which could involve more control effort (Torres-Oviedo and Ting, 2010). However, an earlier study that suggested joint coordination occurs through mechanisms where each coordinated joint is independently controlled (Alexandrov et al., 2005). Specifically, these authors demonstrated that ankle, knee, and hip movements are independently controlled through the same eigen-movements as in feed-forward control (which is governed by central control mechanisms).

In the context of upright stance, ankle and hip motion coordination appears to be in-phase for frequencies below 1.0 Hz, and anti-phase for frequencies above 1.0 Hz (Creath et al., 2005; Zhang et al., 2007). Moreover, in-phase ankle–hip coordination is thought to be regulated through neural control, whereas anti-phase coordination may occur as a direct result of the biomechanics of upright stance

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http://dx.doi.org/10.1016/j.jelekin.2014.07.003
1050-6411/

(Kiemel et al., 2008). Several researchers have shown that in-phase and anti-phase ankle–hip coordination is regulated through numerous ankle, leg, and trunk muscle groups (e.g., the soleus, rectus femoris, and erector spinae), and that there is strong coherence among these muscle groups (Saffer et al., 2008; Sasagawa et al., 2009). Saffer et al. (2008) also showed that the phase lag between muscle activity and joint angle increased from lower (<1 Hz) to higher (>1.6 Hz) frequencies, as a result of both feedback and feedforward control influences.

With aging, there are decreases in muscle mass, volume, and the number of fibers and motor units. These physiological changes lead, commonly, to more restricted mobility and coordination decrements (Porter et al., 1995; Vandervoort, 2002). Aging is also associated with neuronal loss in the brainstem and cerebellum, and an associated loss of neural-controlled joint coordination (Sjöbeck et al., 1999). These and other factors contribute to slower target acquisition times (Barry et al., 2005), compromised whole-body coordination (Hsu et al., 2012), over control of inter-joint coordination (Vernazza-Martin et al., 2008), and slower force generation capability (Barry et al., 2005) with age. As such, it can be postulated that joint coordination among older adults is likely to be different (i.e., diminished), and was of particular interest in the current work.

Joint coordination, while an important characteristic of the human postural control system (Hsu et al., 2013), is a complex construct. Despite extensive existing investigations of upright stance, several aspects related to joint coordination still remain unclear. For example, the time-dependent characteristics of two-joint coordination remain generally unknown, and there is disagreement on whether two-joint coordination is continuous or intermittent. Two important studies have suggested that upright stance control is continuous (Peterka, 2000; Peterka and Loughlin, 2004), wherein a continuous feedback of afferent sensory information triggers muscle contractions and generates corrective joint torques to maintain balance. Several researchers have also recently argued that, despite continuous sensory feedback, intermittent control is the underlying mechanism for maintaining upright stance (Bottaro et al., 2005; Gawthrop et al., 2009; Héroux et al., 2014; Loram and Lakie, 2002; Loram et al., 2004; Vieira et al., 2012). Such studies suggest that predicative control signals “burst” intermittently for controlling upright stance. The generation of bursts of intermittent control signals may be dependent on an inherent clock or on internal/external events (Gawthrop et al., 2014).

Previous methods for assessing coordination have adopted a variety of approaches, including frequency-domain coherence analysis (Hsu et al., 2007), frequency response feedback control analysis (Kiemel et al., 2008), and complex coherence analysis (Saffer et al., 2008). However, these methods did not describe potential time-variant coherence, and since they emphasized frequency domain analysis only, were not able to analyze potential intermittent behaviors. Here, an approach based on wavelet coherence analysis was applied to analyze two-joint coordination in the time–frequency domain. This method has been used in some earlier studies for investigating spatiotemporal coordination characteristics involving two input signals (Grinsted et al., 2004b; Kumar and FoufoulaGeorgiou, 1997) and ankle–hip postural coordination (Varoqui et al., 2011). The wavelet coherence method was applied to assess time dependent joint coordination patterns, during upright stance, specifically with respect to whether such coordination is continuous vs. intermittent, and to evaluate potential age-related differences. Based on previous research, it was expected that two-joint coordination would also exhibit an intermittent control pattern, which also likely varied between age and gender groups. The study goal was thus to explore the intermittency of joint coordination in the time–frequency domain and to assess any differences between age and gender groups.

2. Methods

2.1. Participants and procedures

Data from an earlier experiment (Lin et al., 2009) were used herein. All participants completed an informed consent procedure approved by the Virginia Tech Institutional Review Board, and had no self-reported injuries, illnesses, musculoskeletal disorders, or falls in the year prior to the experiment. A total of 32 participants (gender balanced) completed the study, half of whom were young adults (18–25 years) and half older adults (55–65 years). A complete description of the experimental procedures and data collection is provided in the noted publication, and only summarized here.

Participants completed three trials of quiet upright stance, each lasting 75 s. Segmental kinematics were estimated using surface markers, with a sampling rate of 20 Hz. Raw marker locations were low-pass filtered (Butterworth, 8 Hz cut-off frequency, 4th order, bi-directional) and the first 10s and the last 5s of data from each trial were removed to minimize potential transition effects. Reflective markers were placed bilaterally at both the proximal and distal ends of major body segments. Joint angles were obtained from selected markers as follows: ankle angle, using markers on the lateral malleolus and lateral epicondyle; trunk angle, using markers on anterior superior iliac spine and acromion; and neck angle, using markers on the acromion and temple. Joint angles were defined as between a given body segment and an inertial reference frame, and were obtained separately in the sagittal and frontal planes using an approach similar to previous reports (Black et al., 2007; Creath et al., 2005; Zhang et al., 2007). Subsequently, joint angles were averaged bilaterally for the ankle and trunk, and then demeaned.

2.2. Wavelet coherence

Wavelet coherence is a measure of coherence based on the common power and relative phase between two signals (Grinsted et al., 2004a,b). Here, wavelet coherence was assessed for two selected pairs of joint angles – ankle–trunk (AT) and ankle–head (AH) – in both the sagittal and frontal planes. Prior research has indicated that the ankle plays an essential role in the control of upright stance (Winter et al., 2001), and the latter angles were selected because of the presence of ankle–trunk and trunk–head coordination that appears to be involved in upright posture (Creath et al., 2005; Keshner, 2003).

Wavelet coherence was computed in three steps. First, a continuous wavelet transform was applied to obtain wavelet coefficients $W_n^{\theta}(s)$ for each joint angle θ, at each time index n and scale s (Torrence and Compo, 1998):

$$W_n^{\theta}(s) = \sqrt{\frac{\delta T}{s}} \sum_{n'=1}^{N} \theta_{n'}\, \varphi\left[(n'-n)\frac{\delta T}{s}\right] \tag{1}$$

where $\varphi\left[(n'-n)\frac{\delta T}{s}\right]$ is the wavelet function, with a complex Morlet function used here, using a non-dimensional frequency = 6 (Torrence and Compo, 1998); $(n'-n)$ is the time coefficient of the wavelet function; $\sqrt{\frac{\delta T}{s}}$ is used to normalize the wavelet function at scale s; δT determines the spatial and time resolution of the wavelet coherence (here, 50 ms); and N is the length of the signal (1024 samples or 51.2 s here, to achieve an integral power of two, and derived from the original signal length of 60 s). Wavelet transforms of ankle, trunk, and head angles are illustrated in Fig. 1.

Second, a cross-wavelet transform was completed using:

$$W^{\theta_1\theta_2} = W_n^{\theta_1}\left(W_n^{\theta_2}\right)^{*} \tag{2}$$