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Full Length Article

Analysis of free moment and center of pressure frequency components during quiet standing using magnitude squared coherence

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ABSTRACT

To date, no postural studies have investigated the specific relationship between linear (anteroposterior (AP) and mediolateral (ML)) postural sway and the free moment (FM) over the range of biomechanically important frequencies. The goal of the current paper is to study the relationship between FM and the AP/ML movements during quiet standing with respect to individual frequencies. Mean squared coherence, which measures the degree of the relationship between two signals as a function of frequency, is employed to address this question. The results showed that, in two conditions (eyes opened and eyes closed), at very low frequencies (< 0.5 Hz), AP and FM were strongly correlated (> 0.8) while there was a weak correlation between ML and FM (~ 0.2). The situation reversed from (0.5 to 1.5 Hz), with AP/FM correlation decreasing, and ML/FM correlation peaking slightly below 1.0 Hz. Both conditions were only weakly correlated beyond 1.5 Hz. It is suggested that these observations arise from differences in ankle activation between the left and right sides, whereas at higher frequencies, high coherence between ML and FM is a hip control strategy.

1. Introduction

Measurement and evaluation of ground reaction forces is an important component in the study of human posture. Anteroposterior (AP), mediolateral (ML), and vertical ground reaction forces and corresponding moments can be used to compute center of pressure and the free vertical moment (FM). The FM has the same orientation as the moment about a force platform's vertical axis, but it originates at the center of pressure (Eq. (1)). Quiet two legged standing produces a relatively small FM, whereas movements that increase rotational inertia produce a large FM (Lee, Walter, Deban, & Carrier, 2001). As the term "free moment" has gained wide acceptance in the literature (Beaulieu et al., 2010; Buckley, Jones, & Johnson, 2010; Li, Wang, Crompton, & Gunther, 2001; Zhang, Ye, & Wang, 2010), the authors use this naming convention throughout this paper, rather than the more descriptive term "rotational torque".

Assessment of FM is relatively new, and its relation to more traditional measures (i.e. ground reaction forces and center of pressure) is not yet well understood. Studies have measured FM during quiet standing with healthy adults (Beaulieu et al., 2010) and children with scoliosis (Dalleau, Allard, Beaulieu, Rivard, & Allard, 2007) and cerebral palsy (Ferdjallah, Harris, Smith, & Wertsch, 2002). FM has also been analyzed during dynamic movements, including in runners with a history of tibial spiral fracture (Milner, Davis, & Hamill, 2006), pronation during running (Holden & Cavanagh, 1991), walking with modified foot rotation angle

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(Almosnino, Kajaks, & Costigan, 2009), and in anticipatory postural adjustments (Bleuse, Cassim, Blatt, Defebvre, & Guieu, 2002; Shiratori & Aruin, 2004). In the aforementioned studies, FM characteristics (e.g. peak amplitude, range, direction) have exhibited differences between experimental and control conditions.

Li et al. found that suppression of arm swing during walking changed FM parameters to a greater degree in males than in females (Li et al., 2001). In another study, suppression of arm swing during walking had a much larger impact on the root mean square difference of FM than other postural parameters (26% versus < 10%) (Umberger, 2008). FM increased in conjunction with unilateral load during walking (Zhang et al., 2010). During standing, one arm swing led to a sinusoidal FM that was doubled in amplitude with bilateral in-phase arm swing (Esposti, Esposito, Ce, & Baldissera, 2010). Antiphase swinging produced much lower FM, horizontal ground reaction forces, and metabolic consumption compared to in-phase arm swing. It was concluded (Esposti et al., 2010) that FM may be a reliable index of the effort required for postural stabilization.

The best indicator of postural differences derived from ground reaction force between healthy and scoliotic patients during walking was the asymmetry observed in FM (Kramers-de Quervain, Muller, Stacoff, Grob, & Stussi, 2004). The change in FM with age when descending stairs (Buckley et al., 2010) and during anticipatory postural adjustments (Bleuse, Cassim, Blatt, et al., 2006) found differences between younger and older subjects that were linked to postural stability. Other authors (Beaulieu et al., 2010) studied the relationship between center of pressure (CoP) displacement along the AP and ML axes to whole-body oscillations about the vertical axis during single and double leg upright standing with eyes open and eyes closed. They found a stronger relation between CoP variables and FM with eyes open and that, in both eye conditions, FM and ML CoP variables were correlated to a higher degree.

In a review of experimental and modeling data, Winter (1995) demonstrated that the ankles primarily control the AP CoP and that the hips control ML CoP in quiet parallel standing, but no analysis was performed on the relation between ML and AP centers of pressure and FM in the sagittal plane. Creath, Kiemel, Horak, Peterka, and Jeka (2005) and Zhang, Kiemel, and Jeka (2007) used spectral analysis to evaluate the relation between trunk and lower limb kinematics during quiet standing. Their work found that in AP trunk and lower limb segments were in-phase at lower frequencies (< 1 Hz), whereas ML sway was antiphase at frequencies above 1 Hz. Rather than a simplified inverted pendulum model as proposed by Winter, these authors showed that the ankle and hip joints act as a multi-link pendulum with different sway frequency characteristics. Furthermore, Creath et al. suggest that changes in sensory, task, or perturbation conditions affect how AP and ML frequency characteristics change. Saffer, Kiemel, and Jeka (2008), building on the work of Creath et al. (2005), demonstrated that shank muscle activation (i.e. soleus and gastrocnemius) significantly cohered with leg and trunk postural sway in the sagittal plane, whereas other muscle groups did not. Creath et al. (2005) observed essentially the same phenomena. These previous studies have shown that AP and ML postural sway frequency responses can differ and that they are linked to the ankle and hip, respectively. What is unknown is how these differences contribute to FM.

In the current study, the specific frequency components with respect to FM and both AP and ML were investigated. To the authors' knowledge, no other research has investigated the specific relationship between linear postural sway (AP and ML) and the free moment within the band of biomechanically important frequencies during quiet standing. In this way, occurrences at specific individual frequencies and the relationship between those frequencies from different sources can be analyzed, although it is generally intuitive that any component of FM would be related to anteroposterior and mediolateral movements.

Determining a methodology to effectively evaluate this relationship is often beyond the scope of clinicians, who focus on patient outcomes or on understanding fundamental movements, thereby necessitating signal processing approaches to provide a greater understanding of what underlies these fundamental movements. Saffer's analysis (Saffer et al., 2008) is complex in that it simultaneously evaluates ankle, knee, and hip joint angles with agonist and antagonist muscles at the joints. A study focusing on postural sway directly through COP measures during quiet standing showed that anteroposterior frequency components were consistently higher than mediolateral frequency components in both the eyes open and eyes closed conditions (Ferdjallah, Harris, & Wertsch, 1999). In a multi-degree-of-freedom setting, such as maintaining the center of mass within the base of support, it is apparent that the body uses certain strategies. For instance, ML stability appears to be predominantly controlled at the hip, while AP stability is controlled at the ankle (Winter, 1995). For each joint, the anatomical structure (Hertel, 2002; Kilby, Molenaar, & Newell, 2015), surrounding musculature (Gribble & Hertel, 2004; Saffer et al., 2008; Winter, 1995), and neural control (Mohapatra, Krishnan, & Aruin, 2012; Ting & McKay, 2007) are factors that influence the resultant stability. The complex interaction between AP and ML sway will produce FM, and as previous research has demonstrated that AP and ML motions occur at different frequencies, it is suggested that the coherence between AP, ML, and FM will manifest these differences. These multiple stability strategies are represented in an analysis of coherence between linear postural sway and the free moment.

The current paper addresses a well-defined set of constrained activities so that other unknown parameters do not influence the results. With quiet standing, the free moment is very small, but there should still be a relationship with the linear postural sway parameters that are so often used in biomechanical research. The study was conducted to statistically evaluate the relation between AP and ML centers of pressure and FM during quiet standing by employing magnitude squared coherence (MSC), a frequency correlation technique based on Fourier analysis. MSC is typically used to analyze the relationship between two signals. For the purposes of the present study, MSC is taken to quantify the degree of the relationship between two kinesiological signals, as a function of frequency. Frequency analysis can be used to show trends in postural data that are not easily viewed from time series data. We hypothesized that across the band of biomechanically important frequencies (< 4 Hz) FM would be significantly, but differentially correlated to AP and ML. As previous research has demonstrated clear differences between ML and AP postural sway (Winter, Prince, Frank, Powell, & Zabjek, 1996), it is hypothesized that coherence between ML and FM would be greater than coherence between AP and FM at frequencies above 1 Hz.