Journal of Electromyography and Kinesiology 22 (2012) 131–136

Contents lists available at SciVerse ScienceDirect

Journal of Electromyography and Kinesiology

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

The spectral content of postural sway during quiet stance: Influences of age, vision and somatosensory inputs

Navrag B. Singh [a], William R. Taylor [a], Michael L. Madigan [c,d], Maury A. Nussbaum [b,d,*]

[a] Julius Wolff Institut, Charité – Universitätsmedizin Berlin, Centrum für Sportwissenschaft und Sportmedizin Berlin, Philippstr. 13, Haus 11, D-10115 Berlin, Germany
[b] Industrial & Systems Engineering, Virginia Tech., 250 Durham Hall (0118), Blacksburg, VA 24061, USA
[c] Engineering Science and Mechanics, Virginia Tech., 326 Norris Hall (0219), Blacksburg, VA 24061, USA
[d] Virginia Tech., Wake Forest School of Biomedical Engineering and Sciences, USA

A R T I C L E I N F O

Article history:
Received 21 July 2011
Received in revised form 22 September 2011
Accepted 18 October 2011

Keywords:
Postural control
Spectral analysis
Biomechanics in aging
Sensory feedback
System complexity
Balance impairments

A B S T R A C T

Maintenance of human upright stance requires the acquisition and integration of sensory inputs. Conventional measures of sway have had success in identifying age- and some disease-related changes, but remain unable to address the complexities and dynamics associated with postural control. We investigated the effects of vision, surface compliance, age, and gender on the spectral content of center of pressure (COP) time series. Sixteen healthy young (age 18–24) and older participants (age 55–65) performed trials of quiet, upright stance under different vision (eyes open vs. closed) and surface (hard vs. compliant) conditions. Spectral analyses were conducted to describe COP mean normalized power in discretized bands. Effects of the two sensory modalities and age were distinct in the antero-posterior and medio-lateral directions, and a reorganization of spectral content was evident with increasing task difficulty (eyes open vs. closed and hard vs. compliant surface) and among older adults. These results indicate that vision and surface compliance are predominantly associated with responses from musculature associated with antero-posterior and medio-lateral directions of sway, respectively. Finally, distinguishing between the contributions of different afferent systems to the postural control system using the spectral content of sway bi-directionally may help in diagnosing individuals with balance impairments.

1. Introduction

Quiet standing, although a seemingly trivial task, is inherently unstable. Gravitational forces, imparted on what can be considered an unstable inverted pendulum (Creath et al., 2005; Day et al., 1993; Fitzpatrick et al., 1992; Horak and Nashner, 1986; Maurer and Peterka, 2005; Onambele et al., 2006; Zatsiorsky and Duarte, 2000), along with alterations either external (e.g. perturbations or quality of visual input) or internal (e.g. fatigue, aging) to an individual, all serve as challenges to the postural control system (PCS). The PCS acts primarily as a feedback control system (Creath et al., 2005; Day et al., 1993; Fitzpatrick et al., 1992; Horak and Nashner, 1986; Maurer and Peterka, 2005), acquiring and integrating diverse afferent inputs and generating adaptive and corrective motor commands.

Assessments of PCS function have often been based upon data obtained during trials of quiet, upright stance. A variety of measures have been derived, based typically on either center-of-mass (COM) (Winter et al., 1998, 2003) or center-of-pressure (COP) (Winter et al., 1998, 2003; Prieto et al., 1996; Maki et al., 1994b) time series. Although spatio-temporal measures and measures based on frequency-domain analyses have been reasonably successful in identifying age- and disease-related differences, questions remain as to their value as potential biomarkers for impaired balance (Williams et al., 1997). Analysis of the power spectra of physiological time-series is able to not only provide a distribution of the inherent variance in the time-domain over a range of frequencies (Newell et al., 1997), but is also sensitive to complex attributes associated with physiological systems (Lipsitz and Goldberger, 1992). More specifically, analysis of spectral content has found success in detecting and discriminating PCS impairments (Amblard et al., 1985; Creath et al., 2005; Day et al., 1993; Fitzpatrick et al., 1992; Giacomini et al., 2004; Golomer et al., 1999; Horak and Nashner, 1986), such as the spectral content of sway in subjects with ischemic blocking of leg afferents (Mauritz and Dietz, 1980).

Our focus here is on whether and to what extent the spectral content of COP reflects, or can be used to indicate, PCS functioning related to selected aspects of the internal and external environment. Recent evidence suggests that the use of power spectrum analyses on COP time series can discriminate the key contributions of vestibular, visual, and somatosensory inputs to the PCS at different frequencies (Nagy et al., 2007; Fransson et al., 2007;

* Corresponding author at: Industrial and Systems Engineering, 250 Durham Hall (0118), Blacksburg, VA 24061, USA. Tel.: +1 540 231 6053; fax: +1 540 231 3322.
E-mail address: nussbaum@vt.edu (M.A. Nussbaum).

1050-6411/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jelekin.2011.10.007

Giacomini et al., 2004; Oppenheim et al., 1999; Golomer et al., 1999). Specific frequencies that reflect each sensory modality, however, are still the subject of discussion (Giacomini et al., 2004; Golomer et al., 1999; Nagy et al., 2007; Oppenheim et al., 1999), and ambiguity exists in terms of the range of total frequency content (Golomer et al., 1999; Nagy et al., 2007) and bandwidth size (Giacomini et al., 2004; Golomer et al., 1999; Nagy et al., 2007; Oppenheim et al., 1999). Thus, there are a lack of definitive recommendations in terms of the frequencies at which these postural responses occur, or to which each sensory system contributes, an issue that is key to understanding not only the effectiveness of the PCS at integrating diverse afferent inputs but also the quality of motor commands.

While the influence of visual input and age on the spectral content of postural sway has been previously demonstrated (Amblard et al., 1985; Williams et al., 1997), potential interactive effects of sensory modalities with age or gender on the spectral distribution of the postural sway have not been reported. Furthermore, the PCS appears to use distinct control strategies in the anteroposterior (AP) and mediolateral (ML) directions (Day et al., 1993), and these strategies may be differentially altered with age (Amblard et al., 1985; Kim et al., 2008; Nagy et al., 2007; Williams et al., 1997). Finally, information regarding the distribution of variability at different frequencies would not only help in distinguishing between the effects of various sensory modalities on sway but also in designing patient-specific rehabilitation programs that are aimed at improving balance. We thus investigated the effects of visual and somatosensory inputs on the frequency distribution of sway bi-directionally and with respect to differing age and gender.

2. Methods

Data were obtained from a prior study (Lin et al., 2008), involving 16 young (aged 18–24) and 16 older participants (aged 55–65), gender balanced in each group, recruited from the local community. No participant had any self-reported injuries, illnesses, musculoskeletal disorders, or occurrences of falls in the previous year. Each participant completed an informed consent procedure approved by the local Institutional Review Board.

Following initial practice and familiarization, participants completed several trials (75 s each) of quiet, upright, bilateral stance in four conditions, involving manipulations of visual (eyes open and closed) and somatosensory feedback (compliant and hard standing surface). Individuals were requested to stand as still as possible, with arms by their side. In the eyes open condition, participants focused on a small cross, placed at eye level and 75 cm in front of them. In the compliant surface condition, a foam board (thickness = 2.3 cm) was placed on a force platform (AMTI OR6-7-1000, Watertown, Massachusetts, USA). Three replications of each condition were completed in a randomized order, with at least 1 min between each trial.

During trials, participants stood on the force platform, from which triaxial ground reaction forces were sampled at 100 Hz. These were subsequently transformed to obtain COP times series (Winter et al., 1990) in the AP and ML directions, with the initial 10 and final 5 s deleted to remove boundary effects. To assess stationarity of the current COP time series, the COP signals were first low-pass filtered (Butterworth, 2nd order, bi-directional, 15 Hz cut-off frequency), and then a subset of the data was analysed using both the Kolmogorov–Smirnov distance (Cao et al. 2004) and the exponent from detrended fluctuation analysis (Peng et al. 1995). After zero padding to 8192 data points and de-meaning, Fast Fourier Transforms (FFTs) were used to obtain power spectra up to 10 Hz for each COP time series. Each power spectrum was then normalized to the total signal power and divided into 100 bands with width = 0.1 Hz. Finally, the mean normalized power (MNP) was calculated for each band across the three repetitions within each vision and surface condition.

Mixed-factors analyses of variance (ANOVAs) were used to assess the effects of vision (eyes open vs. closed) and somatosensory feedback (compliant vs. hard surface), both as within-subjects factors, as well as age and gender (included as between-subjects, or blocking, factors). MNPs within each band were the dependent variables, with separate ANOVAs performed for each spectral band and direction. Prior to these analyses, MNP values were natural-log transformed (which yielded normally distributed, homogeneous residuals). Since a total of 100 ANOVAs were performed in each direction, adjustments for multiple post hoc pairwise comparisons were made by controlling false discovery rates (FDR) with a threshold rate of 0.05 (Benjamini and Hochberg, 1995). Generalized eta-squared (η^2) was calculated as an effect size (Olejnik and Algina, 2003) to estimate the proportion of variance in each spectral band due to sensory conditions, age, and gender. All statistical analyses were conducted using SPSS Statistics 18 (IBM SPSS Statistics, USA). Results are given based on the center frequencies of each band (i.e., 0.05, 0.10, 0.15, ..., 9.95 Hz).

3. Results

Results from both the Kolmogorov–Smirnov distance and exponents from detrended fluctuation analysis provided no evidence of deviations from stationarity. Main effects of surface and vision on MNP_{AP} were evident for specific frequencies (Fig. 1a and b). Significant main effects of surface compliance were observed at eight frequency bands (centered at 0.05, 0.25, 0.35, and 3.25–3.65 Hz), while effects of vision on MNP_{AP} were significant in almost all bands <9 Hz. In the lowest band (0.05 Hz) increased spectral content was observed for hard surface and eyes open conditions, whereas in all other higher frequency bands increased power was observed with the compliant surface and eyes closed conditions. There were also main effects of age on MNP_{AP} (Fig. 2a) in two frequency bands centered on 0.75 and 0.85 Hz, although older individuals had higher values in most bands except at the lowest frequency and high frequencies.

Significant main effects of surface and vision were also observed on MNP_{ML} (Fig. 1c and d). Surface compliance had significant effects in several bands across the spectrum, including those at very low (0.05 Hz), low to middle (0.35–0.65 Hz), middle to high (2.05–3.65 Hz) and high (4.05–4.45 and 6.25–6.65 Hz) frequencies. Significant main effects of vision were observed in low and low to middle frequency bands (0.05–0.85 Hz) as well as in several high frequency bands (3.85–5.35 Hz). Similar to the AP direction, there was increased power for hard surface and eyes open conditions in the lowest band (0.05 Hz), whereas at higher frequency bands more power was observed in the eyes closed and compliant surface conditions. Older individuals had higher MNP_{ML} in most bands except the lowest (Fig. 2b), especially in frequency bands between 0.85 and 1.95 Hz and in high frequency bands (4.35–5.45 Hz).

Interactive effects of age $\times$ gender were present on MNP_{AP} and MNP_{ML} (Fig. 2), though these effects occurred at different frequency bands. These effects were significant in middle frequency bands for MNP_{AP} (0.75–0.85 and 1.45–2.35 Hz) vs. middle to very high frequency bands for MNP_{ML} (several bands ranging between 0.65 and 9.75 Hz). At the significant frequency bands, the increase in both MNP_{AP} and MNP_{ML} among older individuals was generally more pronounced in males than in females. In addition, older males showed higher levels of MNP than the remaining three groups at the highest frequency bands in both the AP and ML directions. Older males also exhibited distinct behaviors in the lowest frequency band (0.05 Hz), having the lowest levels of any age/gen-