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

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ABSTRACT

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).

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 × 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-
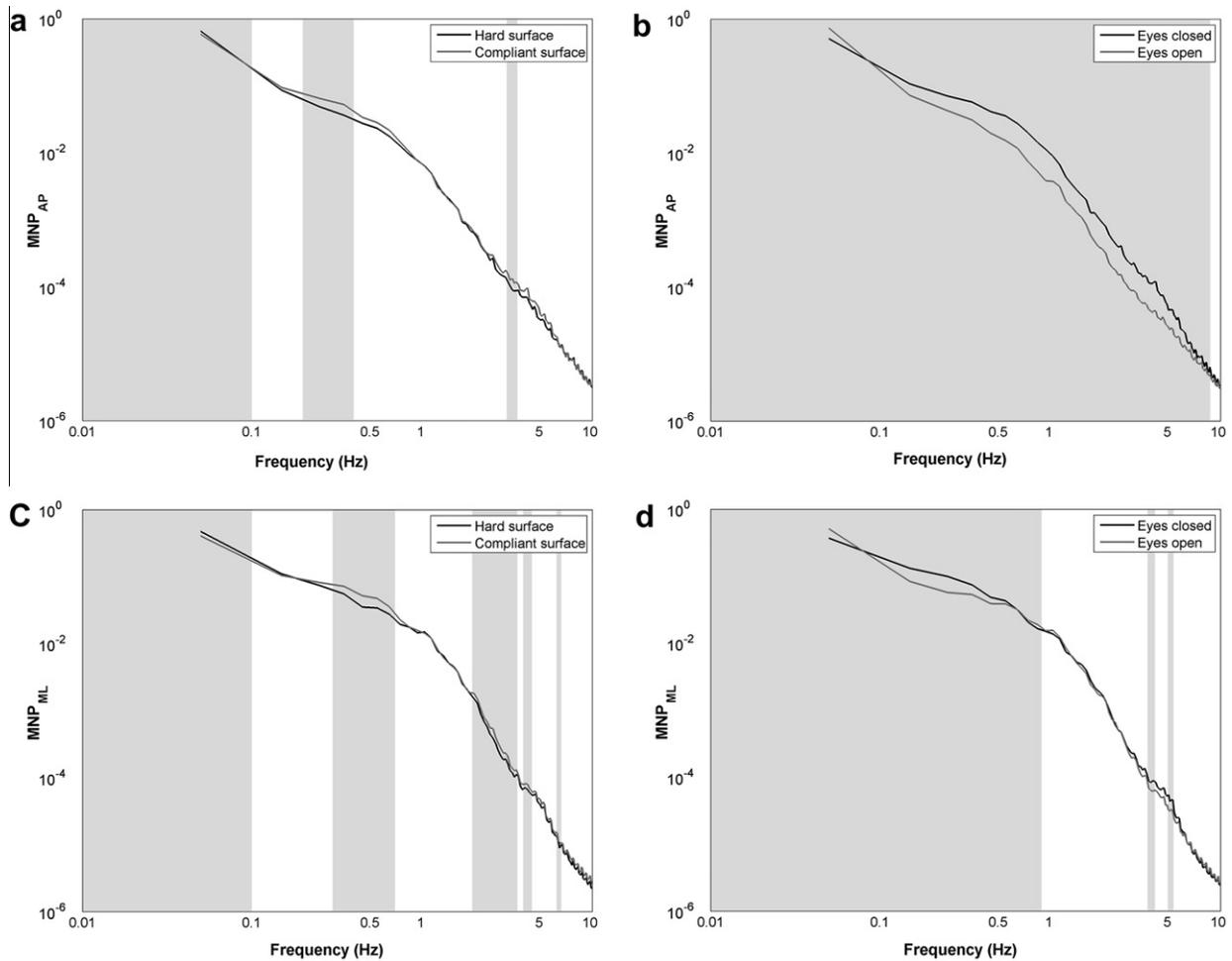
Fig. 1. Effects of surface (a, c) and visual (b, d) conditions on mean normalized power (MNP) as a function of frequency in the anteroposterior (AP; a and b) and mediolateral (ML; c and d) directions. Data are presented on log–log axes (base 10). Mean normalized power is displayed at the center of each spectral band (width = 0.1 Hz), and grey areas indicate specific frequency ranges for which there were significant surface or vision effects.
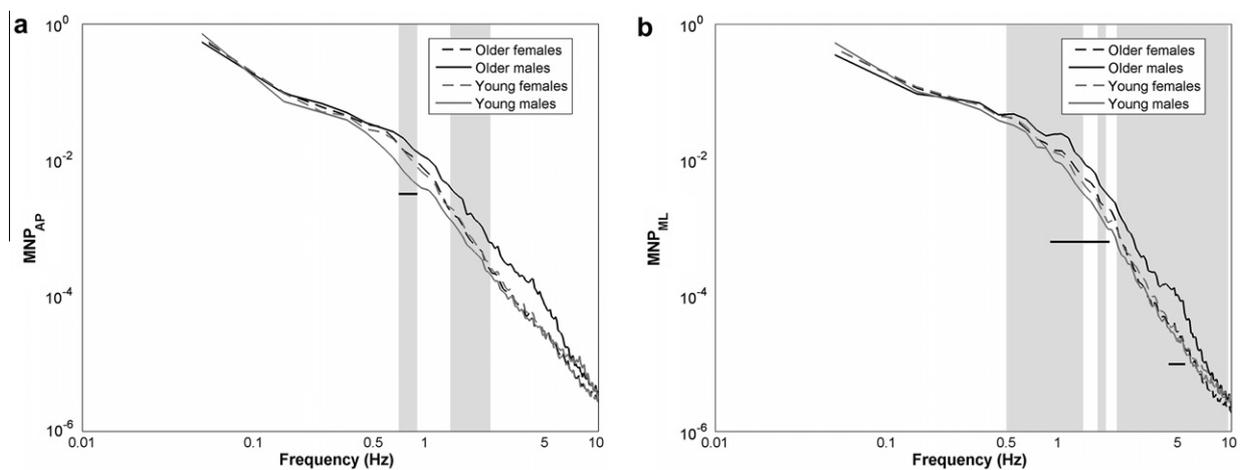

Fig. 2. Age and gender differences in mean normalized power (MNP) as a function of frequency in the anteroposterior (AP; a) and mediolateral (ML; b) directions. Data are presented on log–log axes (base 10). Mean normalized power is displayed at the center of each spectral band (width = 0.1 Hz). Horizontal black bars indicate significant main effects of age, and grey areas indicate specific frequency ranges for which there were significant age × gender interaction effects.

der group, a pattern that was consistent in both directions (AP and ML). Fig. 3 provides an overall summary of the significant effects on MNP at various frequencies, clearly suggesting that vision had a more distributed effect in the AP direction as compared to ML, with effects in ML mostly evident at frequencies below 1 Hz. In contrast,

effects of surface were apparent at middle ranges of frequencies in both directions, in addition to some high frequencies in the ML direction.

In the AP direction, effect sizes (η^2) for age, age × gender, surface, and vision on MNP were less consistent for lower frequency
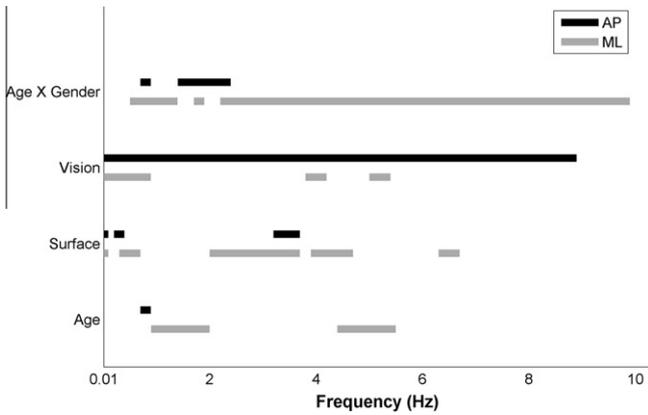
Fig. 3. Summary of significant age, surface, vision, and age x gender effects on mean normalized power (MNP) in the anteroposterior (AP; black solid lines) and mediolateral (ML; gray solid lines) directions. Lines indicate ranges of frequencies at which a given effect was significant on the respective MNP values. Note that frequency is presented on a linear scale.

bands (i.e. <1 Hz) in terms of magnitude and the relative influences of each factor. However, at frequency bands between roughly 1 and 5 Hz (Fig. 4; Top) effect sizes were largest for vision and smallest for surface condition, whereas frequency bands above 6 Hz gender had the largest effect sizes. A more complex pattern was evident in

the ML direction (Fig. 4; Bottom). At the lowest frequency bands (i.e. <1 Hz), effect sizes for vision were the most substantial, whereas for frequency bands between about 1 and 5 Hz effect sizes for surface and vision conditions were quite small. Here, the effects of age and age x gender were dominant, whereas at high frequency bands (8–10 Hz) the effect sizes of surface and age × gender were large, with their relative influence varying with frequency.

4. Discussion

Understanding the mechanisms and strategies used in controlling posture opens perspectives for evaluating the effectiveness of the postural control system to efficiently integrate diverse afferent inputs and generate required motor commands. In this study, we have assessed the relative effects of some internal (age and gender) and external (vision and surface compliance) factors on the spectral content of COP time series during quiet standing. The results suggest that visual input influences corrective responses predominantly for the control of antero-posterior sway at almost all frequencies, whereas surface compliance directs responses mostly for the control of lateral sway at middle and high frequencies. Furthermore, main effects of age and interactive effects of age with gender were larger as well as more distributed across all frequencies of sway in the medio-lateral compared to the antero-posterior directions.
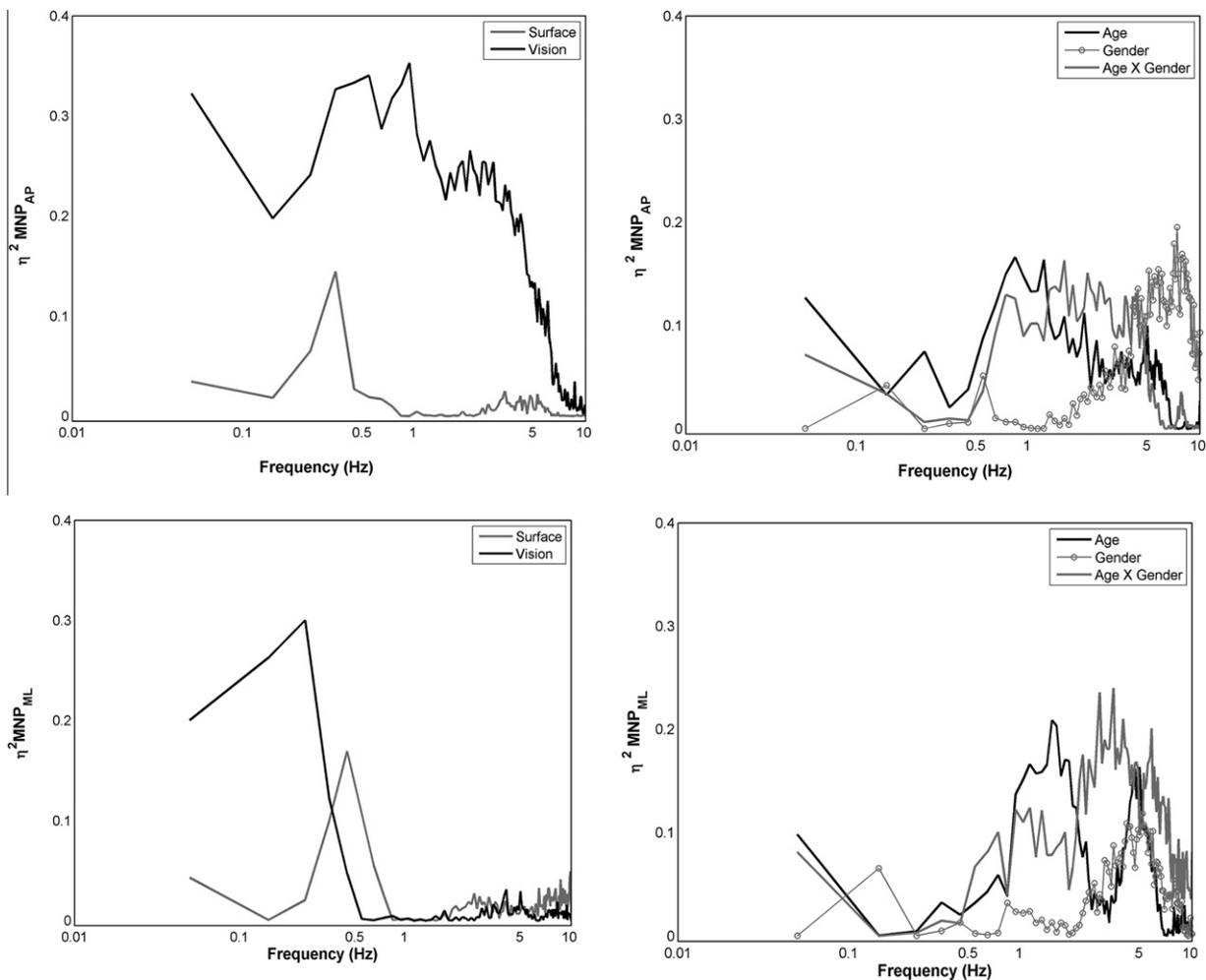

Fig. 4. Effect sizes (η^2) corresponding to the influences of surface, and vision (left), as well as age, gender and the age x gender interaction (right), on mean normalized power (MNP) in the anteroposterior (AP; Top) and mediolateral (ML; Bottom) directions at different frequencies. Frequencies are presented on a log scale (base 10), and mean normalized power is displayed at the center of each spectral band (width = 0.1 Hz).

Age-related deteriorations in balance have been documented in several studies using static posturography, and include increases in sway velocity, RMS distance, and mean power frequency (Maki et al., 1994b). Older individuals here swayed with higher frequency components in both directions as indicated by the spectral content reorganization. Furthermore, evidence here suggests that the spectral content of sway varied little with aging among females (Fig. 1), but males produced a considerable increase in frequencies in both the ML and AP directions. This may be a result of males adopting a balance strategy involving more proximal muscle activation with age. Earlier evidence also supports a gender difference in sway performance among older adults (Matheson et al., 1999), with males having a larger sway during conditions of visio-vestibular conflict.

A major challenge when examining the effects of somatosensory inputs on PCS is that these inputs stem from multiple sources, leading to a variety of approaches that have been used to assess these effects (Amblard et al., 1985; Fransson et al., 2007; Horak and Nashner, 1986; Magnusson et al., 1990; Mauritz and Dietz, 1980; Stal et al., 2003; Haibach et al., 2007) but producing seemingly consistent results in that perturbing somatosensory information leads to increased postural sway (Amblard et al., 1985; Fransson et al., 2007; Haibach et al., 2007; Magnusson et al., 1990). However, the frequencies reported to reflect somatosensory modulation of sway seem to be inconsistent (Giacomini et al., 2004; Oppenheim et al., 1999). Here, introducing a compliant surface (Fig. 2; Left) led to spectral content reorganization, mostly at frequencies between 0.3 and 0.8 Hz in both the AP and ML directions. Such an effect is consistent with previous studies (Fransson et al., 2007; Oppenheim et al., 1999), and suggests that medium–high sway frequencies in both directions are linked with somatosensory inputs. Moreover, a consistent effect of surface compliance was also noted at high frequencies (ranging between 4 and 7 Hz) in only the medio-lateral direction (Figs. 1 and 4). The effects of surface compliance were also larger as well as more extensive in the medio-lateral as compared to the antero-posterior direction. The effect sizes for surface compliance, however, were relatively small, which may have been due to the low thickness (2.3 cm) of the compliant material used (Haibach et al., 2007). These findings, nonetheless, indicate that the introduction of a surface compliance may lead to high frequency responses from musculatures that are predominantly linked with lateral control of sway.

Previous reports appear to be inconsistent in that visual feedback: (1) influences only the low frequencies of postural sway (≤0.5 Hz) (Oppenheim et al., 1999); (2) has an effect over the entire spectrum (Giacomini et al., 2004; Golomer et al., 1999; Nagy et al., 2007); or (3) affects posture in two distinctly different frequencies (Amblard et al., 1985). In the present study, vision affected spectral content in nearly all frequencies (up to 9 Hz) in the AP direction; however, in the ML direction, the effect was evident only at low-middle frequencies (≤1 Hz) and at higher frequencies (>3 Hz). Our results (Figs. 1 and 4) suggest that all three reported characteristics of sway resulting from visual input may indeed be correct, and also confirm the co-existence of different balance mechanisms occurring at different timescales. This is consistent with the concept of slow reorientations at <2 Hz together with rapid stabilizations at >4 Hz, among others (Amblard et al., 1985; Collins and De Luca, 1995; Zatsiorsky and Duarte, 2000). Here, a relative reduction in power in the lowest frequency band (0.05 Hz) was accompanied by increases in power at higher frequencies. These results are in agreement with previous findings that report an increase in total spectral power (Golomer et al., 1999) or increase in power in the middle-higher frequencies in both directions in the absence of vision (Amblard et al., 1985). Furthermore, the findings presented here also indicate that vision had a more pervasive and stronger effect on variability of sway in the AP than the ML direction (Figs. 1 and 4). This would imply that vision is predominantly linked with the ankle strategy (i.e. control using distal musculature) for maintaining balance.

A "stiffening" of the musculoskeletal system (Creath et al., 2005; Kim et al., 2008; Maurer and Peterka, 2005) supports the combined ankle and hip strategy explanation. Based on a postural control model, increased system stiffness and damping lead to decreases in sway displacement and increases in sway velocity (Maurer and Peterka, 2005). A report comparing local dynamic stability parameters among old and young adults showed faster divergence rates for older individuals, suggesting that older adults exhibited faster responses to a local perturbations (Kim et al., 2008). Increased muscle activity, in both ankle and hip musculatures, was likely used to "stiffen" the musculoskeletal system in order to compensate for the increased compliance in the distal musculo-tendon complex especially in the elderly (Onambele et al., 2006). Furthermore, analysis of absolute spectral power (results not presented here) from the same sway data suggested that higher frequencies (>3 Hz) were associated with larger power spectral amplitudes for elderly individuals as compared to their younger counterparts, which is reportedly associated with changes in postural strategy with tendency towards increased high frequency–lower amplitude body sway in patients with phobic postural vertigo (Krafczyk et al., 1999). This "stiffened" response of the postural control system, reported here and elsewhere, in the absence of sensory inputs or with age, that results from increased co-contraction, can explain the proportional reoganization of the spectral content of sway.

Another explanation for the results here might well be due to the use of different postural strategies (i.e., ankle, hip, or combination strategy) to maintain balance (Creath et al., 2005; Horak and Nashner, 1986). The ankle strategy works by repositioning the center of the vertical force, using moments produced at the ankle joint (and thus the distal/calf musculatures) being the primary stabilizers, whereas the hip strategy works by exerting horizontal shear forces against the surface via hip motions (and thus the proximal/hip musculatures) (Horak and Nashner, 1986). The ankle strategy predominantly regulates sway in the AP direction, whereas the hip strategy regulates ML sway (Horak and Nashner, 1986). To compensate for insufficient ankle torque, it is possible that the hip ab/adductors are recruited to assist the ankle in/evertors. In other words, older individuals may opt for a combined ankle and hip strategy by activating muscles in the ankle and hip, probably by increased activation in both musculatures, instead of a pure single-joint strategy during the maintenance of posture, resulting in rapid corrective actions (Creath et al., 2005; Horak and Nashner, 1986).

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. Differences in the spectral content of sway could potentially be used to diagnose aspects of the PCS or the sensory system that could be contributing to balance problems in a particular individual. In a clinical setting, if sway measurements conducted on a patient (or an individual), show differences in the spectral content over frequencies in the middle ranges, e.g. 0.4–0.7 Hz (Figs. 2 and 3), then it might suggest impairments associated with the somatosensory system. In addition, spectral content of medio-lateral and antero-posterior sway seems to be more sensitive to changes in the somatosensory and visual input respectively, in both range as well as magnitude (Figs. 3 and 4). Thus, information regarding the spectral content and variability of sway bi-directionally at different frequencies may help improve the application of sway measurements in a clinical setting by distinguishing the effects of different sensory modalities.

Acknowledgements

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Navrag B. Singh obtained his M.S. (2005) in Industrial and Systems Engineering from Virginia Tech. He is currently working on his PhD at the Julius Wolff Institute, Charité – Universitätsmedizin Berlin. His research interests include force fluctuations, postural control/balance and gait variability and stability.

William R. Taylor achieved his degree in Mechanical Engineering at the University of Bath, England in 1994, where he also completed his Ph.D. in 1999. After moving to Germany in 2001, he now leads the research group "Musculoskeletal Biomechanics" at the Julius Wolff Institute, Charité – Universitätsmedizin Berlin. His research aims to provide new approaches for quantifying joint instability as well as functional outcome in patients, both pre-operatively and after therapy.

Michael L. Madigan earned a PhD degree in Biomedical Engineering from Virginia Commonwealth University in 2001. He is currently an Associate Professor in the Department of Engineering Science and Mechanics at Virginia Tech, and Director of the Kevin P. Granata Biomechanics Laboratory. His research focuses on the dynamics and control of human movement, with specific interest in balance, aging, and neuromuscular fatigue.

Maury A. Nussbaum received an MS (1989) in Bioengineering and a PhD (1994) in Industrial and Operations Engineering from The University of Michigan. He is currently HG Prillaman Professor of Industrial and Systems Engineering at Virginia Tech in Blacksburg, Virginia. His research interests are (in no particular order) occupational biomechanics and ergonomics, localized muscle fatigue, aging, and balance/postural control.