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Segmental Trunk and Head Dynamics during Frontal Plane Tilt Stimuli in Healthy Sitting Adults

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Abstract

A more detailed understanding of trunk behavior during upright sitting is needed to create a foundation to address functional posture impairments. Therefore, we characterized the dynamics of the trunk and head during perturbed sitting. A three-link inverted pendulum model of head and trunk segments was used to analyze kinematics of eight healthy sitting adults. Magnetic sensors were placed at the head and two locations of the trunk (C7 and T7). Six surface tilt stimuli (two spontaneous sway tests [no surface stimulus; eyes open, EO/eyes closed, EC] and four tests with continuous pseudorandom surface tilts [2 peak-to-peak amplitudes of 2° or 8°; EO/EC]) were applied in the frontal plane. We used frequency-response functions (FRFs) to analyze sway across ~0.045–3 Hz and found systematic differences in sway dynamics across segments. Superior segments exhibited larger fluctuations in gain and phase values across frequencies. FRF gains in superior segments were attenuated compared to other segments only at low frequencies but were larger at the higher frequencies. We also tested the influence of stimulus amplitude and visual availability on FRFs. Across all segments, increasing stimulus amplitude and visual availability (EO) resulted in lower gains, however, these effects were most prominent in superior segments. These changes in gain were likely influenced by changes in sensory reliance across test conditions. In conclusion, these results provide a benchmark for future comparisons to segmental responses from individuals with impaired trunk control. We suggest that a frequency-based approach provides detail needed to characterize multi-segment dynamics related to sensorimotor control.

Keywords

Sitting dynamics; Multi-segmental trunk; Frequency responses; Stimulus-responses

INTRODUCTION

Posture control of the head and trunk serves a critical role in functional behaviors. In the healthy, well-coordinated adult, it is easy to assume that trunk/head control is simple.

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CONFLICT OF INTEREST

All authors have no conflicts of interest to disclose.

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However, mechanisms that control the trunk and head are highly complex. The dynamics of the trunk/head posture have been studied in a variety of dynamic standing and locomotor activities (Pozzo et al., 1995; Prince et al., 1994); providing evidence of graded control of the trunk across segments, with attenuation of head movement compared to the trunk. Dynamic reweighting of reliance on sensory feedback (including vision, vestibular, and proprioception) has also been viewed as a prominent phenomenon in posture control (Goodworth and Peterka, 2012, 2010a). However, it is unknown whether postural dynamics in sitting behave the same as in standing or walking. This knowledge is critical for people who exhibit deficits in posture control (i.e. cerebral palsy, spinal cord injury, etc.). These populations often require assistance for sitting, standing, and/or functional activities. To begin addressing this problem, we analyzed head and trunk dynamics in healthy adults to further identify the principles of postural control during sitting.

We use a frequency-based approach to analyze sitting balance across the trunk (two segments) and head. Our approach introduces surface tilt stimuli and visual conditions (eyes open, EO vs. closed, EC) to explore sensory contributions to sitting posture. Frequency response functions (FRFs), measurements including both amplitude (gains) and timing information (phases), were used to characterize the dynamic responses to perturbations across a wide range of frequencies. Gains show the sway response sensitivity as a function of stimulus frequency, while phases indicate timing characteristics between responses and the stimuli within the frequency range. These measures provide more information than standard time domain measures (e.g. root-mean-square, RMS), because the influence of neural and mechanical components may differ across frequencies (Goodworth and Peterka, 2010a; Maaswinkel et al., 2015; Oie et al., 2002; Peterka, 2003). Previous studies have shown body sway gains to decrease across a wide range of frequencies with increasing stimulus amplitude (Goodworth and Peterka, 2010b; Jeka et al., 2000; Peterka, 2002). This phenomenon has been interpreted through feedback systems modeling as sensory reweighting; subjects shifted reliance away from sensory feedback that oriented the body toward the stimuli and shifted toward sensory feedback that oriented the body upright. However, all of the above studies modeled the trunk or entire body in standing as a single-link inverted pendulum. Recently, a few studies have begun studying trunk control in a multi-segmental fashion (Butler et al., 2010; Maaswinkel et al., 2015; Preuss and Fung, 2008; Saavedra and Woollacott, 2015; Saavedra et al., 2012). We use a multi-segment analysis to explore gradation of sensorimotor control across head and trunk segments. This will provide essential information about the complexity of human biomechanics and neural control of posture during sitting.

In the current study, we investigate the dynamics of a three-link inverted pendulum model. Using a surface stimulus to evoke trunk and head sway in sitting posture, we hypothesize that each segment will have a different frequency response and that head motion will be attenuated (i.e., lower gains across frequencies compared to inferior segments). Also, because an upright head orientation provides essential information for visual and vestibular systems (Buchanan and Horak, 2001; Pozzo et al., 1995), we hypothesize that stimulus amplitude and visual availability (EO vs. EC) will influence the head to a greater extent than either trunk segment. This approach will provide detailed benchmarks necessary to begin analyzing impaired sitting posture.

METHODS

Subjects

Eight adults (four males) with no history of balance disorders participated in the experiment. Age and body dimension (mean $\pm$ standard deviation) were 28 ± 6 years of age, 167 ± 7.6 cm in height, 64 ± 10.6 kg in weight, 89 ± 5.3 cm in height from the top of the head to the bench, and 1001 ± 99.4 cm² in area of base-of-support while sitting on the bench. All subjects gave informed consent, approved by the Institutional Review Board at University of Hartford.

Apparatus and Experimental Setups

An articulating bench system (Figure 1) was designed to investigate sitting postural responses to surface tilt stimuli. Continuous tilting of the bench, driven by the support surface, evoked subject's sway in the frontal plane. The surface tilts were transmitted to the bench top through the vertical bench legs hinged with the top forming a parallelogram.

A servomotor controlled surface tilts, and the rotation axis was horizontal and perpendicular to the subject's frontal plane at the center of the support surface (i.e. the center of the bench top). Data was sampled at 200 Hz. A previous study characterized the dynamics of bench motion and showed accurate tilts transmitted from the support surface in both gains and phases at frequencies up to 5 Hz (Goodworth and Saavedra, 2015).

Subjects wore earbud-headphones and listened to a movie while facing an eye-level 24-inch monitor located 95 cm away. A magnetic tracking system (trakSTAR, Ascension Technology, VT, USA) with four magnetic sensors were used to record kinematics. Two sensors were located directly above the tragus of the ear bilaterally on a headband. The other two sensors were securely taped at the subject's back over the spinous process of the seventh cervical vertebrae (C7) and at the mid-point between the left and right inferior angle of scapula (around the seventh thoracic vertebrae, T7). The segment between C7 and the approximate T7 represented the thorax (rib cage), a relatively rigid upper trunk segment and it was straightforward to locate for all subjects anatomically.

External Stimuli for Identification of Sensorimotor Integration

External stimuli have been used to identify mechanisms of posture control in sitting (Butler et al., 2010), standing (Goodworth and Peterka, 2012; Horak et al., 1997; Peterka, 2002), and walking (Goodworth et al., 2015). Surface stimuli were used in the current study to distinguish contributions from different sensory systems to posture responses. When a surface tilts with respect to gravity, the proprioceptive system orients the body toward the tilted surface (away from upright) while the visual and vestibular system orients the body toward upright (Goodworth and Peterka, 2009; Peterka, 2002). We used a combination of surface stimuli amplitudes and EO/EC conditions to distinguish the influence of each system on trunk and head posture control.

Surface tilting velocity was programmed to move according to a continuous pseudorandom ternary sequence (PRTS), mathematically integrated to create the desired tilting position,

and scaled to a specific peak-to-peak value (Peterka, 2002). The stimulus waveform appeared random to subjects and was chosen specifically to compare with another ongoing project investigating trunk balance in infants and children with CP. The bandwidth was 0.046–4.9 Hz and cycle duration was 21.78 s. Assessing balance across multiple frequencies enables a more comprehensive characterization of the balance system (Pintelon and Schoukens, 2012). The surface tilt signals contained less power across higher frequencies compared to previous studies (Goodworth and Peterka, 2009; van Drunen et al., 2015). The stimuli in each test consisted of 5 to 8 repeated cycles of a PRTS waveform (Figure 2A). Repeating waveforms increases accuracy in estimating posture responses dynamics (Cenciarini et al., 2010; Oie et al., 2002).

Procedures

Subjects completed 6 sitting tests. The tests included 2 spontaneous sway tests (no stimulus; EO/EC) and 4 tests with pseudorandom stimuli (2 amplitudes of 2° or 8° peak-to-peak; EO/EC). A warm-up trial (3–4 minute) was administered before data collection for subjects to get familiarized with test conditions. Data reported in the current study were part of a larger data collection session, which lasted about 1.5 hrs.

In all tests, subjects were instructed to put both feet on the footrest, both arms folded on the chest and respond naturally while maintaining upright sitting (Figure 1). Subjects watched or listened to their choice of movies to mask environment and equipment sounds and to maintain alertness throughout data collection. The visual stimuli from movies were not correlated with the support surface stimuli and did not evoke observable movements. No adverse events occurred during and after testing. No subject reported uncomfortable reactions or fatigue after the whole experimental procedure.

Data Processing and Analysis

Data from sensors were converted to frontal plane body sway with respect to gravity based on a three-link inverted pendulum model (Figure 1). Position vectors of individual segments were computed from the center of the bench to T7, from T7 to C7, and from C7 to head center for individual segments. The position vectors were low-pass filtered through second-order zero-phase-shift Butterworth filters with cutoff at 10 Hz. Horizontal coordinates in frontal plane (Y) and vertical coordinates (Z) of each position vector were used to calculate sway angles of each segment with respect to vertical. θ_{Hd} is the head tilt about the C7 axis; θ_{C7} is upper trunk tilt about the T7 axis; and θ_{T7} is mid-trunk tilt about the midpoint of the bench. Sway angles were averaged across stimulus cycles. The first cycle was not used in analyses to avoid transient behavior.

For all averaged sway angles, θ_{T7} , θ_{C7} , and θ_{Hd} , zero-meaned RMS measures were calculated in each test and each subject. To determine the influence of the stimulus amplitude and visual availability on individual segments, data from tests with surface stimulation were analyzed by calculating FRFs between segment sway and the surface tilting angle, and corresponding coherence functions. Goodworth and Peterka (2009) provide a detailed description of these frequency-based measures. Briefly speaking, gains and phases indicate, respectively, the relative magnitude and timing between the tilts of support surface

and individual segments as a function of frequency. Lower gains indicate less sway relative to stimulus, while phases indicate sway-to-stimulus timing, where a negative phase means the sway “lags” the stimulus. Coherence functions with a pseudo-random input reflect the amount of random error in the FRFs estimation (Maki, 1986), where a coherence of one indicates the absence of noise. FRFs were calculated for each cycle and then averaged across cycles. FRFs were further smoothed by averaging across adjacent frequency points. A larger number of adjacent points were averaged for higher frequencies to reduce variance of estimates at higher frequencies while maintaining frequency resolution (Otnes and Enochson, 1972). Coherence functions were computed as the squared magnitude of the stimulus-to-response cross power spectrum divided by the product of the stimulus power spectrum and response power spectrum (Bendat and Piersol, 2010).

Statistical Analysis

Standard descriptive statistics were used for response trajectories and sway RMS. Three-way repeated measures analyses of variance (ANOVAs) with three factors STIMULUS (3 levels: 0°, 2°, and 8°), SEGMENT (3 levels: θ_{T7} , θ_{C7} , and θ_{Hd}), and EYES (2 levels: EC and EO) were used to explore if stimulus amplitude, body segment, and visual availability influenced sway RMS. Main effects were explored with post-hoc pairwise comparisons using the Holm-Bonferroni method (Abdi, 2010). Statistical significance was set at $p = 0.05$. All statistical tests were performed using SPSS 20 (SPSS Inc, Chicago, IL). For statistical comparisons of FRFs and coherence functions, 95% confidence intervals (CIs) are frequently used (Goodworth and Peterka, 2009; Hwang et al., 2014). These were calculated using the percentile bootstrap method with 1,000 bootstrap samples (Zoubir and Boashash, 1998).

RESULTS

RMS Response to Surface Stimuli

The response (average across subjects) of each body segment to surface stimuli is illustrated in Figure 2. In general, all sway waveforms roughly followed the stimulus (Figure 2A), meaning that subjects tended to align their trunk and head toward the surface. The extent of these alignments toward the surface, however, depended on stimulus amplitudes, visual availability and vicinity of the body segments from support surface.

RMS results showed that varying stimulus amplitude and visual availability influenced all body segments (Figure 2C). Specifically, increasing stimulus amplitude influenced each segment's sway (STIMULUS ($p < 0.001$)) and EO resulted in reductions in RMS compared to EC (EYES, $p = 0.011$). This reduction with visual availability was most pronounced at the highest stimulus amplitude STIMULUS $\times$ EYES ($p = 0.019$) (Figure 2B), indicating that visual availability reduced sway more at higher amplitudes compared to lower amplitudes (Figure 2B, C).

RMS values were fairly similar across segments (SEGMENT, $p = 0.070$) (Figure 2B). However, stimulus amplitude influenced segments differently (STIMULUS $\times$ SEGMENT, p

= 0.003) such that the inferior segment (θ_{T7}) aligned to the stimuli closer (larger sway) than the other segments (less sway) at higher stimulus amplitude.

Frequency-Response Analysis of Sway Responses

FRF gains and phases describe the dynamics of segment motion in greater detail. In contrast to RMS, which only showed modest differences across segments, FRFs showed clear systematic differences across segments. In EC conditions, head segment gains and phases exhibited larger fluctuations in value across frequency and larger variability across subjects (i.e., larger 95% CIs in θ_{Hd} compared to θ_{T7} , Figure 3). In all segments, gains below 1 Hz increased with increasing frequency, but this was more prominent for superior segments. Gains above ~1–2 Hz showed an overall decrease with a rapid drop above 3 Hz, yet remained systematically higher for more superior segments. Similarly, although phase lags increased with increasing frequency in all segments, these lags were most apparent for superior segments (especially at frequencies above ~1–2 Hz). Differences across segments were also seen in coherences. At the lowest frequencies (< 0.2 Hz), coherences were higher in θ_{T7} (values above 0.9) compared θ_{C7} and θ_{Hd} (with values ~0.5–.8). Between 0.2 to 2 Hz, coherences gradually dropped in θ_{T7} but exhibited a sharp dip in each of the other two segments.

Subjects exhibited gain decreases with increasing stimulus amplitude at frequencies below 1 Hz for all segments, but these changes were most notable in superior segments. Stimulus amplitude effects on phases were minimal and primarily limited to the lowest frequencies. Above 2 Hz, coherences were higher in the larger stimulus amplitude condition and dropped in value for all segments.

The shape and amplitude-dependency of FRFs in EO were similar to EC conditions (Figure 4). Specifically, increasing stimulus amplitude reduced gains across most frequencies below 1 Hz and these changes were most evident in superior segments compared to the inferior segment (θ_{T7}). Gains in EO were lower in magnitude compared to in EC. This effect of vision was most notable in the superior segments, consistent with the significant interaction effect in RMS results. Visual availability had a minimal effect on phases and coherences.

DISCUSSION

The current study used continuous pseudorandom surface stimuli with healthy sitting adults to characterize the dynamics of trunk and head posture responses. We used three levels of stimulus amplitudes in EO/EC conditions with a three-segment model of the trunk and head to examine the dynamic responses to frontal plane stimuli. Two hypotheses were tested and analyzed as described in the following section.

Hypothesis Testing

Our first hypothesis was that FRFs would vary across the trunk and head segments. In support of this hypothesis, we found systematic variation in the shape of gain, phase, and coherence functions across segments, consistent with graded segmental control of the trunk and head (Prince et al., 1994). In addition, we expected to see an attenuation of head movement compared to the trunk segments, evidenced by lower gains across all frequencies

in the head segment compared to others. This hypothesis was supported only in the lowest frequency. The RMS attenuation of the superior segments (Figure 2A) was congruent with the lowest frequency component of the FRFs consistent with the fact that our stimulus contained most power at the lowest frequency (Goodworth and Saavedra, 2015).

Similar to differences in FRFs across segments, we also found that variability in segment motion across subjects was different across segments. Variability was higher in the superior segments compared to θ_{T7} (i.e., 95% CIs were wider in θ_{C7} and θ_{Hd}). This may result from more varied behavioral control across subjects over the superior segments, which were farther away from the stimulus and the base of support. Similarly, a previous standing study reported variability in upper body dynamics across subjects was larger than lower body variability when subjects adopted a wide stance and responded to surface stimuli (Goodworth and Peterka, 2010b). Coherences also showed distinct trends across segments. θ_{T7} was the highest at low frequencies and the superior segments exhibited a unique concavity between 0.2–2 Hz. This reflects nonlinearity (or increased variability in segment motion) in the responses of the superior segments in the three-link model.

Our second hypothesis was that the head segment would be more sensitive to increasing stimulus amplitude and changing visual availability, evidenced by larger changes in FRFs across test conditions compared to other segments. We observed gain decreases with both increasing stimulus amplitude and EO conditions. However, changing the stimulus amplitude and visual availability (Figure 3 and 4) had a much greater influence on superior segments compared to θ_{T7} . Similarly, the significant STIMULUS $\times$ SEGMENT interaction indicates more attenuation of RMS sway in the superior segments with increasing stimulus amplitude (Figure 2B, C) consistent with previous work observing the gradation in amplitude of trunk responses to perturbations (i.e. muscles around C7 showing less activation than muscles at the lower trunk, Prince et al., 1994). The lack of other significant effects on RMS are likely due to it being a more global measure of posture. Thus, FRF analysis allowed us to clearly see systematic differences across frequencies between segments, while providing information related to stimulus-response timing.

Interpretation of Sway Behavior

Across most frequencies and test conditions, gains exceeded one. This means that subjects swayed more than the surface tilted at these frequencies. Previous standing balance studies have generally shown lower gains at similar stimulus amplitudes (Cenciarini and Peterka, 2006; Goodworth and Peterka, 2010a; Peterka, 2002). We speculate that higher sway in sitting conditions is related to the larger base of support in sitting compared to those used in most previous standing studies. Consistent with this idea, we found in a previous standing study that subjects exhibit larger frontal plane sway in response to external stimuli when adopting a larger base of support (Goodworth and Peterka, 2010b).

At the lowest stimulus frequencies, gains were often less than one, indicating that subjects moved less than the surface tilted. During surface stimuli, proprioception tends to orient the body away from upright and toward the tilted surface. To obtain gains less than one, subjects must utilize sensory feedback from vestibular and/or visual systems (Cenciarini and Peterka, 2006; Goodworth and Peterka, 2012; Nashner et al., 1982; Peterka, 2002). In the current

study, gains less than one were most evident in superior segments, which coincide with the location of visual and vestibular sensory organs. The particularly low gains measured at θ_{C7} and θ_{Hd} in the EO condition may be related to a functional goal of gaze stabilization.

By altering the visual availability and stimulus amplitude, we were able to better understand sensorimotor integration processes across the trunk and head. Gain decreases with increasing stimulus amplitude and in EO compared to EC may be explained by sensory reweighting. Sensory reweighting is a shift in reliance of one sensory system toward another to limit excursions of the body (Cenciarini and Peterka, 2006; Hwang et al., 2014; Maurer et al., 2006; Oie et al., 2002; Peterka, 2002; Pialasse et al., 2015; Ravaioli et al., 2005). Specifically, when an external stimulus increases in amplitude, subjects shift reliance toward sensory feedback that can orient the body upright and away from sensory feedback that orients the body away from upright. Similarly, if vertical orientation information is available through the visual system (such as a stationary visual field in EO conditions), subjects shift reliance toward visual feedback, especially in more challenging scenarios.

Therefore, in the current study, gain decreases with increasing stimulus amplitude may have occurred because subjects shifted reliance away from proprioception and shifted reliance toward vestibular (in EC) and vestibular-plus-visual (in EO); and that subjects used vision more and proprioception less in EO compared to EC. Because sway was attenuated to a greater extent in superior segments during large stimulus and when vision was available, we speculate that neural control may differ across trunk segments and head such that sensory reweighting toward vision and vestibular is used to a greater extent in the control of superior segments.

However, it is also clear that the biomechanics of each segment differed. Mass, moment of inertia, and intrinsic musculoskeletal properties (which can be influenced by co-contraction) all affect FRFs. Previous modeling studies have shown that changes in lower body biomechanics are accompanied by major changes in neural control of balance (Bingham et al., 2011; Goodworth and Peterka, 2012). Data in the current study could be similarly interpreted through the development of a feedback model to quantify neural and biomechanical influences.

Limitations

We cannot interpret with certainty the underlying causes of the differences in FRFs across segments because both mechanical and neural factors influence segment motion. Future modeling (Bingham et al., 2011; Goodworth and Peterka, 2012) and/or expanded experimental conditions (Andreopoulou et al., 2015; Barela et al., 2011) could help illuminate underlying control mechanisms. In addition, to further characterize detailed behaviors of the spine (e.g. different bending modes) requires more measurement points along the spine in future. Also, future studies in the sagittal plane would provide a more complete picture of the multi-segmental nature of the head and trunk posture dynamics.

Conclusion

Using a three-segment model of the head and trunk dynamics we found that responses to frontal plane surface tilt stimuli were frequency-dependent and systematically differed across segments. Visual availability (EO vs. EC) and stimulus amplitude both influenced FRF gains. However, these influences were more pronounced in superior segments, which may be from subjects using sensory reweighting more to control their superior segments. Overall, the frequency analysis approach not only provided information compatible with conventional time-domain analysis (e.g. attenuation of head movement at lower frequencies and RMS), but also unveiled unique frequency-dependent dynamics. A frequency-based approach provides detail needed to characterize multi-segment dynamics related to sensorimotor control while our results provide a benchmark for future comparisons to those with impaired sitting.

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Figure 1.

Experiment apparatus and articulating bench system: A schematic of experiment setup includes the parallelogram bench design and a three-link inverted pendulum model for the trunk and head sway. As the surface tilts the bench legs alternately move up and down. Sensors were placed at the seventh thoracic vertebrae (T7), the seventh cervical vertebrae (C7), and both sides of the head directly above the tragus of the ear. θ_{T7} , θ_{C7} , and θ_{Hd} represent the angles between the vertical gravity line and individual body segments. The angles are computed from the horizontal component in frontal plane (Y) and vertical component (Z) of position vectors of each segment.

Figure 2.

Body segment responses to surface stimuli. (A) average cycle of sway (± 1 SE in grey) obtained by averaging across all stimulus cycles and across subjects showed dependency on stimulus amplitude, visual availability, and vicinity of the body segments from support surface. (B) root-mean-square (RMS) segment sway for each stimulus amplitude (mean $\pm$ SE). (C) segment sway RMS as a function of stimulus amplitude for each segment. The RMS sway values were horizontally offset to avoid error bar overlaps. In (B) and (C), the gray areas indicate values below the input signal RMS of the Support Surface (SS).

Figure 3.

Eyes closed segment frequency-response functions (FRFs) and coherence functions averaged across all subjects show that variation of FRFs across frequency and sensitivity to changing stimulus amplitude is different for each body segment. Error bars on FRFs show 95% CIs on mean gain, phase, and coherence at each frequency. Vertical dotted lines denote the 1 Hz frequency. Horizontal dotted lines indicate the values where gain equals 1, phase equals 0°, and coherence equals 1, respectively. All FRFs values were horizontally offset to avoid error bar overlaps.

Figure 4.

Eyes open frequency-response functions (FRFs) and coherence functions averaged across all subjects with 95% CIs. Vertical dotted lines denote the 1 Hz frequency. Horizontal dotted lines indicate the values where gain equals 1, phase equals 0°, and coherence equals 1, respectively. All FRFs values were horizontally offset to avoid error bar overlaps.