The effect of sensory noise created by compliant and sway-referenced support surfaces on postural stability.

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Abstract

The purpose of the present experiment was to compare in normal human subjects the differential effects on postural stability of introducing somatosensory noise via compliant and/or sway-referenced support surfaces during quiet standing. The use of foam surfaces (two thicknesses: thin (0.95cm) and thick (7.62cm)) and sway-referenced support allowed comparison between two different types of destabilizing factors that increased ankle/foot somatosensory noise. Under some conditions neck extensions were used to increase sensory noise by deviating the vestibular system from its optimal orientation for balance control. The impact of these conditions on postural control was assessed through objective measures of instability.

Thick foam and sway-referenced support conditions generated comparable instability in subjects, as measured by equilibrium score and minimum time-to-contact. However, simultaneous application of the conditions resulted in greater instability, suggesting a higher level of generated sensory noise and thus, different receptor types affected during each manipulation. Indeed, sway-referenced support generated greater anterior-posterior center-of-mass (COM) sway, while thick foam generated greater medio-lateral COM sway and velocity. Neck extension had minimal effect on postural stability until combined with simultaneous thick foam and sway-referenced support. Thin foam never generated enough sensory noise to affect postural stability even with noise added by sway-reference support or neck extension. These results provide an interesting window into the central integration of redundant sensory information and indicate the postural impact of sensory inputs is not solely based on their existence, but also their level of noise.

Keywords: posture, foam, neck extension, vestibular, proprioception

Introduction

Maintaining bipedal postural stability is fundamental to the survival of humans, and multiple sensory sources are utilized to facilitate postural control, including: the visual, vestibular and somatosensory systems. Within these sensory systems further subdivisions or specific modalities can be identified, each providing unique and/or redundant information. This creates an intricate sensory integration task for maintaining postural equilibrium.

At any given moment or scenario an individual's postural stability state can be viewed from the perspective of sensory noise (uncertainty) within each contributing sensory system. Varying levels of sensory noise exist within and between individuals. For example, sensory noise in vestibular inputs can increase with age-related hair cell degradation and can be internally generated from head positions or movements which deviate from the optimal orientation of the vestibular apparatus (Asseman and Gahery 2005; Paloski et al. 2006). In fact, the sensory noise generated by a 30 degree static neck extension is sufficient to reduce postural stability (Paloski et al. 2006). Likewise, sensory noise within ankle proprioception and plantar exteroception generated by a sway-referenced support surface, foam surfaces, anaesthetized feet, etc. all negatively impact postural stability (Shumway-Cook and Horak 1986; Kogler et al. 2000; Horak et al. 2002; Meyer et al. 2004).

For clinical assessment of balance disorders, the Equitest computerized dynamic posturography system (NeuroCom International, Clackamas, OR) provides sensory organization test (SOT) conditions, which specifically introduce sensory imprecision to ankle/foot somatosensation for assessing potential sensory deficiencies. These tests generate sensory noise within the feet/ankles through anterior-posterior (AP) support platform rotations, sway-referenced to body center-of-mass (COM) sway. Similar ankle/foot sensory noise is also thought to be produced by a foam support surface (Shumway-Cook and Horak 1986).

Therefore, the aim of this study was to examine the differential effects of various sensory noise sources within postural sensory systems. Ankle/foot somatosensory noise was generated by a sway-referenced and a foam support surface, while vestibular noise was created with neck extension.

Methods

Subjects

Twelve subjects (6 males, 6 females: age range 23 to 47 years) participated in this study. Each participant was in good general health, passed a NASA-modified United States Air Force Class III-equivalent medical examination, and reported no history of balance or vestibular abnormalities. All subject selection criteria and experimental procedures were approved by the Johnson Space Center Committee for Protection of Human Subjects. All subjects provided written informed consent prior to inclusion.

Apparatus

A computerized dynamic posturography system (Equitest, NeuroCom International, Clackamas, OR) was used to evaluate balance control. Subjects wore a safety harness and stood on the platform; their ankle joints were aligned with the support surface rotational axis. Audio communications and a constant level of pink noise to mask ambient auditory cues were provided to subjects through headphones. Pudgee foam pads (polyurethane open-cell gel-foam, Dynamic Systems, Inc., Leicester, CA) were used to create foam support surfaces. Three sizes of left and right footprints were cut from thin (0.95cm, ~480kg/m^3 density) and thick foam pads (7.62cm, ~240kg/m^3 density).

Procedure

All subjects performed a set of balance control trials during which they were instructed to maintain stable, natural upright posture with arms folded across the chest. Each trial (20 s duration) was performed with absent vision (eyes closed), one of two somatosensory conditions (fixed support (SOT2), sway-referenced support (SOT5)) and one of two vestibular conditions (head erect, head statically pitched back 20° (P)). During SOT5 conditions the foot support surface was sway-referenced by rotating the force platform in the sagittal plane in direct proportion to the subject's estimated instantaneous COM sway angle. Four trials were performed for each of the four experimental conditions, totaling 16 trials. This protocol was repeated on three consecutive days, each with a different foam support surface: no foam, thin foam, and thick foam. The presentation order of the foam support surface condition was randomized.

Analysis

COM was calculated by low pass filtering the center-of-pressure waveform obtained from the NeuroCom support surface force plate. AP sway, medio-lateral (ML) sway, AP velocity, ML velocity, equilibrium score (EQscore), and minimum time-to-contact (TTC_{min}) were subsequently calculated from the COM waveform. AP and ML sway represented the mean absolute sway amplitude, $\overline{S}$, of COM,

$$\overline{S} = \frac{1}{N_t} \sum_{i=1}^{N_t} \left| x_i - \overline{x} \right|,$$

and AP and ML velocity, a first derivative of COM positional data, represented the mean absolute velocity

$$\bar{V} = \frac{1}{N_t} \sum_{i=1}^{N_t} |v_i| \, ,$$

in their respective directions. N_t is the number of data points in a 20 s trial. The EQscore was calculated from peak-to-peak COM sway amplitudes, and TTC_{min} represented the minimum value of TTC calculated from the COM directional velocity and the distance between COM and the stability boundary to which it was moving towards (Forth et al. 2006). Repeated measures analysis with Bonferroni adjustments was used to determine differences between conditions.

Results

(Insert figure 1)

For SOT2 conditions, thin foam created no significant impact on postural stability measured by EQscores ($p>0.05$), although thick foam generated significantly lower EQscores than no foam conditions ($p=0.0001$) (Figure 1). In contrast, different levels of foam did not modify the EQscore for SOT5 ($p>0.05$). Comparisons of specific conditions revealed that thick foam (SOT2-thick foam) and a sway-referenced support (SOT5-no foam) produced comparable EQscores, but simultaneous application (SOT5-thick foam) produced significantly lower EQscores than thick foam alone (SOT2-thick foam) ($p=0.0001$). Neck extensions failed to affect the EQscore for SOT2P or SOT5P, apart from a substantial reduction in EQscore for SOT5P-thick foam ($p=0.002$). No subjects registered a fall in any condition.

Similar trends were also observed for the TTC_{min} and measures of AP sway, ML sway, AP velocity and ML velocity. Except, significantly less AP sway was generated by the addition of thick foam to SOT5 than SOT2 ($p=0.003$) (Figure 2). Neck extensions generated similar patterns of decreased stability in AP sway, ML sway, AP velocity and ML velocity. This included sufficiently increased SOT5-thick foam AP sway to be consistent with instability patterns induced by neck extension in the other measures.

(Insert figure 2)

A specific comparison between SOT5 and SOT2-thick foam showed the sway-referenced support surface generated significantly greater AP sway than foam ($p=0.048$), although AP velocity was equivalent ($p>005$). In contrast, thick foam generated greater ML sway ($p = 0.043$) and ML velocity ($p=0.002$) than SOT5.

Discussion

Foam surfaces, sway-referenced support, and neck extension all present sensory noise which reduces postural stability. In the present study, thick foam and sway-reference support surfaces generated equivalent levels of instability, however greater instability was gained from combining the two simultaneously. This suggests foam and sway-reference support surfaces generated sensory noise in different sensory receptors. Sway-referencing of the support surface is primarily designed to increase noise in ankle proprioceptors, and likely only generates a secondary level of imprecision in plantar haptic receptors. Thick foam, on the other hand, probably creates substantial noise in foot haptic receptors and less disruption to ankle proprioceptors. Though, the eversion/ inversion movements of the ankle joint facilitated by this compliant surface must also be considered.

Furthermore, the differential sensory modality effect of thick foam and sway-referenced support may be attributed to the multidirectional nature of sensory inaccuracy created by thick foam, compared with the single direction of inaccuracies generated by sway-referenced support in the AP plane. Indeed, thick foam generated greater ML sway and velocity, while sway-referenced support surface generated greater AP sway. These findings are consistent with Allum et al. (2002) who demonstrated subjects orientated sideways on a sway-referenced platform, experiencing a roll plane sway-reference, produce trunk movements analogous to foam conditions (Allum et al. 2002). Thus, ML sensitive receptors of the ankle/foot are more affected by a thick foam surface than AP sway-referenced support surface.

Interestingly, in the current study we also demonstrated sway-referenced support (SOT5) and thick foam (SOT2-thick foam) conditions reached similar AP velocities, whereas SOT5 generated greater AP sway. A source of high AP velocity while on thick foam may result from foam compression during sway and corrective movements, although a complementary rise in AP sway would also be expected. Alternatively, SOT5 AP velocity may have been muted due to a mechanical limitation of sway-referencing which was insensitive to high frequency, low amplitude sway oscillations. Also, the elevated AP sway for SOT5 may be due to a strategy adopted to extract more proprioceptive information from the sway-referenced surface by initiating controlled or moderate velocity sway.

Neck extensions had minimal effect on postural stability until they were combined with simultaneous thick foam and SOT5. Rather than conflicting with previous work (Kogler et al. 2000; Paloski et al. 2006), this minimal impact may have resulted from a subject sample that included high performers who either generated less sensory noise with neck extension, or may have relied less on the internally generated vestibular noise in the sensory integration. To answer these questions is beyond the scope of this study. However, it is interesting to note that neck extensions were substantially disruptive to stability when combined with simultaneous foam and SOT5. This finding implies neck extension does present sensory inaccuracies, despite them only being exposed with further compromised redundant systems. Neck extension combined with foam or SOT5 alone did not present such instability, neither did the combined foam and SOT5 without neck extension. This finding is inconsistent with assertions of greater vestibular contributions for sway-referenced support than foam surfaces (Jeka et al. 2004), as selective instability for conditions containing neck extension coupled with SOT5 would be expected. Indeed, the substantial drop in postural stability for simultaneous thick foam, SOT5 and neck extension may indicate the level to which ankle/foot sensory contributions were utilized, despite the sensory noise during neck extension conditions with foam only or SOT5 only conditions.

In contrast to thick foam, thin foam never generated enough noise to affect postural stability even with additional noise from a sway-referenced support or neck extension. The sensory input for postural control was only compromised by thick foam. Nevertheless, a benefit of this result is that thin foam could be used during postural testing to alleviate foot discomfort created by the hard support surface of force plates, without altering posture measurements (e.g. for bed rest and diabetic patients).

A limitation of this study was the differing densities of the foam, which restricts comparisons of foam thickness in isolation. Thus, all comparative foam results reported in this study represent a combination of differing thickness and densities. Another limitation of this study was that all conditions were performed with eyes closed. The complete elimination of vision, a sensory contributor to posture, may alter the integration of remaining senses as they become inaccurate. The drawback, of course, being vision is a potent redundant sensory source that often needs to be removed to yield instability for measurable differences.

However, in the absence of vision, these findings exposed differences in the seemingly similar destabilizing factors, foam surface and sway-reference support surface. We highlighted the potential differences in receptors utilized and provided a window into the sensory integration of noisy redundant inputs. Further work that can measure or manipulate specific sensory noise levels will greatly expand the understanding of sensory integration for postural control.

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Figure 1. The equilibrium score (±sem) for SOT2 and SOT5 at three levels of foam, with (P) and without and neck extension.

Figure 2. The AP and ML sway and velocity (+sem) for SOT2 and SOT5 at no foam and thick foam, with (P) and without neck extension.