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Destabilization of human balance control by static and dynamic head tilts

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Abstract

To better understand the effects of varying head movement frequencies on human balance control, 12 healthy adult humans were studied during static and dynamic (0.14, 0.33, 0.6 Hz) head tilts of ±30° in the pitch and roll planes. Postural sway was measured during upright stance with eyes closed and altered somatosensory inputs provided by a computerized dynamic posturography (CDP) system. Subjects were able to maintain upright stance with static head tilts, although postural sway was increased during neck extension. Postural stability was decreased during dynamic head tilts, and the degree of destabilization varied directly with increasing frequency of head tilt. In the absence of vision and accurate foot support surface inputs, postural stability may be compromised during dynamic head tilts due to a decreased ability of the vestibular system to discern the orientation of gravity. This instability may compound the risk of falling following recovery from balance disorders or adaptation to altered gravity conditions such as space flight. Thus, dynamic head tilts may improve the diagnostic sensitivity of computerized dynamic posturography, particularly for healthy subjects recovering from temporary balance control deficits.

Keywords: Posture; Otolith; Spatial orientation; Vestibulo-spinal; Head tilt

1. Introduction

Stable control of balance and locomotion requires accurate spatial orientation of body segments with respect to gravitational vertical. This may be obtained by integrating afferent orientation information from multiple sensory end organs [1]. The vestibular system likely provides key inputs, primarily through the otolith organs, which can directly sense the orientation of the head with respect to gravity. Accurately determining gravitational vertical becomes a more challenging task when the head is in motion, especially at higher frequencies [2,3].

Owing to dynamic properties of the sensory and biomechanical constraints of human balance control [4], spatial orientation processing may vary with head movement frequency. During low frequency linear acceleration, for example, eye movements are characterized by counter-rolling and counter-pitching that compensate for head tilt relative to gravity [5]. These otolith-mediated tilt responses exhibit low-pass characteristics, decreasing in amplitude at frequencies above 0.3 Hz [6]. At higher frequencies, otolith-ocular responses appear to use a head reference frame to serve gaze-stabilizing functions that compensate for head translation [7]. Therefore, otolith input at frequencies around or above this 0.3 Hz cross-over frequency may provide ambiguous information regarding motion in gravitational coordinates [4,8].

To test the hypothesis that there is a frequency-dependent effect of head tilt on balance control, we studied postural stability in human subjects performing voluntary head tilts in the pitch and roll planes. During quiet upright stance without vision, a common spatial orientation reference frame is likely constructed by the CNS using gravitational

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reference information. Dynamic head tilts cause phasic changes in vestibular afferent information and simultaneously modify the orientation of the head with respect to gravity. Thus, estimating a common spatial reference frame from otolith-mediated gravitational reference information may be more difficult during head tilts, and any resulting inaccuracies would be expected to increase balance instability.

2. Materials and methods

The effects of static and dynamic head tilts on balance control were studied in 12 adult human volunteers (6 males, 6 females; age range 22–50 years). Each participant was in good general health as evidenced by passing a U.S. Air Force Class III medical examination and none reported 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, and all subjects provided informed consent prior to inclusion.

Balance control was evaluated using a computerized dynamic posturography (CDP) system (EquiTest® System, NeuroCom International, Clackamas, OR). To enhance the assessment of vestibular contributions, subjects performed each 20 s trial with absent vision (eyes closed) and dynamically altered somatosensory reference information (EquiTest sensory organization test, SOT 5). The foot support surface reference was altered by rotating the force platform in the sagittal plane in direct proportion to the estimated instantaneous center-of-mass (COM) sway angle (i.e., support surface was subject sway-referenced). Throughout each trial, the subject was instructed to maintain stable upright posture with arms folded across the chest, and eyes closed. External auditory orientation cues were masked by white noise supplied through headphones (weighing approximately 390 g).

A number of static and dynamic head tilts conditions were studied. During static head tilt trials, subjects attempted to maintain head erect (static control condition, see Fig. 1A) or tilted by $\pm 30^\circ$ (extension $+30^\circ$, flexion -30°, lateral left -30°, or lateral right $+30^\circ$), as measured by a head position sensor described below. During dynamic head tilt trials, subjects attempted to perform continuous $\pm 30^\circ$ sinusoidal head oscillations paced by an audible tone, transmitted through the headphones, at frequencies of 0.14, 0.33, or 0.60 Hz (see Fig. 1B and C for 0.33 Hz). As a dynamic control condition, subjects maintained head erect and tracked the 0.33 Hz auditory tone by indicating the peaks using a hand-held pushbutton. This condition added the dynamic information-processing task without the sensory and inertial disturbances associated with dynamic head movements.

Pitch and roll plane data were collected in separate sessions for all subjects, randomly assigned between subjects, and performed on consecutive days such that six of the subjects performed the pitch trials on the first day and those same subjects performed the roll trials the next day, and vice versa for the remaining six subjects. Each session comprised three blocks of six static and dynamic trials. The order of the static and dynamic tilts was randomized within each block and counterbalanced across subjects. A static condition control trial was performed before and after each block.

Infrared markers placed on the headset frame were used to quantify head position using an OptoTrak System (Model 3020, Northern Digital Inc., Ontario, Canada). While the subject was standing erect with head and eyes in a natural forward gazing position, the head position sensor was set to 0° by adjusting the headset frame. Prior to beginning each static trial, the test operator used real-time head position display information to guide the subject in achieving a consistent upright position or head tilt of $\pm 30^\circ$ in pitch or roll. For dynamic head movements, the test operator continuously monitored the head movement of the subject through the $\pm 30^\circ$ range and gave corrective instruction before beginning the trial. Head position data were differentiated digitally to compute head velocity. Amplitudes of the dynamic head tilts were obtained from sinusoidal curve fits of the position and velocity data.

Center-of-mass sway angles were estimated from instantaneous anterior-posterior (AP) and medial-lateral (ML) center-of-force positions, which were computed from force transducers mounted within the EquiTest force plates [9]. The AP peak-to-peak sway angle, θ (in degrees), was used to compute the equilibrium score (EQ), $EQ = 100 \times (1 - (\theta/12.5))$, where 12.5° is the maximum theoretical peak-to-peak sway in the sagittal plane. For $\theta \geq 12.5^\circ$, which is scored as a fall, the EQ score is zero.

Statistical analysis of EQ scores is confounded by skewing of the EQ score population distributions (see Fig. 2 for example), and, under some conditions, by "falls", which are discrete events that cannot be considered part of the continuous EQ distribution. When "falls" occur, the trial ends, and the minimum EQ value of zero is commonly assigned. Standard statistical analysis techniques are not applicable to the resulting, skewed hybrid discrete-continuous distribution. Therefore, an alternative approach was used in this study. First, the EQ scores for a given test condition were modeled by a mixed discrete-continuous distribution arising from a "latent" EQ score. The latter, being observable only when there is no fall, follows a Beta distribution[1], scaled to the range 0–100, whose parameters depend on the tilt condition [10]. The solid curve in Fig. 2 shows the Beta model density for the latent EQ distribution for the static control condition in the present study. In this case, there is negligible probability of a fall hence the Beta density also applies to the observed EQ. The fifth percentile EQ value for the static control condition (EQ = 57.5; Fig. 2, vertical line) was considered the lower

[1] The Beta distribution probability density has the form $f(y) = [\Gamma(p+q)/\Gamma(p)\,\Gamma(q)]y^{p-1}(1-y)^{q-1}$ $(0 < y < 1)$, where p and q are positive-valued parameters and $\Gamma(\cdot)$ is the gamma function.