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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.

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]. Otolith-ocular responses at higher frequencies 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 cross-over frequency range may provide ambiguous information regarding motion in gravitational coordinates [4, 8].

To examine whether 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. It was hypothesized that during quiet upright stance, in the absence of vision, a common spatial reference frame is constructed by the CNS using gravitational reference information transduced primarily by otolith organs of the vestibular system. 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.

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 yrs). 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 system (Equitest, 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 naturally

upright posture with arms folded across the chest, and eyes closed. External

auditory orientation cues were masked by white noise supplied through

headphones (weighing approx. 390 grams).

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) or tilted by ±30° (extension +30°, flexion –30°, lateral left –

30°, or lateral right +30°), as measured by a head position sensor described

below. During dynamic head tilt trials, subjects attempted to perform continuous

±30° sinusoidal head oscillations (paced by an audible tone) at a frequency of

0.14, 0.33, or 0.60 Hz. As a dynamic control condition, subjects maintained head

erect and tracked a 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 performed on consecutive days. 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 ±30° in pitch or roll. For dynamic head movements, the test operator continuously monitored the head movement of the subject through the ±30° 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 ($\theta = p\text{-}p$ *sway* in degrees), was used to compute the equilibrium score (EQ), $EQ = 100 \times \left(1 - (\theta/12.5)\right)$, where $12.5°$ is the maximum theoretical θ, *p-p sway*, in the sagittal plane. For $\theta \geq 12.5°$, which is scored as a fall, the EQ score is zero.

As exemplified in Figure 1, which shows the distribution of scores for the standard SOT 5 from this study, a typical EQ distribution is not normally distributed, being skewed leftward. Furthermore, falls are automatically assigned the minimum value of zero, in which case, the EQ distribution becomes partially mixed and partially continuous. For these reasons, standard methods such as analysis of variance are not appropriate for comparing mean scores. Instead, 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. In this model, the probability of a fall depends on the realized latent EQ and thus affects the always-observed EQ [10]. The solid curve in Figure 1 shows the Beta model density for the latent EQ distribution when the standard SOT 5 is given to normal healthy subjects. In this case, there is negligible probability of a fall

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[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.

hence the Beta density also applies to the observed EQ. The 5th percentile EQ (57.5) for this static control condition (Figure 1, vertical line) was considered the lower bound for stable postural control. A simple way of characterizing the individual test conditions is in terms of the proportion of the latent EQ distribution falling below this critical value. However statistical inference comparing test conditions ($\alpha = 0.05$) was made by comparing estimates of the Beta distribution parameters using a form of maximum likelihood modified for the repeated measures design as implemented in [10].

RESULTS

Subjects were able to maintain head tilt angles close to the 30° goal, with static and dynamic tilt magnitudes averaging 27.0°±1.2° and 28.5°±1.5°, respectively. In order to maintain the peak head displacements constant across frequencies, the velocities increased proportional to frequency (31.6 ± 1.2, 69.5 ± 1.5, 112.7 ± 2.0 °/s for pitch and 29.4 ± 0.7, 63.0 ± 1.2, 102.8 ± 1.3 °/s for roll at 0.14, 0.33 and 0.6 Hz, respectively). Figure 2 shows time traces from a typical subject during standard static SOT 5 (A), roll head movement (B), and pitch head movement (C) trials at 0.33 Hz. The head position traces show that the subject was able to follow the tone quite well (see Figures 2B and 2C). The sway traces show that medial-lateral (ML) sway was virtually unaffected by head

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movements, even when those movements were in the roll plane. The peak-to-peak ML sway ($0.73° \pm 0.03°$, mean± sem across all trials) was greater than 2° on only 13 of 528 trials. On the other hand, the anterior-posterior (AP) sway was increased by pitch and roll head movements by a similar order of magnitude.

Of 288 dynamic head movement trials, 15 falls were observed (10 for pitch and 5 for roll), and of the 240 static trials, only one fall was recorded; recall that falls are assigned an EQ score equal to zero. Figure 3 shows the EQ scores of all subjects and trials, categorized by condition. Notice that with neck extension (Figure 3A), more trials fell below the 5th percentile EQ score for standard SOT 5 trials (horizontal line at EQ = 57.5) than for other static conditions. Also, Figure 3B shows that more scores are below 5th percentile with dynamic head movements, and there is an increased trend for lower scores as the frequency increases from 0.14 Hz to 0.6 Hz, for both pitch and roll.

Postural stability was not significantly changed by static neck flexion or by static roll tilts to either the left or right; however, postural stability was decreased ($P < 0.001$) by static neck extension (Figure 4 and Table 1). Using the approximate maximum likelihood methodology (AML) as in [10] (see Methods), statistical models for the latent EQ score and the probability of a fall were fit to the observed EQ scores for each head tilt condition. From these we calculated the mixed discrete continuous distribution of actual EQ scores. For the static control case, the 5th percentile of the latent EQ distribution was 57.5 (Figure 1,

vertical line). We then defined an index of relative performance for the other tilt conditions to be the expected percentage of latent EQ scores below this threshold. Estimated distributions of latent EQ scores for static flexion, extension, left roll and right roll are also shown in Figure 4. Note that the EQ distribution was clearly shifted towards lower values for the extension case. This effect was significant ($P < 0.001$, AML) and is manifested in the raw data (Figure 3A) for which 12 of 36 of static extension EQ scores were below the threshold (including one fall) as compared with 4 of 96 (no falls) for the control case (Table 1). The estimated EQ distributions for other static tilt conditions were not significantly different from the control case. No falls occurred under any static conditions other than the one case under extension.

Figures 5 and 6 show the effect of dynamic head movement frequency on the EQ distribution in the pitch and roll planes, respectively. Note that postural stability was significantly disrupted by dynamic head movements in both the pitch and roll planes, and, in each plane, balance control was progressively more destabilized as head movement frequency increased (Table 1). Formally, this frequency effect was highly significant ($P < 0.001$, AML). However there was no significant difference between the distributions of EQ scores for the dynamic control condition (4.3% below threshold) and the static control condition (also 4.3% below threshold). Table 1 details the calculated expected proportions of latent EQ scores below the 5th percentile for all experimental conditions and

summarizes the results of statistical inference comparing the effects of the conditions on the distribution of EQ score.

To check goodness of fit for the statistical model, we compared the cumulative distribution of actual EQ scores for the most provocative condition of dynamic pitch at 60 Hz (7 falls) to the theoretical cumulative distribution calculated from the statistical model. The result in Figure 7 shows that there is excellent agreement between the empirical and model-based distributions.

DISCUSSION

These results demonstrate that, in normal subjects, balance control is destabilized by dynamic head tilts, and that the degree of postural instability varies directly with the frequency of head tilt. The static head tilt findings are consistent with previous reports of postural instability with neck extensions [11], but, with absent vision and distorted proprioceptive orientation cues, they underscore the importance of vestibular afferent information in balance control. Since canal information during the static tilt trials was limited to low frequencies associated with A-P sway [4], the decreased postural stability associated with neck extension likely resulted from tilting the utricular otoliths out of their optimal working range (a 30° extension would decrease utricular sensitivity by about 40%), which is cited by other authors [11, 12]. Conversely, the pitch flexion tilts, which did not alter stability, likely increased utricular sensitivity by

only about 15%. Also, these results show static lateral tilts were not statistically different from head erect, similar to Chandra and Shepard's findings [13].

Our findings support the concept that the same low frequency central vestibular processing responsible for the gyroscopic properties of the post-rotatory VOR may influence the sensory transformations essential for balance control. The dynamic head tilt results demonstrate a head movement, frequency-dependent destabilization of balance control. These results may reflect spatio-temporal processing characteristics of the central vestibular system [14]. Fitger and Brandt demonstrated a relationship between the reorientation of the eye response axis towards alignment with gravity and the return of stabilization of posture in standing subjects who made lateral head tilts immediately after a period of slow rotation of the support surface [15].

Angelaki and Hess used a similar post-rotatory tilt paradigm in monkeys to demonstrate that the high frequency responses tended to be in a head-fixed reference frame, while the lower frequency responses were reoriented towards alignment with gravity [16]. Previous data suggests that otolith-mediated tilt responses become diminished around the higher frequencies we employed in our study [6]. The utilization of canal input for providing information about orientation relative to gravity at these higher frequencies may also be limited by the need for coordinate transformations from head-fixed to a spatial reference frames [17]. While the angular head velocities during dynamic head tilts

increased proportional to frequency in our study, the increased postural sway at higher frequencies therefore appears to reflect the low-pass characteristics of otolith input regarding orientation relative to gravity similar to that reflected in ocular tilt responses [6].

The frequency-dependent response of the balance control system may also reflect CNS optimization for the biomechanical constraints of different stabilizing strategies. Ankle sway strategies, for example, are constrained to low frequencies (< 0.2 Hz) due to the large moment of inertia about this joint, while hip sway strategies are effective at higher frequencies ($0.5 - 2.5$ Hz), but cannot be used to maintain balance at low frequencies [18]. Spatial processing for the frequencies of head and trunk movements encountered during locomotion may be optimized using head-coordinates to support gaze-stabilizing reflexes [19].

One potential confound in the present study is that the larger angular velocities at higher frequencies may have introduced frequency-dependent inertial perturbations to the balance control systems. However, postural sway occurred primarily in the sagittal plane (AP direction) even when roll head movements were in the coronal plane (ML direction). Figures 2B and 2C reinforce this observation that postural sway was not significantly increased medial-laterally, even during roll head movements. There were systematic differences between the pitch and roll head movements in the AP sway amplitudes, but these differences were not frequency-dependent, and were small

when compared with the amplitudes of the frequency-dependent destabilization. Thus, a frequency-dependent increase in mechanical perturbation introduced by dynamic head tilts does not appear to explain the frequency-dependent destabilization observed.

Balance control was not destabilized by a secondary information-processing task, the dynamic control condition where the subject indicated the peaks of an auditory signal modulated at 0.33 Hz using a pushbutton (see Figure 3A, S5 vs. S5+). Subjects performed as well or better with this task. Therefore, the postural instability observed during dynamic head tilts was not likely due to decreased attention in performing the task.

Addition of dynamic head pitch movements and static neck extensions to computerized dynamic posturography protocols might provide a useful enhancement, particularly in evaluating subjects with marginal balance control dysfunction who can compensate with increased task vigilance or sensory substitution. Such subjects may appear to be normal under quiescent circumstances, but may become disoriented and/or lose balance when subjected to challenging environmental situations. When central processing of vestibular inputs is disrupted through either pathology or adaptation to altered gravito-inertial conditions, the ability to maintain postural balance during head tilts will be compromised.

McGrath *et al.* demonstrated that active head tilts during the Equitest

sensory organization tests increased the sensitivity in detecting ataxia induced by long duration centrifuge runs, while the standard SOT protocol with head upright did not show significant changes between pre- and post-centrifugation [20]. Clark and Tolhurst also reported that the "head-shake" SOT protocol (HS-SOT, NeuroCom Intl., Inc.) improved the sensitivity of posturography in detecting subtle differences in balance function between normal athletes and non-athletes [21]. Additionally, preliminary data from our laboratory show that when healthy subjects are tested after a temporary vestibular disturbance, such as making head movements while on a short radius centrifuge or upon return from extended stays in microgravity, head movements present an additional challenge to maintain balance, even with increased task vigilance.

In summary, our results indicate that healthy subjects can adequately compensate for different head orientations with respect to gravity by maintaining postural stability during static and low frequency dynamic head tilts, in the absence of vision and accurate somatosensory inputs. Postural instability may be increased with higher frequency head tilts due to a decreased ability to discern the orientation of the head and body with respect to the gravitational vertical. Dynamic head tilts may improve the diagnostic sensitivity of computerized dynamic posturography and fall risk assessment following recovery from balance disorders or adaptation to altered gravity conditions such as space flight.

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non-athletes using the sensory organization test and the head-shake

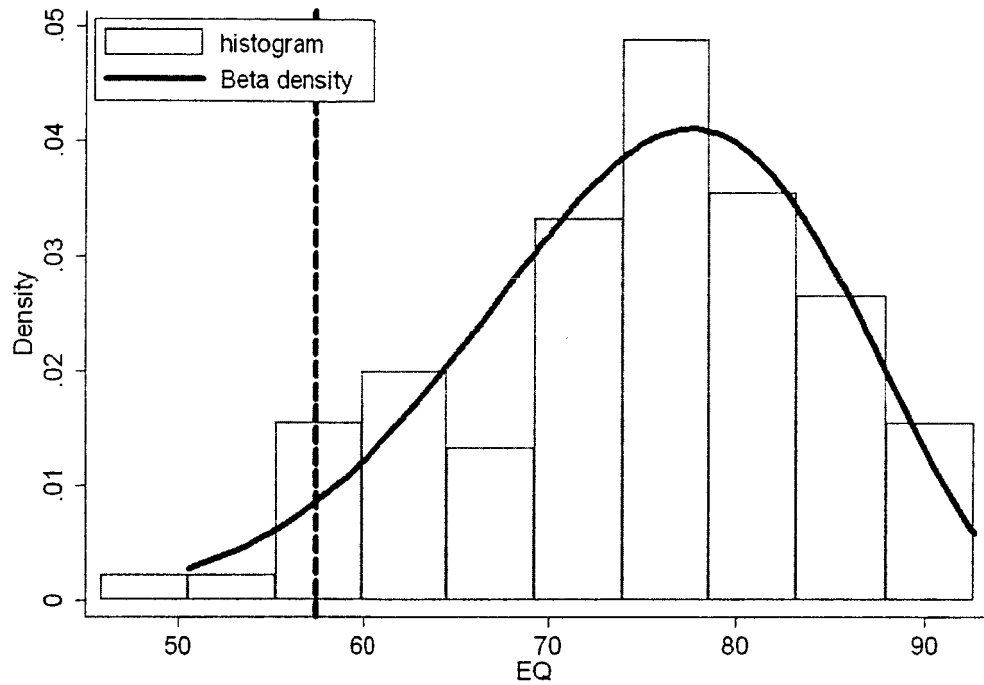sensory organization test. Med Sci Sports Exerc 2000;32:S144.

Figure 1. Bar chart shows the distribution of standard SOT 5 EQ scores.

Because of the skewed nature of the histogram, the EQ data cannot be

analyzed with standard normal statistical analysis. Therefore, the

Beta density, or latent EQ densities, represented by the solid curved

line will be computed from the raw EQ scores and be used to

compare different head tilt conditions. The dashed vertical line is the

5th percentile EQ score, $EQ_{5th\%} = 57.5$.

Head Erect

(A)

Roll Head Movements: 0.33 Hz

(B)

Pitch Head Movements: 0.33 Hz
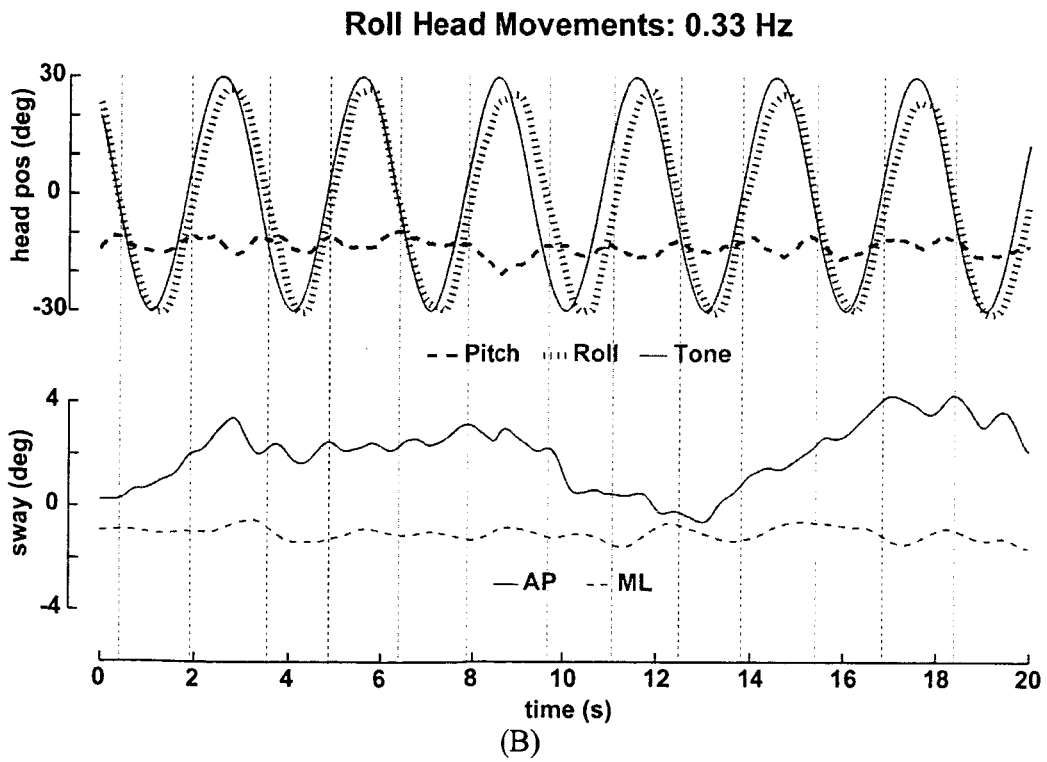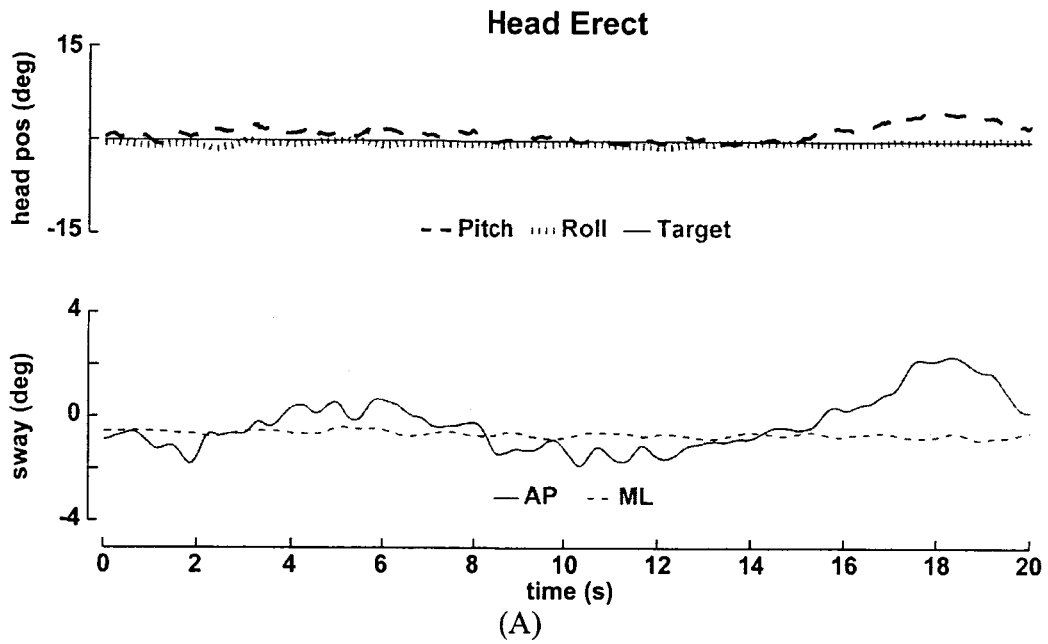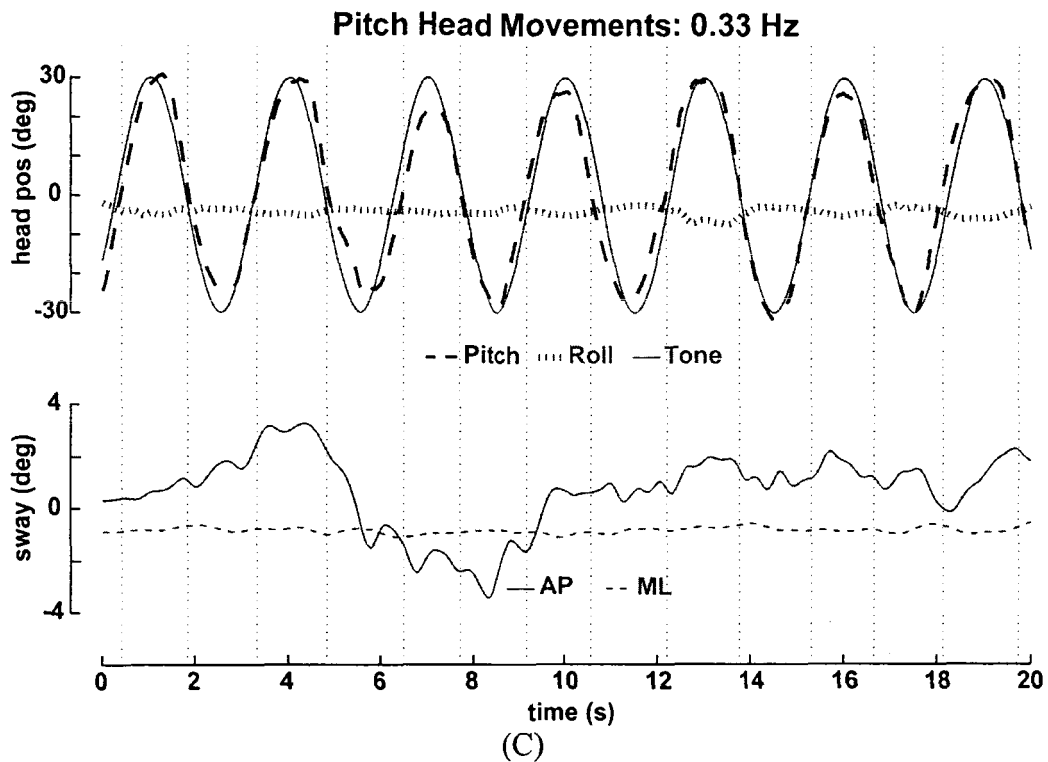
Figure 2. Time traces from a typical subject during (A) standard SOT 5, (B) roll head movement trials, and (C) pitch head movement at 0.33 Hz. The top frames show head position during the 20 second trials, along with the auditory tone. The bottom frames show the COM sway in both anterior-posterior (AP) and medial-lateral (ML) directions.

Static Control

Dynamic Control

Roll Left

Roll Right

Neck Flexion

Neck Extension
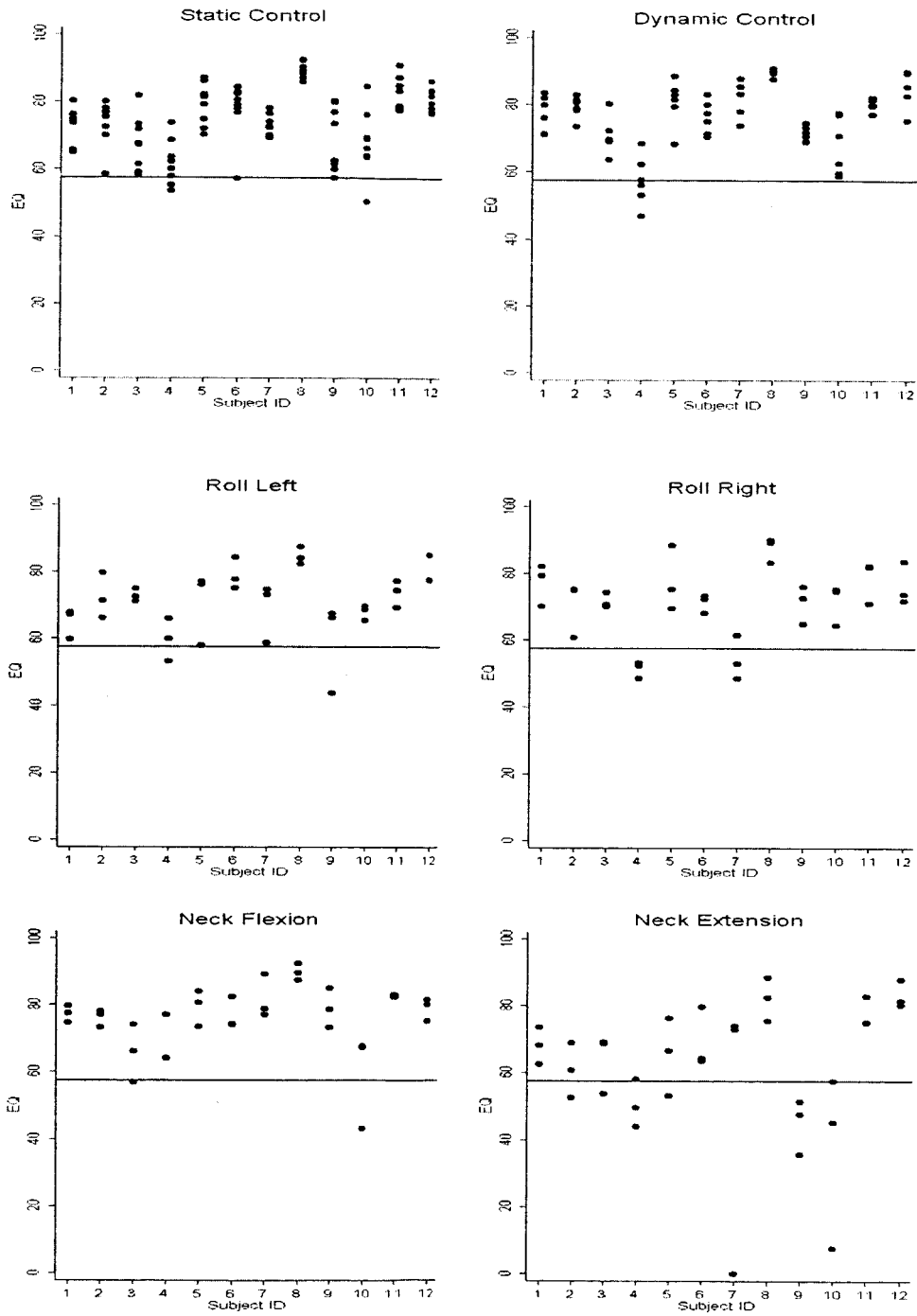
(A)
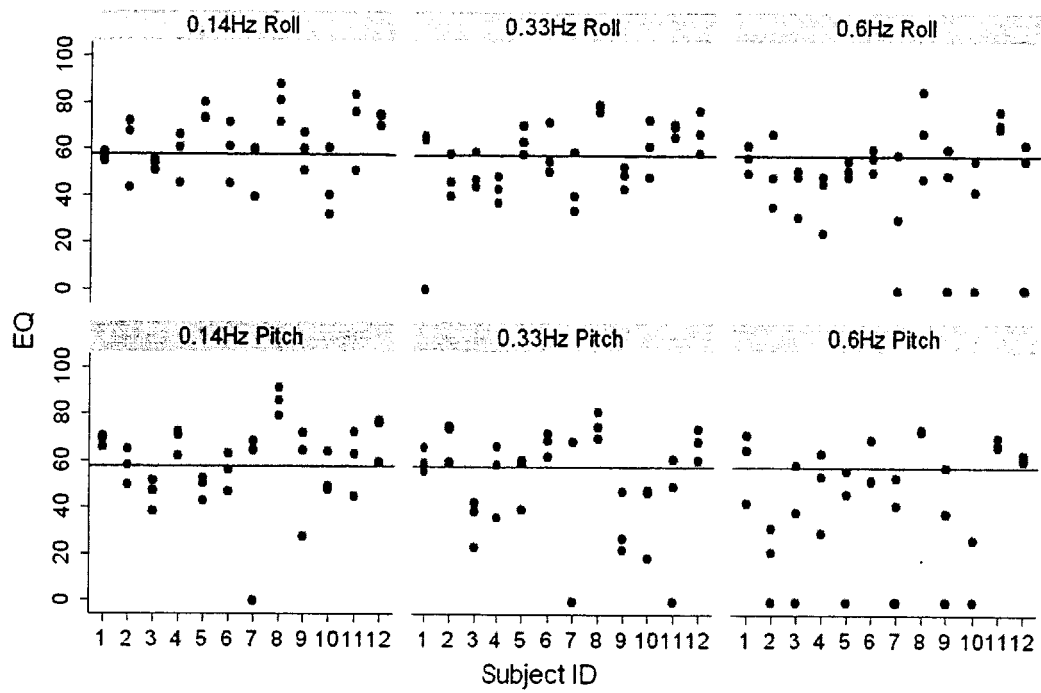
(B)

Figure 3.   Equilibrium scores for all 12 subjects and all trials. The horizontal

lines represent the 5th percentile score for standard SOT 5 trials.

(A) EQ scores for static tilt conditions, (B) EQ scores for dynamic
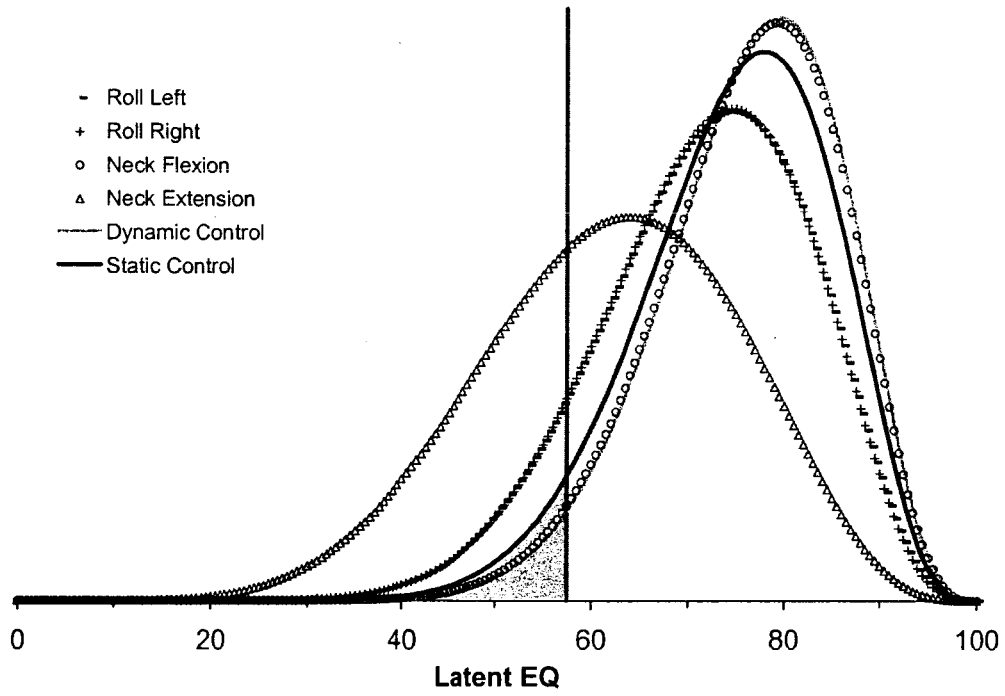
head movement conditions.

Figure 4.   Effects of static head tilts on latent EQ distribution.   Vertical line is

the 5th percentile latent EQ (= 57.5) for the static control condition.
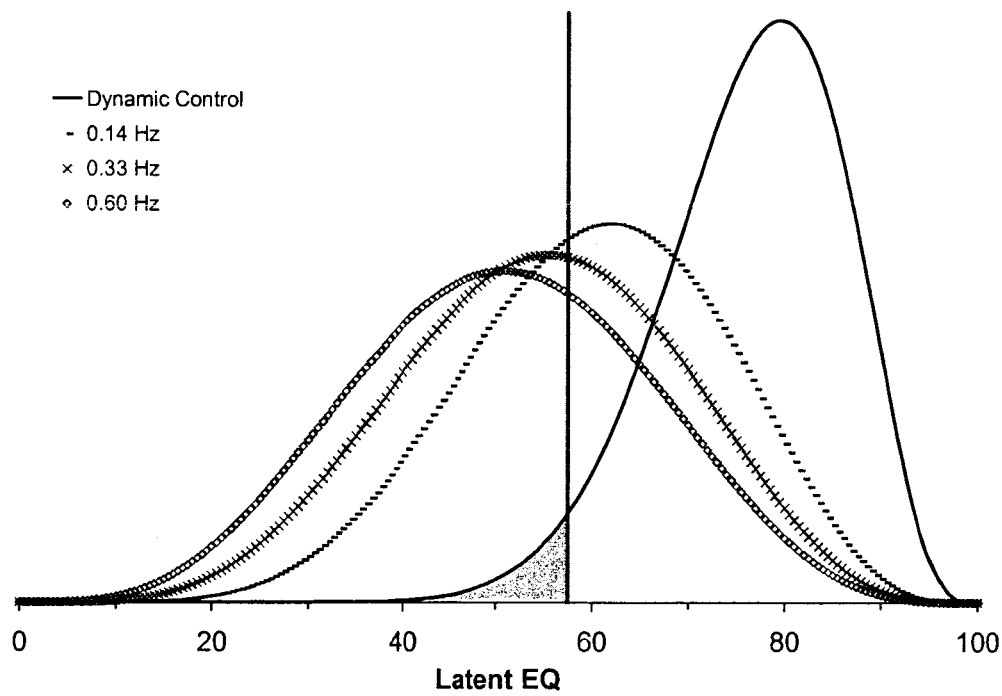
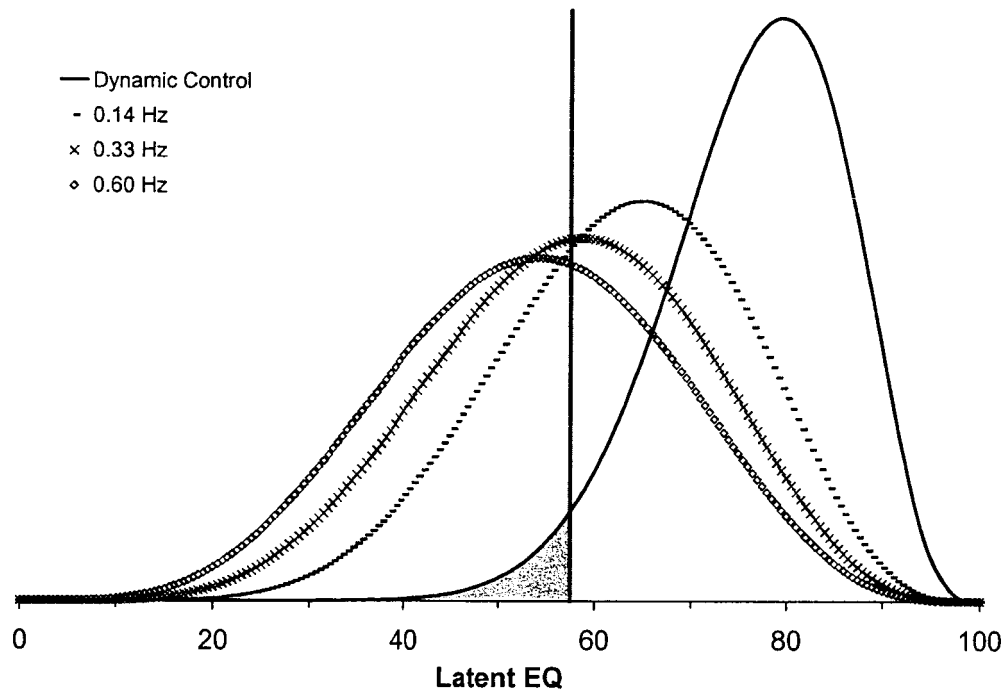Figure 5.   Effects of dynamic pitch plane head tilts on latent EQ distribution.

Figure 6.   Effects of dynamic roll plane head tilts on latent EQ distribution.
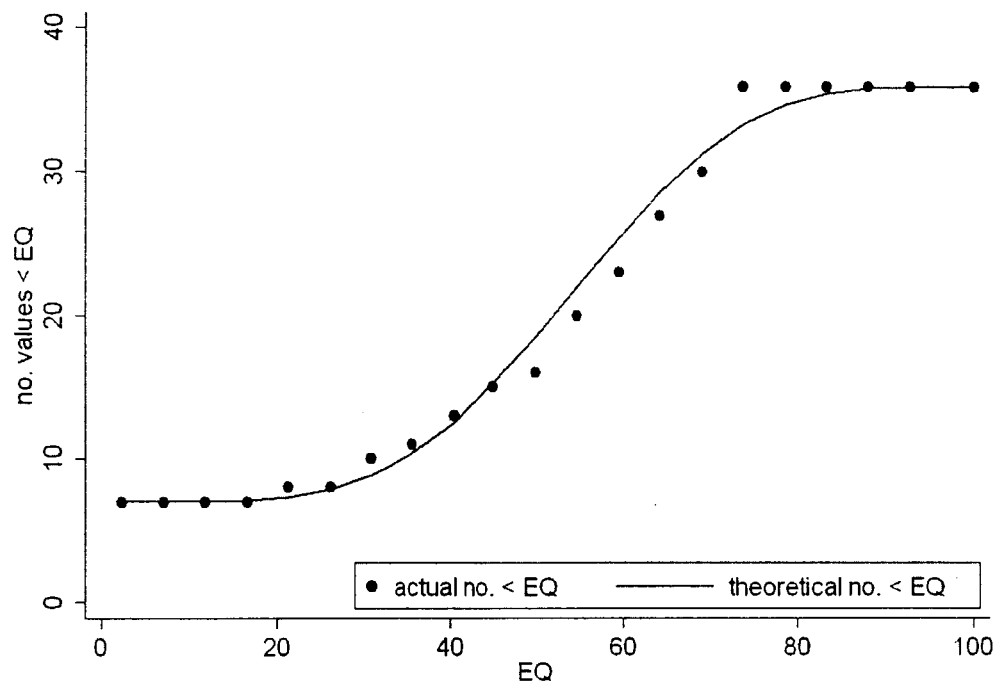
Figure 7. Goodness of fit for the statistical model for the most provocative

condition of dynamic pitch at 60 Hz (7 falls).

Table 1. Estimated percent area of latent EQ scores below 5th percentile (latent

EQ < 57.5).

| | | static | dynamic | | |
			0.14 Hz	0.33 Hz	0.60 Hz
pitch	flexion	3.4%	39.9% *	54.4% *,†	65.5% *,†
	extension	35.1% *			
roll	right	10.3%	32.4% *	47.1% *,†	59.2% *,†
	left	10.7%			

* distribution of EQ scores statistically different from nominal (standard SOT5), P < 0.001

† distribution of EQ scores statistically different than next lower frequency in same plane, P < 0.001