Recovery of Postural Equilibrium Control Following Space Flight

(DSO 605)

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BACKGROUND

Human sensory-motor systems have evolved to optimize coordinated body movements and posture control in the terrestrial gravitational field. The central nervous system (CNS) has developed neurosensory systems that monitor and process sensory inputs to assess the biomechanical state of the body (spatial orientation), and neuromotor systems that create, select, and issue motor commands to correct biomechanical state errors [1-3]. Neurosensory systems respond to the sudden loss of graviceptor (otolith) stimulation during spaceflight by remodeling the sensory information integration processes used to assess spatial orientation [4,5]. Also, neuromotor systems respond to the sudden loss of the static gravitational biomechanical load by modifying the repertoire of motor command strategies and synergies used for movement control [6]. These in-flight sensory-motor adaptations optimize neural control of movement in microgravity but, unfortunately, are maladaptive for the terrestrial gravitational field. Among the operationally relevant consequences of this maladaptation is a disruption in postural equilibrium control immediately after return to Earth [7].

Terrestrial posture control systems develop to maintain biomechanical stability during normal lifetime activities. Early in life the CNS learns to maintain stable control of the body center of mass during quiet stance, as well as in anticipation of, or in response to, postural disturbances created by voluntary movements or external disturbances. To accomplish this, the CNS uses inputs from visual, vestibular, proprioceptive, and somatosensory receptors to assess the current biomechanical state of the body [1]. This state feedback is used in conjunction with internal models of body kinematics and dynamics [2] to determine the spatial orientation and relative stability of the body. Also, based on these determinations, the CNS selects and commands the most appropriate motor control strategies and synergies to return the body to the desired equilibrium state [3, 8].

Sensory feedback is critical to posture control. Normally, the CNS continuously, and subconsciously, assesses the differences between the actual biomechanical state observed by the available sensory feedback systems and the desired biomechanical state generated by higher level brain centers. When the differences (errors) are small, closed loop control neuronal circuits may adjust the motor outputs to compensate. However, when the errors are large, an open loop control mode may be triggered. Based on previous experience as well as the magnitude, direction, and rate of change of the error state vector, the CNS selects a stereotyped response from its memorized repertoire. It then issues the set of motor commands encoded in this response memory, triggering predetermined muscles at predetermined latencies without regard for the concomitant sensory feedback. Following this open loop command volley, the CNS immediately resumes continuous assessment of the current biomechanical state.

Motor performance and biomechanics are also critical to posture control. Changes in muscle strength, muscle tone, or reflex activity, as well as changes in body mass distribution, intersegmental orientation, or support surface characteristics will alter both the kinematic and dynamic responses to a particular set of motor commands. During quiet stance, the continuous CNS adjustment of motor outputs generally compensates for moderate motor performance and biomechanical deficits. However, following sudden perturbations, the success of resulting motor command volleys in recovering postural equilibrium depends critically on motor performance and biomechanics.

During spaceflight, the continuous, omnipresent, Earth-vertical spatial reference that is normally provided by gravity and sensed by the otolith organs and other corporal graviceptors is absent. This causes incongruence between the expected and actual sensory afference resulting from body movements. This incongruence may lead to space motion sickness (SMS) [9], perceptual illusions, and malcoordination. When sustained, the incongruence may also drive central adaptive processes that result in new internal models of the reafferent signals expected from efferent motor commands. The new internal models have been described previously in terms of reinterpretation [4] or neglect [5] of gravity-mediated otolith inputs. The end result of this adaptation is that the CNS no longer seeks gravitational stimuli for use in estimating spatial orientation. While this may be advantageous for the amelioration

of SMS and is likely to optimize central neural control of coordinated body movements in the absence of gravity, it also appears to significantly disrupt control of coordinated body movements immediately after return to Earth [10]. Among the postflight effects of in-flight neurosensory adaptation to microgravity is the disruption of postural stability control, which has been demonstrated in both astronauts and cosmonauts following spaceflight [6, 7, 11-21]. The sustained absence of gravity also affects neuromotor components of the CNS. For instance, loss of gravity causes (1) weight unloading that triggers muscle disuse disturbances, (2) elimination of tonic antigravity muscle activation, (3) reduction of support reactions, and (4) changes in biomechanics characterized, for example, by altered relationships between the mass of, and the force required to move, a body segment [16].

Previous investigators in both the U.S. and Russian space programs have examined the characteristics and mechanisms of postflight postural ataxia. One class of investigations examined posture control by studying the abilities of crew members to maintain stable upright posture during quiet stance with normal and modified sensory feedback. The first such paradigm used in the U.S. program required astronauts to stand on narrow rails with their eyes either open or closed [12-14, 22, 23]. Results obtained using this paradigm demonstrated substantial postflight performance decrements during the eyes closed tests, with the magnitude of the postflight ataxia being greatest during the first postflight test. Recovery appeared to be related to mission length. Similar results were obtained early in the Russian program, where investigators used stabilogram recordings of (1) quiet standing with eyes open and eyes closed, (2) standing in the sharpened Romberg posture, and (3) standing with the head tilted either forward or backward [24-26]. Subsequent studies of postural stability during quiet stance before and after flight have employed more complex paradigms. For example, von Baumgarten et al. [27] required crew members to stand on an Earth-fixed stabilometer beneath a tilting room with eyes open, eyes closed, conflicting visual-vestibular input in which the room was tilted with a sinusoidal motion, and altered somatosensory input in which the subject stood on foam rubber placed atop the stabilometer. They found an increased reliance on visual feedback for posture control immediately after spaceflight, and impaired postural stability for up to 5 days after return to Earth.

Another class of postural investigations examined the abilities of crew members to recover stable upright posture following external perturbations of their upright stance. In the U.S. program, external postural perturbations were provided most frequently by moving the support surface upon which the subject stood. For example, Anderson et al. [11] used sudden stepwise translations of the support surface. They found that the segmental biomechanical responses were exaggerated, the latency of the initial soleus muscle electromyographical (EMG) response was increased, and the time required to achieve a new equilibrium position was greater after spaceflight than before. Kenyon and Young [14], using sudden stepwise pitch rotations of the support surface, found that the late (long loop) EMG response was higher in amplitude after flight than before. In the Russian space program, investigators have frequently used postural perturbations at the chest, rather than the base of support, to study ataxia after flight. For example, Grigoriev and Yegorov [28] studied postflight posture control in the three prime crew members of the long duration MIR-Quant expedition. When compared to preflight values, they found that on the 6th day after flight, less force was required to perturb posture, and both the time to recover from the perturbation and overall muscle activity following the perturbation increased. Similar changes were also reported in larger groups of subjects following other long duration missions, short duration missions, and microgravity simulation experiments [6, 15, 26, 29]. On the basis of these studies, the authors concluded that support unloading played an important role in the genesis of postural ataxia in short duration (up to 30 days) exposure to real and simulated microgravity. This was attributed to a reduction in afferent inflow from the support areas and the subsequent decline in antigravity (extensor) muscle tone, as well as to a hypersensitivity of the spinal reflex mechanisms. They suggested that, for longer duration hypogravity exposures, peripheral disorders, such as muscle hypotrophy, alterations of neuromuscular transfer functions, and alterations of muscle membrane properties were also important. Finally, they suggested that on long duration spaceflights, disturbances to the processes of reorganization of motor patterns occurred, and that recovery time depended strongly on mission duration.

Postflight postural equilibrium disturbances have important implications to the potential success of emergency egress from the Shuttle immediately after landing. Despite the fact that there appears to be a rapid initial readaptation to the terrestrial environment, subjective reports from crew members indicate that, at least in certain instances, it would have been difficult to egress from the vehicle soon after wheels stop. Previous findings that the microgravity adapted individual depends more heavily on visual system inputs for posture control suggest that the severity of the postflight ataxia would increase dramatically if the crew compartment were filled with smoke or darkened by malfunctioning lights. Under these circumstances, emergency egress would be difficult or impossible. These egress difficulties are likely to be further exacerbated by the 6-degree forward pitch attitude of the vehicle, should emergency egress be required on the runway following landing. This forward pitch could add to the disequilibrium by (1) shifting the apparent (visual) vertical within the vehicle from that surrounding the vehicle, and (2) shifting the visual vertical with respect to the

gravitational (otolith) vertical. Furthermore, these egress difficulties could also be increased by the perceptions of self-motion and/or surround-motion reported to be elicited by head movements during entry and immediately after flight [4, 30]. Finally, these difficulties might be further exacerbated by changes in effector characteristics such as muscle tone and strength, and by the de facto requirement that emergency egress be performed wearing a massive, bulky launch and entry suit (LES).

A number of studies have been performed to investigate the etiology and severity of postflight postural ataxia. The results from each of these studies are generally consistent with the hypotheses under investigation in Detailed Supplementary Objective (DSO) 605. However, the combination of small population size and lack of corroborating evidence in abnormal human subjects has left considerable doubt concerning the degree to which non-vestibular factors may account for the observed postflight ataxia. A small number of subjects tested is the main problem shared by all of the previous studies of posture control changes associated with spaceflight. Interpretation of the results of experiments on two to four subjects cannot be conclusive, particularly in light of the wide variations in demographic factors such as age, gender, flight experience, and mission duration that could potentially affect the results. Furthermore, development and/or evaluation of specific countermeasures to the untoward effects of in-flight sensory-motor adaptation can only be accomplished when the influence of these demographic factors is understood.

DSO 605 was designed to build on the results of previous studies of postflight postural ataxia and to extend these results by (1) examining the components of neurosensory control of posture with a more sensitive posturography technique than previously used, (2) systematically evaluating the total postflight recovery process, (3) controlling explicitly for previous spaceflight experience, and (4) studying enough subjects to draw statistically significant conclusions. The ultimate goals of this study were (1) to characterize the recovery process for postural equilibrium control in crew members returning from Shuttle missions, and (2) to validate the dynamic posturography system as a dependent measure for future evaluation of vestibular and/or sensory-motor countermeasures.

The long term objective of this investigation was to determine the underlying mechanisms contributing to postflight postural ataxia in astronauts participating in extended duration Orbiter spaceflight missions. It was expected that this knowledge would lead to insights that would guide the development of effective countermeasures to the effects of sensory-motor adaptation to spaceflight. The following hypotheses were tested:

1. In-flight loss of gravitational otolith stimulation, coupled with concomitant reductions in biomechanical constraints to body motion, lead to adaptive changes in the CNS that eliminate the use of gravity-mediated otolith information in estimating spatial orientation, and supplant it (partially) by increasing the weighting of visual spatial information. This will cause postflight reductions in the effectiveness of vestibular control of posture, while concomitantly increasing the dependence on visual inputs for posture control.

2. The effectiveness of posture control during quiet stance, and in response to stability threatening external disturbances, will be reduced early after spaceflight because of retention of in-flight sensory-motor adaptation. Both the magnitude and the recovery time of this postflight postural ataxia will increase with mission duration because of the increased time for in-flight sensory-motor adaptation to microgravity.

3. Repeated exposures to microgravity result in a training effect such that the magnitude and the recovery time course of postflight postural ataxia decrease with flight experience. Astronauts having previous spaceflight experience will exhibit less severe ataxia than those flying for the first time.

METHODS

Two experiment paradigms were performed by 40 crew members before, during, and after Shuttle missions of varying duration. The first of these paradigms focused primarily on neuromotor performance by quantifying the response to sudden, stability threatening base-of-support perturbations. The second paradigm focused on neurosensory performance by quantifying postural sway during quiet upright stance with normal, reduced, and altered sensory feedback. All participating subjects performed the two paradigms on at least three occasions before flight to provide an accurate, stable set of unit gravity control data from which postflight changes could be determined. All subjects also performed the two paradigms on up to five occasions after flight to capture the full sensory-motor readaptation time course. Postflight tests began on landing day, as soon after Orbiter wheels stop as possible, and were scheduled on an approximately logarithmic time scale over the subsequent 8 days (Table 5.4-1).

Of the 40 subjects studied: 11 were from short duration (4-7 day) missions, 18 from medium duration (8-10 day) missions, and 11 from long duration (11-16 day) missions. Seventeen of the subjects were first time (rookie) fliers, and 23 were experienced (veterans).

All testing was performed using a modified version of the Equitest computerized dynamic posturography system developed by Neurocom, International (Clackamas, OR, USA) for clinical assessment of disorders in balance control. The posturography system consisted of a computer controlled, motor driven dual foot plate capable of both rotational and translational movements, and a computer controlled, motor driven visual surround capable of

Table 5.4-1. DSO 605 experiment test schedule

Preflight (JSC/Bldg.37)

L-60 days (+/–5 days):	Crew Briefing and Control Session No. 1	60 min
L-30 days (+/–5 days):	Control Session No. 2	30 min
L-10 days (+/–2 days):	Control Session No. 3	30 min

Postflight-Early (KSC or DFRC)

R+1 hour (or sooner):	Study Session No. 1	30 min
R+3 hours (+/–1 hr):	Study Session No. 2	20 min

Postflight-Late (JSC/Bldg. 37)

R+48 hours (+/–6 hrs):	Study Session No. 3	30 min
R+96 hours (+/–12 hrs):	Study Session No. 4	30 min
R+8 days (+/–1 day):	Study Session No. 5	30 min

Key: L–n = n days before launch
R+n = n hrs (or days) after return
JSC = Johnson Space Center
KSC = Kennedy Space Center
DFRC = Dryden Flight Research Center

rotational movements about an axis colinear with the subject's ankles. Force transducers located beneath the dual foot plate were used to monitor and record the subject's weight distribution and reaction torques during testing. To improve the sensitivity of the posturography system, it was modified to monitor and record the EMG activity of various antigravity muscles as well as dynamic changes in sagittal plane hip position, shoulder position, and head angular velocity throughout the testing periods. Also, to eliminate auditory spatial orientation cues from external sources, the subject was required to don headphones, through which wide-band masking noise was provided.

Upon arrival at the test facility, the subject completed a pretest questionnaire designed to identify any uncontrolled factors that could potentially influence the test results. The subject's height was measured during the first preflight and postflight session. Prior to posture testing, the subject donned loose fitting short pants to facilitate EMG electrode placement and joint position monitoring. The skin surface at each EMG electrode site was prepared for placement of a pre-gelled disposable silver/silver chloride surface electrode, by shaving away any existing hair and scrubbing the region with an abrasive skin cleanser (Omni-Prep). Pairs of electrodes were attached to the skin surface above the medial gastrocnemius, tibialis anterior, hamstrings (primarily biceps femoris), and quadriceps (primarily rectus femoris) muscle groups. A single ground electrode was placed adjacent to the medial gastrocnemius pair. The impedance between each monitoring electrode and the ground reference electrode was then measured. If the electrode impedance was above 100 Kohms, the electrode was replaced. During electrode placement, the subject was briefly interviewed, on camera, to determine the sensations and perceptions experienced during landing, egress, and/or previous posture testing. Before the subject stepped onto the posture platform, the operator powered up the posturography system and zeroed any sensor offsets. The subject then donned a safety harness and mounted the platform. The operator next fastened the safety harness to the safety bar that looped over the subject's head, positioned the subject on the platform, and attached the body segment position measuring devices (sway bars). Finally, the subject donned headphones used to provide the masking noise and couple the angular rate sensors to the subject's head.

Each test session began with a set of motor control tests, during which the subject attempted to recover upright postural equilibrium as quickly as possible after support surface perturbations. These were (1) three sequential backward translation trials (≈ 5.7 cm during 400 msec), (2) five sequential toes-up rotation trials (8 degrees during 400 msec), (3) three sequential forward translation trials (≈ 5.7 cm during 400 msec), and (4) five sequential toes-down rotation trials (8 degrees during 400 msec). The duration of each trial was approximately 3 seconds, and the time between trials was usually less than 5 seconds. Support surface translations and rotations were applied automatically under computer control.

Immediately following the motor control tests, the test session proceeded with a set of sensory organization tests, during which the subject attempted to maintain upright balance control under the following conditions (1) eyes open, fixed support surface, (2) eyes closed, fixed support surface, (3) sway referenced vision, fixed support surface, (4) eyes open, sway referenced support surface, (5) eyes closed, sway referenced support surface, and (6) sway referenced vision, sway referenced support surface. Each of these conditions was repeated three times during the test session in random order. The duration of each trial was 20 seconds, and the time between trials was normally less than 5 seconds. Throughout the test period, the test operator controlled the execution of the test protocols at the posturography system computer rack, while standing near enough to the platform to steady the subject when disorientation or loss of balance occurred. The operator was required to depress a foot switch to execute the test procedures. When the posturography system detected that the subject had fallen (lost balance), it automatically interrupted the test procedure and waited for the operator's command to abort or continue the test. Following the sensory organization tests, the subject was deinstrumented and stepped down from the posture platform. EMG electrodes were then removed and the electrode sites cleaned with sterile alcohol pads. While the electrodes were being removed, the subject was again briefly interviewed on camera, to determine the sensations and perceptions experienced during landing, egress, and/or the posture testing.

The posturography system support surface comprised

two 23 by 46 cm foot plates, connected together by a pin joint and supported by four temperature compensated load cell force transducers symmetrically mounted on a supporting center plate. The four load cells independently sensed the anterior and posterior normal forces applied to the support surface by each foot. A fifth temperature compensated force transducer, mounted centrally between the support surface and supporting center plate, sensed shearing forces applied to the support surface in the antero-posterior direction. During each test, outputs from the five force transducers were amplified, digitized at 103 Hz, and stored electronically. Calibration of the force transducers was verified before each test using custom calibration fixtures.

The force plate data were combined algebraically to compute the instantaneous antero-posterior and medio-lateral coordinates of the center of pressure as a function of time. These center of pressure data were subsequently low pass filtered (-3 dB point at 1 Hz) to obtain an estimate of the center of gravity position as a function of time. The center of gravity was assumed to be located at 55% of the subject's height [31]. Its position was then converted geometrically to a center of gravity sway angle.

For the sensory organization tests, the peak to peak center of gravity sway angles (p-p sway) were determined for each 20 second trial. For some comparisons, the p-p sway data were used to compute a measure of postural stability known as the equilibrium score:

$$\text{Equilibrium Score} = \left[1 - \frac{\text{p-p sway}}{12.5}\right] \times 100$$

where 12.5 was the maximum stable sway amplitude expected in a normal population

The equilibrium score varied directly with postural stability. To provide an overall assessment of the subject's postural stability at each test session, a composite equilibrium score was computed by summing the average equilibrium scores from test 1 (eyes open, fixed support surface) and test 2 (eyes closed, fixed support surface) with the individual equilibrium scores from each trial of tests 3 to 6. The resulting equilibrium scores, scaled to 1000, were compared with a large normative database compiled by the posture platform system manufacturer [32].

Sagittal plane segmental body movements were monitored throughout each test using lightweight wooden sway bars attached to hooks mounted on the subject's posterior midline at the level of the greater trochanters and the seventh cervical vertebrae. The opposite end of each sway bar was attached to a potentiometer mounted on a column fixed to the base of the platform system. Sagittal plane hip and shoulder sway displacements, relative to an Earth-fixed spatial coordinate system, were determined through geometric manipulation of the outputs of the sway bar potentiometers. These outputs were digitized at 103 Hz

and stored electronically. Calibration of the hip and shoulder sway monitoring systems was verified before each test session using a custom calibration fixture. Head movements were also monitored throughout each test. Sagittal and frontal plane head angular velocities were sensed using angular rate sensors (Watson Model ARS-C241-1AR, Watson Industries, Inc., Eau Claire, WI) attached to the subject's headset. Rate sensor outputs were digitized at 103 Hz and stored electronically. Head angular positions were determined, relative to the starting position at each trial, by digital integration of the rate sensor data.

A link segment mathematical model [33] was developed and used for analyzing intersegmental coordination during the dynamic posturographic tests (Figure 1). Inputs to the model were the five time-varying segment angles, θ_i ($i = 1, 2, 3, 4$), measured using the sway bars and angular rate sensors. The knee angle was not monitored during these tests and was assumed to remain constant. Two other time-varying angles, θ_0^* and θ_3^*, oriented fixed angular distances from θ_0 and θ_3, respectively, indicated the locations of the centers of mass for the two non-axisymmetric segments of feet and torso/arms. θ_0^* was determined from anthropometric data tables, but θ_3^* was determined empirically. Outputs from the model included a number of kinematic and kinetic parameters commonly used to analyze postural biomechanics:

Joint Positions: By assigning the origin of the sagittal plane reference axes to the ankle joint, and assuming that the heels and toes always remain in contact with the support surface, the instantaneous horizontal (x_{j_i}) and vertical (y_{j_i}) positions of the ankle, knee, hip, and cervico-thoracic joints, as well as the location of a fictive joint at the bottom of the foot (the point on the support surface closest to the ankle joint), were computed at each sampled data point ($k = 1, 2, …, n$) from:

$$x_j(k) = L\cos\theta(k)$$
$$y_j(k) = L\sin\theta(k).$$

Center of Mass Positions: The instantaneous locations of the segment centers of mass (x_{cm_i}, y_{cm_i}) were computed from:

$$x_{cm}(k) = D\cos\theta(k)$$
$$y_{cm}(k) = D\sin\theta(k).$$

Center of Mass Accelerations: From the second derivatives of the center of mass position equations:

$$\ddot{x}_{cm}(k) = -D\left[\alpha(k)\sin\theta(k) + \omega^2(k)\cos\theta(k)\right]$$
$$\ddot{y}_{cm}(k) = -D\left[\alpha(k)\cos\theta(k) - \omega^2(k)\sin\theta(k)\right].$$

Center of Gravity: The instantaneous antero-posterior position of the center of gravity (CG), which is the vertical projection of the whole body center of mass

position, was computed from:

$$CG(k) = \frac{1}{M} mx_{cm}(k).$$

Joint Forces: The total horizontal (F_{x_i}) and vertical (F_{y_i}) forces acting at the foot support surface interface ($i = 0$) as well as at the ankle, knee, hip, and cervico-thoracic joints ($i = 1, 2, 3, 4$), were computed from:

$$F_x(k) = M\ddot{x}_{cm}(k)$$
$$F_y(k) = M[\ddot{y}_{cm}(k) + g].$$

Ground Reaction Forces: The normal (F_n) and shear (F_s) components of the ground reaction force were computed from:

$$F_n(k) = F_{y_0}(k) \cos \theta_0(k) - F_{x_0}(k) \sin \theta_0(k)$$
$$F_s(k) = F_{x_0}(k) \cos \theta_0(k) + F_{y_0}(k) \sin \theta_0(k).$$

Joint Torques: The net torques (T_i) acting about each joint, including the fictive joint at the support surface, were computed from:

$$T(k) = J\ddot{\theta}(k) - \Delta_y(k)F_x(k) + \Delta_x(k)F_y(k).$$

Center of Pressure: The center of pressure was computed from the support surface torque by:

$$CP(k) = \frac{T_0(k)}{F_n(k)}.$$

The segmental and whole body kinematic data were also analyzed to determine what, if any, stereotypical movement patterns were employed during the execution of each task, and how these patterns were affected by adaptation to microgravity and readaptation to Earth. In particular, ankle and hip whole body sway strategies [34], and stable platform and strapped down head-trunk segmental strategies [21, 35] were sought. Temporal sequences demonstrating recovery of the p-p sway and equilibrium score measurements were created from the postflight test sessions. These sequences were then fit to multiexponential readaptation models using the Levenberg-Marquardt nonlinear least squares technique [18, 36].

EMG activities of the primary postural muscles on the left side of the body were monitored using surface electrodes to establish motor reaction times and temporal activation patterns associated with specific motor synergies/strategies. EMG potentials sensed by these electrodes were band-pass filtered (-3 dB points at 1 Hz and 100 Hz) and amplified (2000 v/v) using Grass Model 7P511 AC Preamplifiers. These processed analog signals were then digitized at 412 Hz and stored electronically.

Sensory organization test data were analyzed using the StatView and SuperANOVA statistical analysis software packages (both from Abacus Concepts, Inc., Berkeley, CA). Differences in p-p sway amplitude between the preflight and postflight test sessions were investigated using repeated measures analysis of variance (ANOVA) for each balance control test. The roles of the visual, proprioceptive, and vestibular sensory systems in balance control were assessed using a one-between (rookies, veterans), three-within (vision, proprioception, vestibular, i.e., spaceflight), full-interaction ANOVA model with specific contrasts. To meet the equal variance assumption of the ANOVA model, p-p sway amplitude data were subjected to natural logarithmic transformation prior to analysis. Anti-transforming the results of these analyses resulted in standard errors that were asymmetric about the mean. Differences in p-p sway amplitude between the mission position groups were investigated using analysis of covariance (ANCOVA) for each test condition. Postflight values were used as the dependent variable; rookie or veteran status was used as a group factor; and preflight values were used as the covariable. Use of ANCOVA with preflight values as the covariable permitted comparison of postflight means for the two groups that were independent of preflight values.

The effects of the continuous demographic variables (height, weight, and mission duration) were assessed using multiple regression analyses to determine whether any relationships existed between the demographic variables and the changes in p-p sway amplitude associated with spaceflight. For each test condition, the dependent parameter was the postflight p-p sway amplitude. The independent parameters were the preflight p-p sway amplitude and the demographic parameter of interest. Probabilities were adjusted, when necessary, to the greater of the values obtained from the Huynh and Feldt [37] and the Geisser and Greenhouse [38] corrections for violations of assumptions of the repeated measures ANOVA model. Null hypotheses were rejected when the adjusted probabilities were less than 0.05.

RESULTS AND DISCUSSION

Inability to Use Vestibular Information Following Spaceflight

Sensory organization test results from 34 crew members summarized in Tables 5.4-2 and 3, and in Figures 5.4-2 through 7 and 10, are in review for publication [7].

Typical Subject: Preflight and postflight antero-posterior (a-p) center of gravity sway time series traces for a typical subject for each of the six test conditions are presented in Figure 5.4-2. Each of the traces in this figure represent subject response to a different set of sensory orientation reference conditions. The lower center and lower

Table 5.4-2. Subject demographic information

Subject	Age, yrs	Height, cm	Weight, kg	Flt No.	Length, days	L–2, days	L–1, days	R+0, hrs
Mean	41.4	180.0	78.4	1.9	9.11	-45.0	-14.1	2.72
SEM	0.84	1.08	1.77	0.16	0.55	3.83	0.78	0.13
Min	32	165	48	1	4.09	-111	-25	1.62
Max	50	191	99	4	16.63	-22	-7	4.50

Key: Flt No.   = subject flight number (1 = first-time flier, 2 = second-time flier, etc.)
     Length   = mission duration
     L–2, L–1 = time before launch of preflight data collections
     R+0   = time after landing (wheel stop) of initial postflight data collection

right panels represent responses to test conditions during which vestibular inputs provided the only theoretically accurate sensory feedback. All other test conditions provided the subject with fully or partially redundant sensory orientation information from the visual, vestibular, and/or proprioceptive systems.

Before flight (Figure 5.4-2, "pre" traces), changes in visual cues had little effect on this subject's a-p sway amplitude when the proprioceptive cues were left intact, as shown in the upper row-fixed support surface. When the proprioceptive inputs were altered, as shown in the lower row-sway referenced support surface, the subject's a-p sway amplitude increased for all visual conditions. The greatest increases occurred when visual cues were either absent (eyes closed) or simultaneously sway referenced, forcing the subject to rely on vestibular inputs as the only veridical spatial orientation reference cues.

Immediately after spaceflight (Figure 5.4-2, "post" traces), the subject's a-p sway amplitude increased under all test conditions when compared to preflight values. The increased amplitudes observed under sway referenced support conditions (lower row) were balance threatening. When both visual and proprioceptive cues were sway referenced, this subject's center of gravity oscillated between his/her forward and backward stability limits.

Stabilograms corresponding to each of the time series traces in Figure 5.4-2 are shown in Figure 5.4-3. The stabilograms demonstrate that, in addition to the increased a-p sway amplitudes, the subject's mediolateral (m-l) sway amplitudes were also increased on each test condition after flight. The increased center of gravity sway was relatively symmetric about the equilibrium point during tests 1 and 2 (upper left and upper center). However, under the other four test conditions, the a-p sway amplitudes were clearly larger than the m-l sway amplitudes.

Sensory Test Performances: Landing day data were obtained, in all six sensory organization test conditions, for 34 of the 40 subjects (Table 5.4-2). Cumulative distribution functions for the average p-p sway amplitudes observed in these 34 subjects before and after spaceflight, under each of the six sensory organization test conditions, are presented in Figure 5.4-4. These population data are qualitatively similar to the single subject sway data presented above. Note that, with the possible exception of the most stable performers on tests 1 and 2 (Figure 5.4-4, upper left and upper center panels), the entire cumulative distribution function for each test condition was shifted to the right, toward higher center of gravity sway, and lower postural stability, values. Furthermore, the preflight and postflight sways were significantly correlated in all but test 2. The correlation coefficients ranged from 0.51 to 0.65 (Table 5.4-3).

Compared to preflight, significant sway amplitude increases were observed early after flight (2.72 ± 0.13 hrs) in all six test conditions. The mean and standard error values for these data are presented in Table 5.4-3 and plotted in Figure 5.4-5. Under the standard Romberg conditions (Table 5.4-3, tests 1 and 2), the sway amplitude increased by only 0.27 degrees (35%) with eyes open and 0.35 degrees (25%) with eyes closed. Under sensory conflict conditions, the sway amplitude increased by 0.60 degrees (60%) when the visual surround was sway referenced (test 3), by 0.94 degrees (69%) when the support surface was sway referenced and eyes were open (test 4), by 1.97 degrees (63%) when the support surface was sway referenced and eyes were closed (test 5), and by 3.12 degrees (104%) when both the visual surround and the support surface were sway referenced (test 6). While the sway was increased on all sensory organization tests after flight, the increased sway was only stability threatening under the postflight conditions during which vestibular inputs provided the only theoretically accurate sensory feedback (tests 5 and 6).

Sensory Analyses: Data from all preflight and postflight sensory organization test conditions were fit to a single ANOVA model to determine the interdependent relationships between sensory inputs in the control of postural stability (p-p sway amplitude). Significant alterations in the main effects of visual, proprioceptive, and vestibular

Table 5.4-3. Preflight and postflight data for the six experiment test conditions

Test No.	Visual Cues	Somatosensory Cues	Preflight Sway, deg		R+0 Sway, deg		r
			Mean	SEM	Mean	SEM	
1	normal	normal	0.76	+0.05/–0.04	1.03	+0.07/–0.07	0.56
2	absent	normal	1.37	+0.08/–0.07	1.72	+0.13/–0.12	ns
3	sway-referenced	normal	1.00	+0.07/–0.06	1.60	+0.11/–0.10	0.51
4	normal	sway-referenced	1.36	+0.09/–0.09	2.30	+0.15/–0.14	0.65
5	absent	sway-referenced	3.12	+0.16/–0.15	5.09	+0.32/–0.30	0.59
6	sway-referenced	sway-referenced	3.00	+0.23/–0.21	6.12	+0.38/–0.36	0.51

The columns labeled Preflight Sway present the means and standard errors of the average p-p sway amplitude observed in the 34 astronaut subjects during preflight and landing day testing. Standard errors are not symmetric about the means because the statistical analysis was performed on the data after natural logarithmic transformation. All landing day (R+0) means were found to be significantly higher than preflight means for the same test condition. Column r presents the correlation coefficients obtained between the Preflight and R+0 data. (ns = not significant) (reprinted from 7)

system contributions to balance control were demonstrated (Figure 5.4-6). For all subjects and test sessions combined, altering visual cues (Figure 5.4-6a) approximately doubled sway amplitude, from 1.31 degrees with eyes open to 2.61 degrees with eyes closed, or 2.49 degrees with vision sway referenced ($F = 295$, $df = 2, 64$, $p < 0.0001$). There was no significant difference between the eyes closed condition and the sway referenced vision condition. Mechanically altering proprioceptive cues (Figure 5.4-6b) nearly tripled sway amplitude, from 1.24 degrees with a fixed support surface to 3.25 degrees with a sway referenced support surface ($F = 924$, $df = 1, 32$, $p < 0.0001$). Altering vestibular inputs (Figure 5.4-6c) by 4 to17 days adaptation to microgravity increased sway amplitude by 60%, from 1.61 degrees before flight to 2.56 degrees after flight ($F = 156$, $df = 1, 32$, $p < 0.0001$).

Significant interactions were also observed among the independent variables between the main effects (Figure 5.4-7). For instance, the effects of altering visual cues were exaggerated by simultaneously altering proprioceptive cues ($F = 77.8$, $df = 2, 64$, $p < 0.0001$) (Figure 5.4-7a) and/or vestibular system contributions ($F = 10.3$, $df = 2, 64$, $p < 0.0001$) (Figure 5.4-7b). Also, the effects of altering proprioceptive cues were exaggerated by simultaneously altering vestibular system contributions ($F = 20.7$, $df = 1, 32$, $p < 0.0001$) (Figure 5.4-7c).

Time Course of Recovery of Postural Equilibrium Control Following Spaceflight

Data presented in Figure 5.4-8, obtained from13 DSO 605 crew member subjects aboard six separate Shuttle missions ranging from 4 to 10 days in duration, were previously published [18]. Normalized composite equilibrium data from the 10 subjects having landing day measurement sessions were qualitatively similar. Compared

to their preflight measurements, which were usually above the 80th percentile scores for a normative population, every subject exhibited a substantial decrease in postural stability on landing day. Four of the 10 had clinically abnormal scores, being below the normative population 5th percentile. All subjects reported similar subjective feelings of rapidly increasing stability (initial readaptation) that were corroborated quantitatively in each of the four subjects studied twice on landing day. Although there was some variability in the time required, preflight stability levels were reachieved in all subjects by 8 days after wheels stop.

Based on these results, postflight readaptation was modeled as a double exponential process (Figure 5.4-8). Normalized composite equilibrium score data were fit to this model using the Levenberg-Marquardt nonlinear least squares technique [36]. The results of this exercise demonstrated that (1) at wheels stop, the average returning crew member was below the limit of clinical normality, (2) the initial rapid phase of readaptation had a time constant on the order of 2.7 hrs and accounted for about 50% of the postural instability, and (3) the slower secondary phase of readaptation had a time constant on the order of 100 hrs and also accounted for about 50% of the postural instability.

Head-Trunk Coordination Strategies Following Spaceflight

Motor control test results from 28 astronauts aboard 14 separate Shuttle missions of 4 to 10 days in duration were analyzed. The hypothesis that postflight postural biomechanics are affected by adopted strategies aimed at minimizing head movements was investigated to better understand the mechanisms underlying postflight postural ataxia. Subjects were exposed to three sequential sudden support surface translations in the posterior direction

before flight. Ground reaction forces and segmental body motions were monitored and used to compute sagittal plane center of pressure and sway trajectories [33]. Sway responses to translational perturbations were exaggerated on R+0 compared to preflight. The center of force and hip sway trajectories were generally more labile, or under-damped, on R+0 than before flight (Figure 5.4-9), and the learning associated with successive sequential perturbations disappeared in some subjects after flight. In some subjects, head movements were exaggerated on R+0; however, in other subjects, head movements were substantially reduced compared to preflight. Under these circumstances, hip sway was generally found to be increased while shoulder sway and/or head movement in space were found to be decreased compared to preflight. The strap down and stable platform head trunk coordination strategies postulated by Nashner [35] were often observed after flight, but rarely observed before flight. The biomechanical changes appeared to follow recovery trajectories similar to those found in the sensory test performance measurements, with preflight patterns returning by R+4 or R+8 days. We conclude that postflight postural instabilities resulted in part from new constraints on biomechanical movement caused by the CNS adopting strategies designed to minimize head movement.

Effects of Previous Spaceflight Experience

Comparisons of performances on sensory organization tests between the rookie and veteran groups demonstrate significant differences between subjects having previous spaceflight experience and those having none (Figure 5.4-10). Preflight performances were statistically indistinguishable between these groups on every sensory organization test. Similarly, postflight performances on tests 1, 2, 3, and 4 were not different between rookies and veterans. On the postflight conditions in which vestibular inputs provided the only theoretically accurate sensory feedback (tests 5 and 6), however, rookies exhibited significantly higher (p=0.02) sway than veterans.

These observations demonstrate that experienced space travelers were better able to use vestibular information immediately after flight than first time fliers. Since experienced astronauts had previously made the transitions between unit gravity and microgravity, they may have been partially dual-adapted and able to more readily transition from one set of internal models to the other. The fact that no differences were observed between rookies and veterans on tests 1 through 4 further supports our assertion that altered processing of vestibular system inputs is the primary mechanism of postflight postural ataxia.

Effects of Mission Duration and Demographic Factors

Postflight p-p sway amplitude was not significantly affected by mission duration, subject height, or subject weight for any test condition. There were weak, but not significant relationships between postflight sway amplitude and age on test 3 (slope = –0.04 deg/yr, p = 0.04, r^2 = 0.31) and test 6 (slope = –0.19 deg/yr, p = 0.006, r^2 = 0.41), in which vision was sway referenced with and without accurate proprioceptive cues. As there were only two female crew members studied, no gender effects could be examined.

A significant effect of mission position was found only for test 6 (sway referenced vision and support surface; F = 4.7, df = 2, 30, p < 0.02). Mission commanders had the most stable landing day performances on this test condition (mean ± sem = 4.9 ± 0.61 deg), followed by mission specialists (mean ± sem = 6.3 ± 0.44 deg), and mission pilots (mean ± sem. = 7.4 ± 0.55 deg). The number of payload specialists studied was too small to allow their inclusion in this analysis.

CONCLUSION

DSO 605 represents the first large n study of balance control following spaceflight. Data collected during DSO 605 confirm the theory that postural ataxia following short duration spaceflight is of vestibular origin. We used the computerized dynamic posturography technique developed by Nashner et al. [39] to study the role of the vestibular system in balance control in astronauts during quiet stance before and after spaceflight. Our results demonstrate unequivocally that balance control is disrupted in all astronauts immediately after return from space. The most severely affected returning crew members performed in the same way as vestibular deficient patients exposed to this test battery. We conclude that otolith mediated spatial reference provided by the terrestrial gravitational force vector is not used by the astronauts' balance control systems immediately after spaceflight.

Because the postflight ataxia appears to be mediated primarily by CNS adaptation to the altered vestibular inputs caused by loss of gravitational stimulation, we believe that intermittent periods of exposure to artificial gravity may provide an effective in-flight countermeasure. Specifically, we propose that in-flight centrifugation will allow crew members to retain their terrestrial sensory-motor adapted states while simultaneously developing microgravity adapted states. The dual-adapted astronaut should be able to make the transition from microgravity to unit gravity with minimal sensory-motor effects. We have begun a ground based program aimed at developing short arm centrifuge prescriptions designed to optimize adaptation to altered gravitational environments. Results from these experiments are expected to lead directly to in-flight evaluation of the proposed centrifuge countermeasure.

Because our computerized dynamic posturography system was able to (1) quantify the postflight postural ataxia reported by crew members and observed by flight surgeons

and scientists, (2) track the recovery of normal (preflight) balance control, (3) differentiate between rookie and veteran subjects, and (4) provide normative and clinical databases for comparison, and because our study successfully characterized postflight balance control recovery in a large cross-section of Shuttle crew members, we recommend that this system and protocol be adopted as a standard dependent measure for evaluating the efficacy of countermeasures and/or evaluating the postflight effects of changing mission durations or activities.

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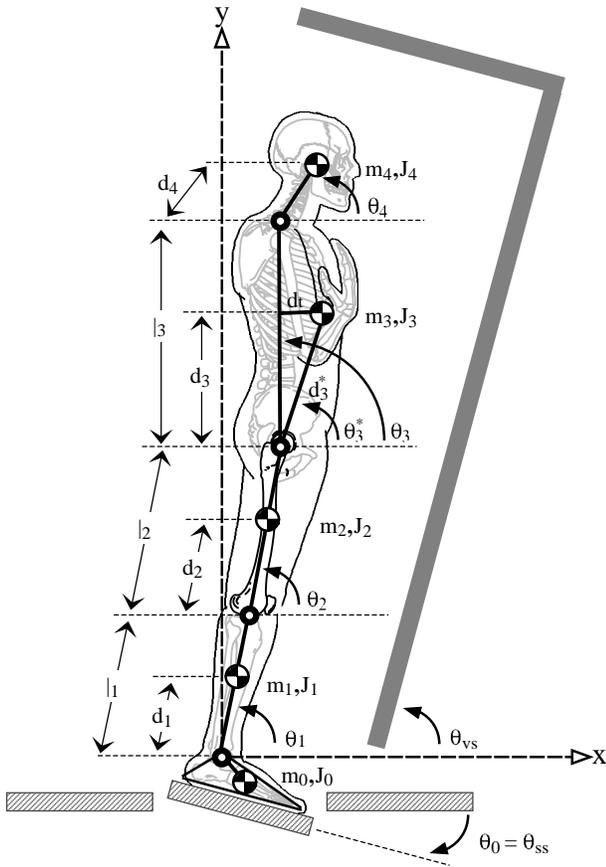
Figure 5.4-1. Link segment biomedical model.
Lengths, angles, masses, etc. are defined
in the text. (reprinted from 33)
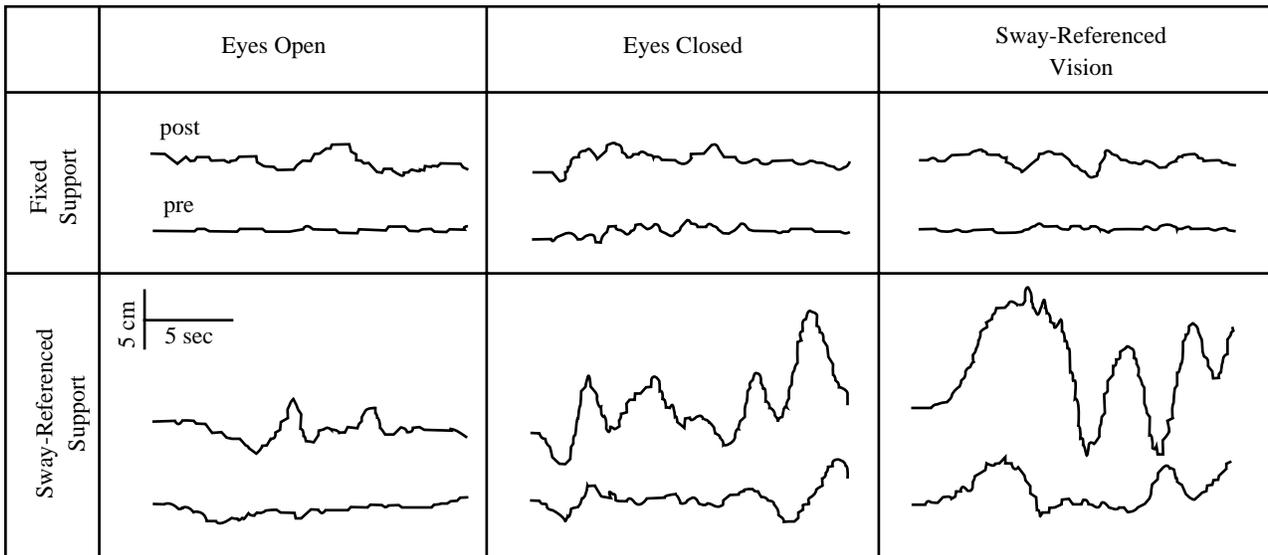
Figure 5.4-2. Preflight and postflight antero-posterior (a-p) center of gravity sway time series traces for each of the
six sensory organization test conditions for a typical subject. Each column in this figure represents a different visual
condition. Each row represents a different proprioceptive (support surface) condition. The two traces in each panel
represent different vestibular conditions. The lower traces (pre) represent the preflight performances and the upper
traces (post) represent the postflight performances. (reprinted from 7)
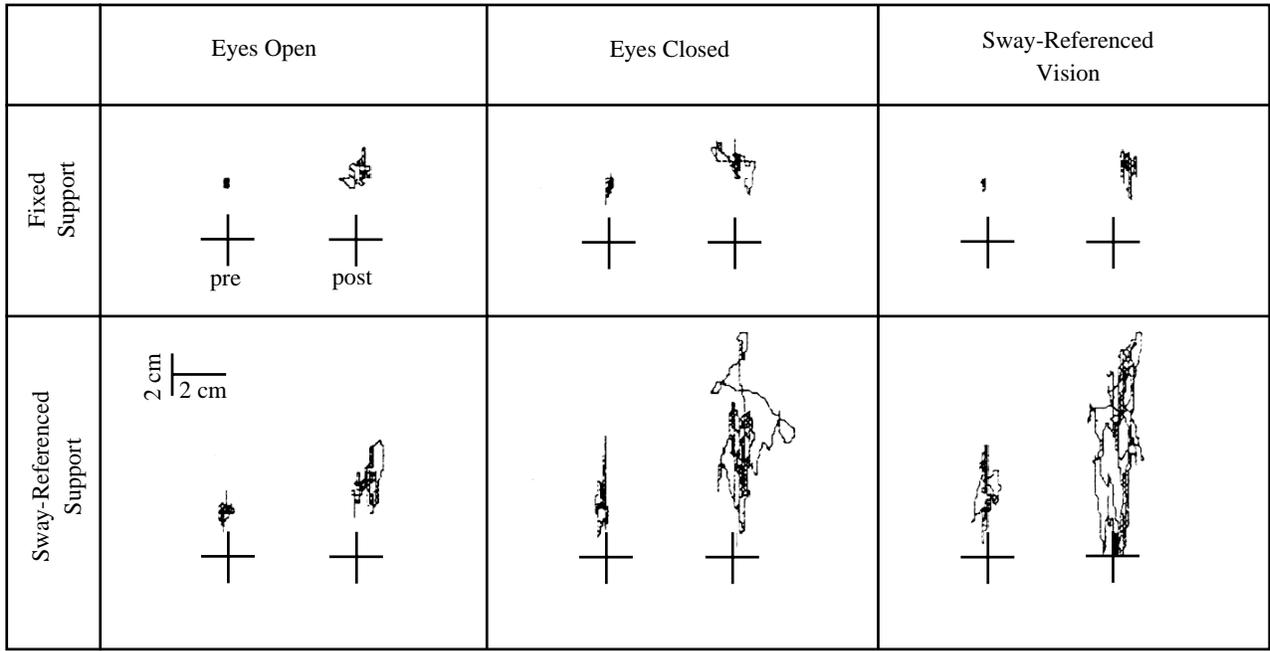
Figure 5.4-3. Preflight and postflight stabilograms corresponding to the a-p center of gravity sway traces of figure 5.4-2. Panel arangement is similar to figure 5.4-2. Antero-posterior (body x-axis) sway is plotted on the ordinate, with the top of the plot representing the body forward direction. Medio-lateral (body y-axis) sway is plotted on the abscissa, with the right of the plot representing the body rightward direction. The cross in each plot represents the location midway between the subject's right and left medial malleoli.
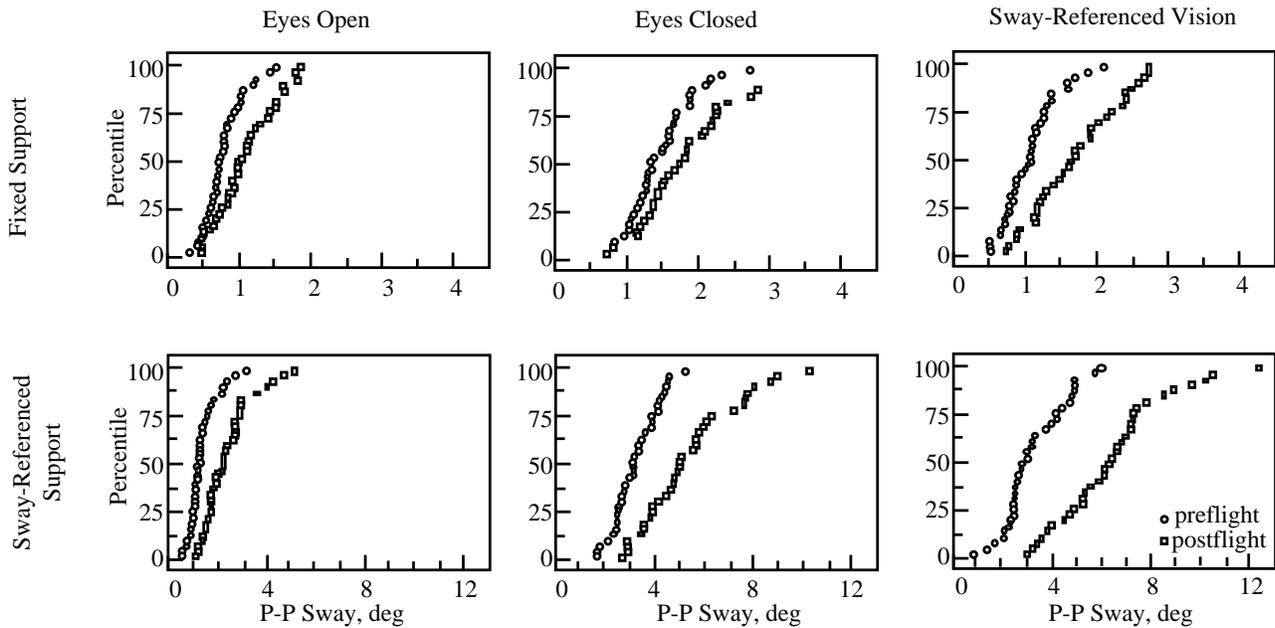
Figure 5.4-4. Preflight (circles) and postflight (squares) cumulative distribution functions of the peak to peak (p-p) a-p center of gravity sway for the 34 subjects of each of the six sensory organization test conditions. Panel arrangement is similar to figure 5.4-2. Note difference in abscissa scaling between fixed support surface conditions and sway referenced support surface conditions. (reprinted from 7)
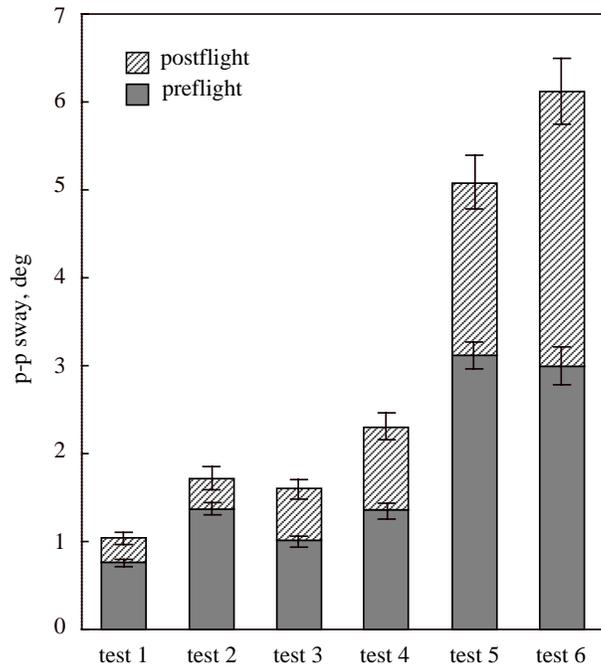
Figure 5.4-5. Mean (± s.e.m.) p-p a-p center of gravity sway for each of the six sensory organization tests preflight and postflight. Sway was significantly increased on every test after flight. (reprinted from 7)
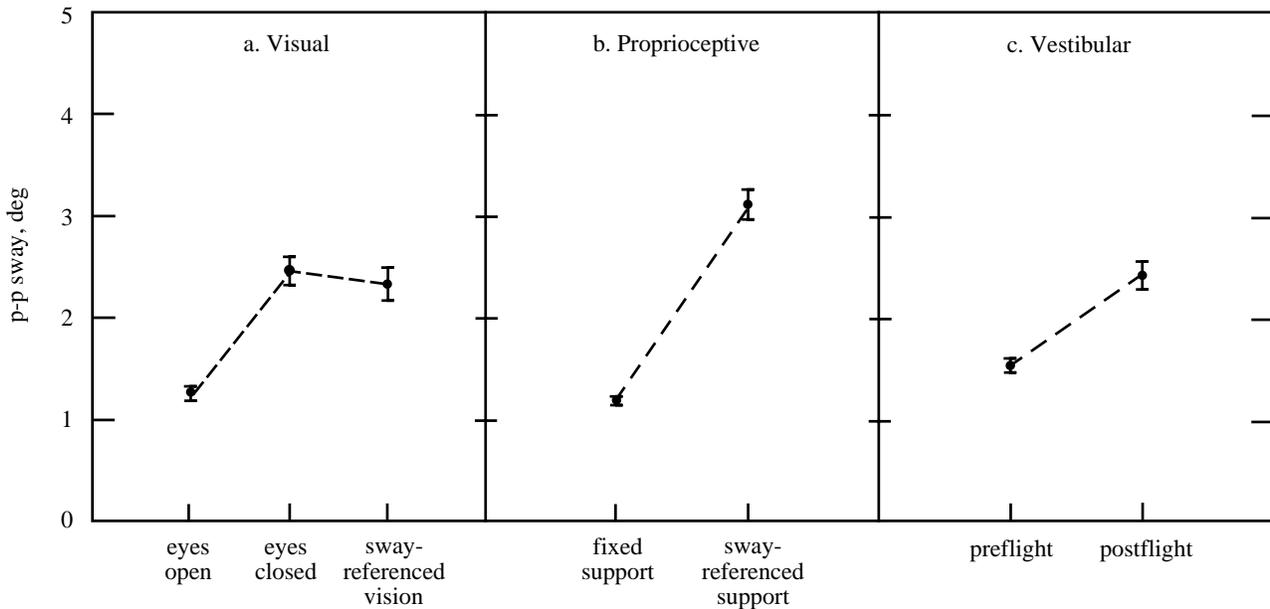
Figure 5.4-6. Mean (± s.e.m.) p-p a-p center of gravity sway data demonstrating the independent roles of sensory inputs to balance control. a. Sway was significantly increased when visual inputs were either absent (eyes closed) or sway referenced. Sway with absent vision was statistically indistinguishable from that with vision sway referenced. b. Sway was significantly increased when proprioceptive inputs were sway referenced. c. Sway was significantly increased when vestibular inputs were disrupted by adaptation to microgravity during space flight.
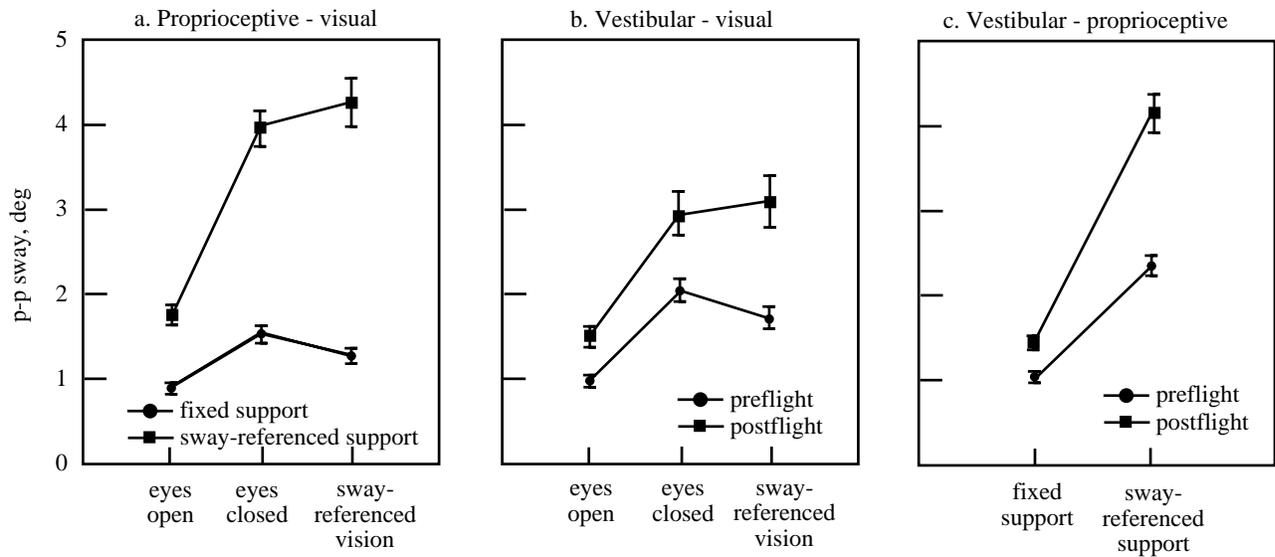
Figure 5.4-7. Mean (± s.e.m.) p-p a-p center of gravity sway data demonstrating the interactions among the independent variables between the main effects. a. The destabilizing effects of altering visual cues were significantly increased by simultaneously altering proprioceptive cues. b. The destabilizing effects of altering visual cues were also significantly increased by simultaneously altering vestibular cues. c. The destabilizing effects of altering proprioceptive cues were significantly increased by simultaneously altering vestibular cues.
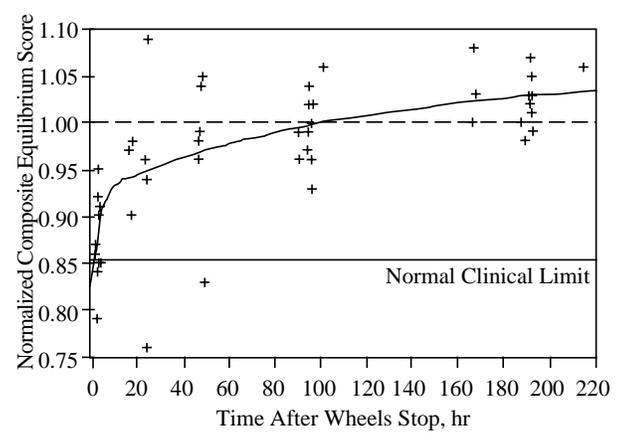
Figure 5.4-8. Model of postflight balance control recovery dynamics. (reprinted from 18)