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Multivariate changes in coordination of postural control following spaceflight

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Abstract

Postural and gait instabilities in astronauts returning from spaceflight are thought to result from in-flight adaptation of central nervous system processing of sensory inputs from the vestibular, proprioceptive, and visual systems. We hypothesized that reorganization of posture control relying on these multiple inputs would result in not only greater amounts of sway, but also changes in interjoint coordination. We tested this hypothesis by examining the multivariate characteristics of postural sway and comparing the postural control gain used for maintenance of upright stance during the altered sensory conditions of the Sensory Organization Test (EquiTest, Neurocom Intl.). We used the covariance of hip and ankle kinematics as a measure of joint motion and interjoint coordination, and then utilized discriminant analysis to further examine these characteristics in a group of 10 first-time astronauts. In five of the six conditions, the most important difference was an increased relative utilization of the hip strategy, which would not be evident using conventional balance measures such as peak or root-mean-square sway. This finding was supported by indications of increased hip torque gains relative to lower extremity and neck motion in at least four conditions ($p < 0.05$). In contrast, ankle torque gains to these motions did not appear to change. These results suggest that after spaceflight, astronauts exhibit significant multivariate changes in multijoint coordination, of which increased sway is only one component. These changes are consistent with reweighting of vestibular inputs and changes in control strategy in a multivariable control system.

Keywords: Posture; Balance; Joint coordination; Multivariate analysis; Spaceflight; Spatial orientation; Sensory Organization Test

1. Introduction

Conventional measures of postural sway, such as root-mean-square (rms) motion of the center of mass or center of pressure, are univariate in the sense that they provide single quantities summarizing overall motion of the body. The multijoint dynamics of the human body and the difficulty of simultaneously controlling these joints would suggest that in addition to stabilizing the center of mass, the central nervous system is confronted with the problem of coordinating the joints. We propose that sway is actually a multivariate response, involving multiple joints and multiple sensors (Kuo et al., 1998). A loss of one or more sensors then implies not only an increase in sway, but also an alteration in joint coordination. By examining the multivariate response, we can characterize postural sway more specifically and gain clues about the nature or cause of a balance problem such as postural instability following spaceflight.

Astronauts display a variety of postural difficulties upon returning to earth, including an inability to maintain a stable posture with eyes closed, using a wide stance to stand and walk, feeling sensations of lateral acceleration while walking, and an inability to detect small changes in head position (Kenyon and Young, 1986). One explanation of these observations is that gain on otolith signals may be reduced, consequently leading to a decrease in the ability to sense linear acceleration. An alternative hypothesis is that otolith signals are reinterpreted to represent only linear acceleration rather than pitch or roll of the head (Parker et al., 1985). Maintenance of this reinterpretation following spaceflight is maladaptive, resulting in postural instability with eyes

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closed and increased reliance on visual information for orientation (Young et al., 1984). Previous studies have assessed these changes in postural control following spaceflight with single summary measures (Homick and Reschke, 1977; Kenyon and Young, 1986; Paloski et al., 1992; Young et al., 1984).

There is evidence that hip responses to triggered perturbations are altered following spaceflight. Reschke et al. (1984) found evidence of an immediate strategy change in postflight postural responses, including more motion of the waist relative to the shoulders and deceased damping in the eyes closed condition. Anderson et al. (1986) found that in preflight testing, the astronauts moved shoulders and hips in phase with each other, while in postflight testing the subjects showed a more disjoint behavior, specifically with more hip movement. They suggested that a change in posture with more flexion at the hip may be the easiest way to move about in weightlessness. Alternatively, increased hip motions postflight may be due to the fact that motions about the waist would permit faster acceleration of the COM and thus faster correction of postural displacements (Kuo and Zajac, 1993). Kenyon and Young (1986) suggested that astronauts had more hip motion post-flight in an effort to minimize the motion of the head.

It is unclear whether these changes are limited to pre-programmed triggered responses, or if they also occur in the feedback loop active during quiet stance. If quiet stance is affected, it is reasonable to expect that changes could occur not only in amount of sway, but also interjoint coordination, because each sensor has a unique contribution to control of each joint (Kuo et al. 1998). Moreover, it is possible that coordinative changes could alternatively be attributed to adaptations which affect the detection of motion, or to changes in control gains.

We used multivariate analysis of postural sway to test for changes in posture control during quiet stance following spaceflight. Multivariate measures make it possible to differentiate between increases in sway and changes in interjoint coordination. Altered sensory conditions were employed to test whether these changes could be attributed to altered perception of self-motion, while indicators of control gains were used to test for changes in control separate from perception. We also compared the multivariate results with conventional univariate measures to test whether there were postural changes which could not be accounted for using only conventional measures.

2. Methods

2.1. Subjects and data collection

The Sensory Organization Test (EquiTest, Neurocom International) is regularly used to examine peak-to-peak sway in altered sensory environments. In this test, also known as dynamic posturography, subjects stand quietly on a computer-controlled movable platform under six sensory conditions which alter the available visual and proprioceptive information (Table 1). The support platform rotates about the axis of the ankles and is synchronized with sagittal plane sway of the subject. By maintaining the ankle joint at an approximately fixed angle, proprioceptive input to the foot and leg is greatly reduced in this ‘platform sway-referenced’ condition. The visual surround can similarly be servo-controlled to render visual input inaccurate as an orientation reference (‘visual sway-referenced’).

Table 1
Conditions of the sensory organization test (EquiTest, Neurocom Intl.)

Condition	Sensory feedback		
	Visual	Proprioceptive	Vestibular
1	Normal	Normal	Normal
2	Absent	Normal	Normal
3	Sway-referenced	Normal	Normal
4	Normal	Sway-referenced	Normal
5	Absent	Sway-referenced	Normal
6	Sway-referenced	Sway-referenced	Normal

Data from 10 astronauts (9 male, 1 female; mean age = 38.4 yr ± 2.76 SD) were selected based on the following criteria. All gave informed consent and completed the Sensory Organization Test (SOT) at NASA Johnson Space Center. Each was undergoing his/her first spaceflight mission of 7–16 days duration, and was seen for preflight balance testing at 10 days before liftoff, as well as postflight analysis within a few hours after egress. Our final selection criterion was that each subject was successful in completing at least one trial of each SOT condition for pre- and post- spaceflight testing. Three potential subjects were not included in the group due to this criterion.

The astronauts were asked to stand quietly for 20 s per trial, with one to three trials performed for each SOT condition. Kinematics of hip and shoulder motion were measured in the sagittal plane using sway bars sensed with potentiometers. Head motion was measured using a rate sensor mounted on the head. These measurements were used to compute approximate neck, hip and shank angles, assuming relatively little knee motion. Each angle was defined with zero corresponding to the upright position, with positive sign denoting extension. The shank angle was defined relative to the earth-fixed vertical and is equivalent to the ankle angle when the platform is earth-fixed. The center-of-pressure (COP) location was calculated from force transducers within the platform. Additional details of the apparatus, procedure, and measurement methods are given by Paloski et al. (1992).

A total of 13 (out of 180) postflight trials were not used in the analysis because the astronauts either failed to maintain balance without stepping or the data were incomplete. The covariances were averaged over the number of successful trials.

Data were sampled at 103 Hz and filtered with a digital, third order, bandpass Butterworth filter with cutoffs at 0.5 and 3.5 Hz. The high cutoff was employed to filter out noise and the low cutoff was used to ensure that summary values were calculated on at least 10 cycles of the lowest frequency component within the data.

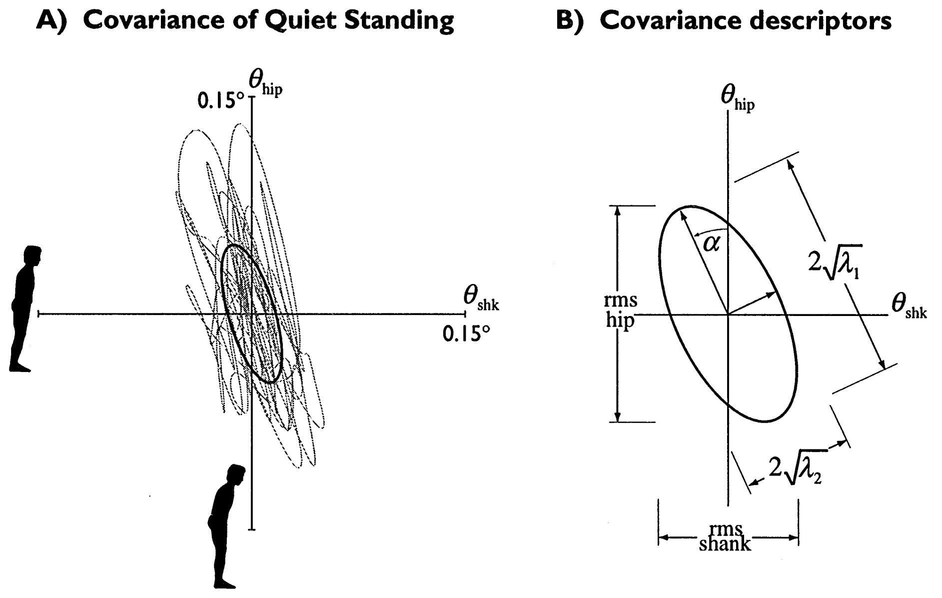
2.2. Covariance Measures

We used covariances to describe sway and joint coordination during SOT conditions. The covariance matrix is a multivariate generalization of the scalar variance (or square of rms) and includes as entries the individual variance for each joint, as well as measures of how each joint covaries with the others. We plotted the covariance of hip and shank angles with an ellipse corresponding to 1-σ of covariance (Fig. 1). A quantitative description may be obtained by computing the eigenvalues and eigenvectors of the covariance matrix. The eigenvalues, λ_1 and λ_2, describe the (squared) lengths of the major and minor axes, respectively, while the eigenvectors describe their orientation, summarized by the angle, α, of the ellipse's major axis with respect to the horizontal. The covariance matrix was also used to estimate the variance of center-of-mass (COM) sway (described in Kuo et al., 1998).

The extent of the covariance ellipse along any given axis is proportional to rms motion about a single joint. The overall size of the ellipse summarizes the amount of overall motion, and the relative orientation of the ellipse is an indication of the degree to which motion of the joints is correlated. Biomechanical constraints act such that the long axis of the ellipse (λ_1) represents the amount of hip strategy utilized by the subject, while the minor axis of the ellipse (λ_2) is an approximate indicator of the amount of COM sway (Kuo et al., 1998; Kuo and Zajac, 1993). In the multivariate model of sensory integration, altered sensory conditions should result in systematic changes in covariance of a more complex nature than simply a change in size. If sway changes in a multivariate way, the covariance ellipse should exhibit changes involving some combination of size, shape, and orientation. A univariate measure such as COP or COM variance might not detect these changes, instead merely indicating whether postural sway was greater or lesser under each sensory condition.

2.3. Joint torques and postural control gains

We computed summary measures of control gains in order to differentiate between possible contributing causes of changes in interjoint coordination. If increase in


A) Covariance of Quiet Standing

B) Covariance descriptors

Fig. 1. Covariance measures to describe sway and joint coordination. (A) Covariance during quiet standing describes motion of shank and hip angles, as shown by posture icons. Ellipse shows $1 - \sigma$ contour of constant standard error. (B) Illustration of definitions of covariance descriptors, using matrix entries (rms of hip and shank angles) and eigenvector parameters (λ_1, λ_2, α). Length of the ellipse along either coordinate axis is proportional to rms motion about either the hip or ankle joint. The overall size of the ellipse summarizes the amount of overall motion. The major axis of the ellipse, described by λ_1, represents the amount of hip strategy utilized by the subject. The minor axis of the ellipse, described by λ_2, is an indicator of the amount of center of mass sway. The orientation of the ellipse, described by α, indicates the degree to which motion of the joints is correlated (Kuo et al., 1998).

sway about a joint is due to sensor noise or decreased ability to detect small motions as opposed to reweighting of sensors, then joint torques would change in proportion to the increased sway, but postflight control gains would be expected to remain comparable to preflight values. Hip and ankle joint torques were computed from joint kinematics using a least-squares estimation approach to inverse dynamics in order to reduce the effects of measurement noise (Kuo, 1998). The amount of rms joint torque relative to the amount of rms joint motion was used as an indirect indicator of the gain of the postural control system. Gain indicators were computed using rms hip and ankle torque as output, and rms neck, hip, and shank angles as input. An additional univariate indicator, COP/COM, was calculated from corresponding measures.

2.4. Statistical methods

Multivariate analysis of variance (MANOVA) was performed to test whether the proposed measures were able to detect significant changes in both overall sway and in ankle–hip coordination. Other statistical tests included paired t-tests based on rms values of COP and COM, and paired t^2-tests applied to the multivariate eigenvector parameters. Paired t-tests were also conducted on the postural control gains. All of the univariate and multivariate descriptors, as well as the postural control gains, were normalized relative to the preflight results of SOT condition 1 in order to highlight the within-subject differences between conditions. In each test, the null hypothesis was for no significant differences between pre- and post-flight means across any of the six SOT conditions.

Discriminant analysis was performed to determine which multivariate measures were most responsible for any detected differences. Discriminant proportions describe the degree to which a particular discriminant contributes to the overall difference between groups. Discriminant vectors are interpreted as the axes of a coordinate system in measurement space which best reveals group separation. If the proportion for any one discriminant function is nearly 1, most of the changes in sway can be summarized using a single parameter; hence a univariate measure.

3. Results

3.1. Increase in sway was statistically significant with a notable increase in hip strategy

Univariate (COP, COM) and multivariate (λ_1, λ_2, and α) results indicated significant differences between pre- and post-spaceflight assessments for all six conditions of the Sensory Organization Test (Figs. 2 and 3). Paired t-tests indicated significant ($p < 0.03$) increases in sway between pre- and post-spaceflight tests across all six SOT conditions. Figs 2a and b illustrates the mean rms of COP and COM sway across the six conditions, respectively. Similarly, paired t^2-tests indicated significant differences ($p < 0.04$) in the multivariate descriptors across all six SOT conditions, as illustrated in Fig. 3.

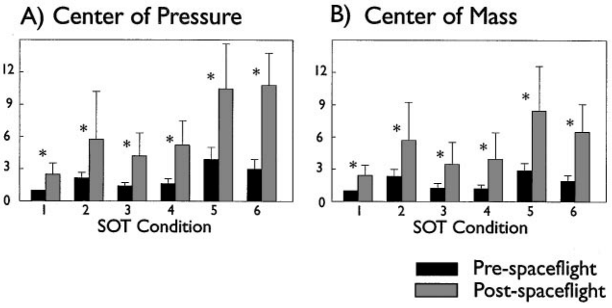


Fig. 2. Univariate descriptors of postural sway. (A) Center of pressure (COP) as measured by the force platform and (B) center of mass (COM) as calculated from covariances of hip and ankle joint angles. Both measures had significant increases following spaceflight for all six conditions of the Sensory Organization Test (SOT) ($p < 0.03$). All results were normalized to preflight results for SOT condition 1 (quiet stance with eyes open).

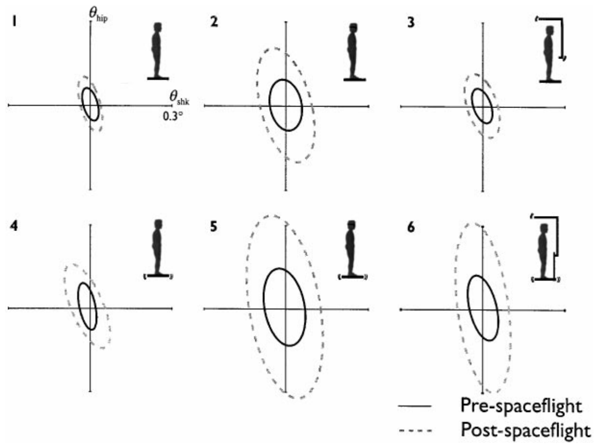


Fig. 3. Covariance ellipses of hip and shank kinematics, where each pre-spaceflight or post-spaceflight ellipse represents the mean covariances of shank and hip angles across the 10 astronauts. Using the multivariate descriptors, λ_1, λ_2, and α, we found significant changes in both postural sway and joint coordination following spaceflight for all six conditions of the Sensory Organization Test ($p < 0.04$). All results were normalized to preflight results for SOT condition 1 (quiet stance with eyes open).

Discriminant analysis of the relative contribution of each of the multivariate measures, λ_1, λ_2, and α, to the overall separation of the data comparing pre- and post-spaceflight results indicated varying proportions among the six SOT conditions (Fig. 4). In order to aid comparisons, all discriminant vectors are scaled to unit length. While the descriptor λ_2 is most similar to examining only

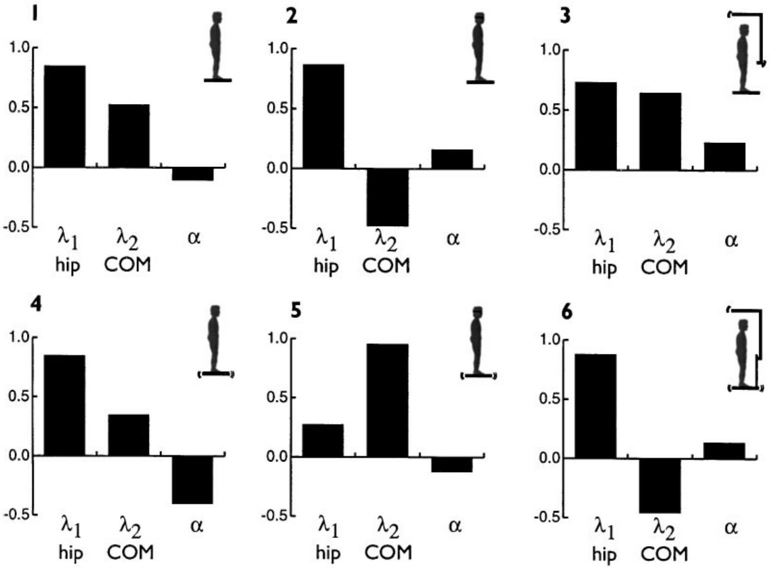


Fig. 4. Discriminant analysis of the relative contribution of each of λ_1, λ_2, and α to the overall separation of the data comparing pre- and post-spaceflight results. All discriminant vectors are scaled to unit length. Each of the multivariate descriptors has varying proportions among the six SOT conditions, indicating relative changes in the coordination of postural control that would not be represented by a single measure of sway.

COM sway, only changes in sway during SOT condition 5 were sufficiently described by this one parameter. Each of the other conditions showed a change in interjoint coordination of sway which was revealed only by multivariate analysis (having significant proportions along λ_1 and/or α). This change, an increase in the relative proportion of hip strategy, was statistically more evident than the increase in COM sway for five of the six SOT conditions.

For example, discriminant vectors for SOT condition 1 have proportions 71.6% for λ_1 (hip strategy), 27.3% for λ_2 (COM), and 1.1% for α, meaning that less than three-fourths of the pre- vs post-spaceflight differences could be captured by a single linear combination of the measurement variables. The remaining differences require at least one additional measurement and are thus beyond the capability of univariate measures to detect them. For SOT conditions 1, 2, 4, and 6, λ_1 had the largest discriminant. For SOT 3, discriminant components associated with λ_1 and λ_2 had similar proportions, which is illustrated in the overall enlarging of the ellipse for postflight, but not necessarily along one axis more than the other. For SOT 4, a change in orientation of the mean covariance ellipse can be noted from Fig. 3, and the discriminant components showed by far the highest proportion along α (16%) as compared with any of the other SOT conditions (range of 2–10%). Thus it appears that platform sway-referencing had a different effect on maintenance of balance than visual sway-referencing, though these SOT conditions had similar results when examining only univariate descriptors of sway.

3.2. Following spaceflight, hip joint torque response to movement was increased

Several indirect indicators of the gain of the postural response were computed for both pre- and post-spaceflight assessments (Figs. 5 and 6). The univariate gain indicator, COP/COM, was generally increased following spaceflight, but this increase was only statistically significant for SOT condition 6 (Fig. 5e). This result was supported by the multivariate gain indicators, which showed that ankle torque responses underwent little change: $T_{\mathrm{ank}}/\theta_{\mathrm{shank}}$ (rms ankle torque relative to rms ankle motion) showed significant change for only SOT condition 6, and $T_{\mathrm{ank}}/\theta_{\mathrm{hip}}$ (rms ankle torque relative to rms hip motion) showed no significant change for any of the SOT conditions. In contrast, the indicators describing hip joint gain were significantly increased following spaceflight. The indicator for hip torque response to ankle motion, $T_{\mathrm{hip}}/\theta_{\mathrm{shank}}$, was significantly increased for conditions 1–3, and 6, and was nearly significant for condition 4 ($p = 0.052$), while the response to hip motion, $T_{\mathrm{hip}}/\theta_{\mathrm{hip}}$, increased significantly for SOT conditions 1–4, and 6.

Following spaceflight, the astronauts exhibited a statistically significant increase in head pitch angle during altered vision conditions (SOT 3 and 6), but not for the altered proprioceptive conditions (SOT 4 and 5) (Table 2). Correspondingly, hip joint torque responses to head motion were significantly greater for SOT conditions 2–6, while there was no noticeable change in ankle joint response to head motion (Fig. 6a and b).

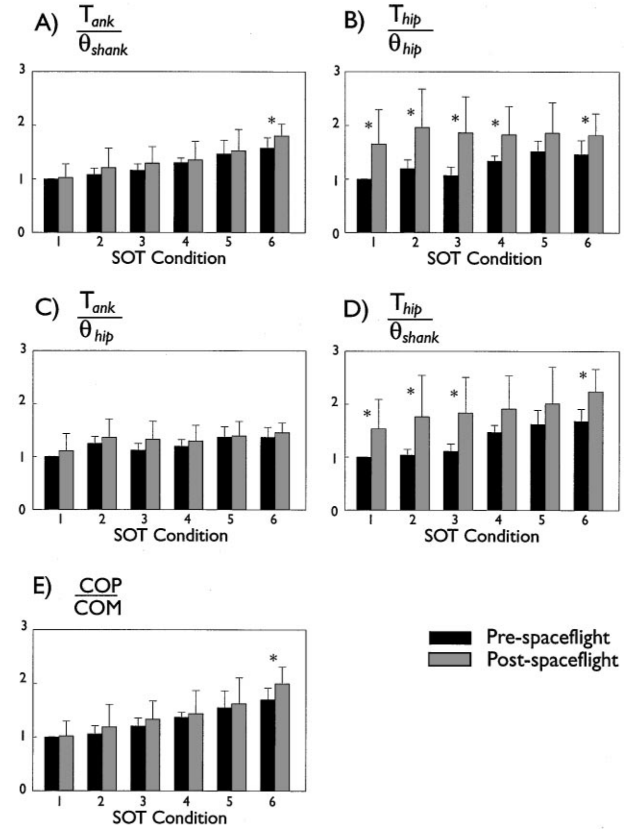


Fig. 5. Postural control gain indicators of ankle and hip joint torque response to movement at the ankle and hip, computed by dividing rms torque by rms joint motion. Ankle joint response to motion at the hip ($T_{\text{ank}}/\Theta_{\text{hip}}$; A) or ankle ($T_{\text{ank}}/\Theta_{\text{shank}}$; C) showed little change following spaceflight. Root-mean-square (rms) hip torque relative to both rms hip and ankle sway ($T_{\text{hip}}/\Theta_{\text{hip}}$; B) ($T_{\text{hip}}/\Theta_{\text{shank}}$; D) was noticeably greater following spaceflight for SOT conditions 1, 2, 3, and 6 ($p < 0.05$) with $T_{\text{hip}}/\Theta_{\text{hip}}$ also showing significance for SOT condition 4. The gain of univariate measures (E), COP/COM, was generally increased following spaceflight, but this increase was only statistically significant for SOT condition 6 ($p < 0.05$). All results were normalized to preflight results for SOT condition 1 (quiet stance with eyes open).

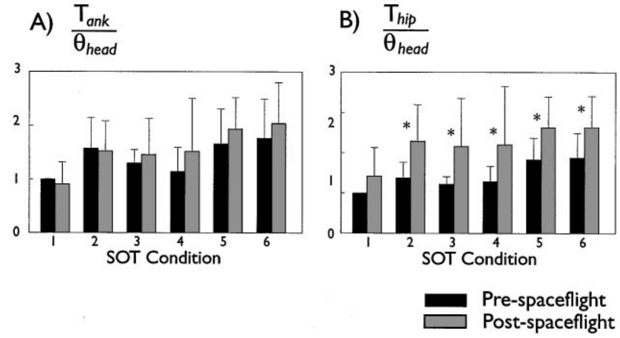


Fig. 6. Postural response gains of hip and ankle joint response to head pitch angle. Following spaceflight, hip joint response to head pitch angle ($T_{\text{hip}}/\Theta_{\text{head}}$; A) was increased for SOT conditions 2–6 ($p < 0.05$), while ankle joint response to head pitch angle ($T_{\text{ank}}/\Theta_{\text{head}}$; B) was unchanged. All results were normalized to preflight results for SOT condition 1 (quiet stance with eyes open).

4. Discussion

Changes in postural control following spaceflight are multivariate in nature, as shown by the covariance ellipses that have increases along different dimensions (Fig. 3). This indicates not only a change in the amount of sway, but a change in joint coordination as well. For all altered sensory conditions except SOT 5, the multivariate measures showed the most significant increase in hip strategy. For only one condition (5), was the increase in COM motion more significant than the increase in hip strategy. These differences would not be evident using a single univariate measure.

The increased hip joint torque response to movement of the ankle indicates that the increased hip motion observed by Anderson et al. (1986) is due to an increase in control gain. An increase in hip joint response to movement of the head was also observed, possibly because the astronauts chose a strategy of keeping the head fixed relative to the trunk (Paloski et al., 1992). Because the coordinative changes varied with sensory condition, it appears that they are at least partially explained by changes in sensory processing, which may affect the astronauts to perceive spatial orientation. These findings are consistent with those reported by Bloomberg et al. (1997) in astronauts walking on a treadmill following spaceflight. The apparent increase in overall gain of hip torque in response to joint motion following spaceflight suggests that there is a change in the feedback response to perceived motion as well. These changes may be due to and are consistent with adaptive locomotion strategies used in weightlessness, as well as lingering increased sensitivity to otolith signals which were diminished during spaceflight.

We did not find an increase in ankle joint response to either lower extremity or head motion. Kozlovskaya

Table 2
Average rms values (± SD) of head pitch angle for pre- and post-spaceflight testing in a group of 10 first-time astronauts (*$p < 0.05$)

SOT condition	1	2	3	4	5	6
Pre-spaceflight rms Θ_{head}	0.08 (0.04)	0.11 (0.04)	0.08 (0.03)	0.12 (0.04)	0.18 (0.05)	0.13 (0.05)
Post-spaceflight rms Θ_{head}	0.14* (0.08)	0.17 (0.12)	0.13* (0.05)	0.18 (0.09)	0.25 (0.11)	0.27* (0.09)

et al. (1981) found increased levels of lower limb muscle activity post-spaceflight and Homick and Reschke (1977) stated that hyperactivity of the Achilles tendon reflex may result in overreaction and overcompensation of the part of subjects to slight changes in ankle position. We suggest that the astronauts exhibit overcompensation to changes in ankle position, but that these corrections are made by execution of hip strategy. As Anderson et al. (1986) have stated, ankle joint torque is not experienced in spaceflight in the context of postural stability because static tilt has no meaning in weightlessness.

During pre-spaceflight testing, the astronauts were able to make use of what few visual cues were available and on average exhibited excellent (above normal) performance on SOT conditions 3 and 6. For postflight testing, the results for SOT conditions 2 and 5 showed noticeably increased sway, and thus performance was worse with eyes closed whether or not the platform was sway-referenced. Following spaceflight, the astronauts exhibited an increase in head pitch angle during altered vision conditions (3 and 6), but not for the altered proprioceptive conditions (4 and 5), further suggesting that they are dependent on vision in order to stabilize the head following spaceflight. Conditions 5 and 6 increase reliance on vestibular information by compromising both vision and somatosensory input. The resulting increases in overall sway and use of hip strategy show that neither vision nor somatosensory input need be present for execution of the hip strategy (Horak et al., 1990).

Our results imply that the contributions of somatosensory, visual, and vestibular information for postural control are altered following spaceflight. The otolith-reinterpretation hypothesis suggests that astronauts have reduced information from their vestibular apparatus following spaceflight, and our results identify changes in their trunk movement and resulting greater use of the hip joint to maintain postural equilibrium. The increase in hip strategy is consistent with the evidence that the vestibular system plays a large role in control of the trunk (Shupert and Horak, 1996). The post-spaceflight increase in rms hip joint torque is more than would be expected if the postural control gain was unchanged. (A smaller increase in hip joint torque would be expected to accompany the increase in hip joint motion if gains were fixed.) We therefore propose that there are changes in both sensory processing for motion perception and in hip control gains following spaceflight, and that these changes are only revealed by multivariate measures. The gain changes may compensate for altered processing of vestibular input. More complete understanding of changes in joint coordination following spaceflight may aid efforts to develop training methods for improvement of postural control and alleviation of symptoms in astronauts as well as in vestibular deficient patients.

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References

Anderson, D.J., Reschke, M.F., Homick, J.E., Werness, S.A.S., 1986. Dynamic posture analysis of Spacelab-1 crew members. Experimental Brain Research 64, 380–391.

Bloomberg, J.J., Peters, B.T., Smith, S.L., Huebner, W.P., Reschke, M.F., 1997. Locomotor head-trunk coordination strategies following spaceflight. Journal of Vestibular Research 7, 161–177.

Collins, J.J., De Luca, C.J., Pavlik, A.E., Roy, S.H., Emley, M.S., 1995. The effects of spaceflight on open-loop and closed-loop postural control mechanisms: human neurovestibular studies on SLS-2. Experimental Brain Research 107, 145–150.

Homick, J.L., Reschke, M.F., 1977. Postural equilibrium following exposure to weightless space flight. Acta Otolaryngol 83, 455–464.

Horak, F.B., Nashner, L.M., Diener, H.C., 1990. Postural strategies associated with somatosensory and vestibular loss. Experimental Brain Research 82, 167–177.

Kenyon, R.V., Young, L.R., 1986. M.I.T./Canadian vestibular experiments on the Spacelab-1 mission: 5. Postural responses following exposure to weightlessness. Experimental Brain Research 64, 335–346.

Kozlovskaya, I.B., Kreidich, Y.V., Rakham, O.V., 1981. Mechansisms of the effects of weightlessness on the motor system of man. Physiologist Supplement 24, 59–64.

Kuo, A.D., Zajac, F.E., 1993. Human standing posture: multi-joint movement strategies based on biomechanical constraints. Progress in Brain Research 9, 349–358.

Kuo, A.D., 1998. A least squares estimation method for improving precision of inverse dynamics computations. ASME Journal of Biomechanical Engineering 120, 149–160.

Kuo, A.D., Speers, R.A., Peterka, R.J., Horak, F.B., 1998. Effect of altered sensory conditions on multivariate descriptors of human postural sway. Experimental Brain Research 122, 185–195.

Paloski, W.H., Reschke, M.F., Black, F.O., Doxey, D.D., Harm, D.L., 1992. Recovery of postural equilibrium control following spaceflight. Annals New York Academy of Sciences, 744–754.

Paloski, W.H., Black, F.O., Reschke, M.F., Calkins, D.S., Shupert, C., 1993. Vestibular ataxia following shuttle flights: effects of microgravity on otolith-mediated sensorimotor control of posture. American Journal of Otology 14(1), 9–17.

Parker, D.E., Reschke, M., Arrott, A.P., Homick, J.L., Lichtenberg, B.K., 1985. Otolith tilt-translation reinterpretation following prolonged weightlesness: implications for preflight training. Aviation, Space, and Environmental Medicine, 601–606.

Peterka, R.J., Black, F.O., 1990. Age-related changes in human posture control: sensory organization tests. Journal of Vestibular Research 1, 73–85.

Reschke, M.F., Anderson, D.J., Homick, J.L., 1984. Vestibulospinal reflexes as a function of microgravity. Science 225, 212–214.

Shupert, C.L., Horak, F.B., 1996. Effects of vestibular loss on head stabilization in response to head an body perturbations. Journal of Vestibular Research (submitted).

Young, L.R., Oman, C.M., Watt, D.G.D., Money, K.E., Lichtenberg, B.K., 1984. Spatial orientation in weightlessness and readaptation to earth's gravity. Science 225, 205–208.