Assessing Sensorimotor Function Following ISS with Computerized Dynamic Posturography

Scott J. Wood; William H. Paloski; Jonathan B. Clark

INTRODUCTION: Postflight postural ataxia reflects both the control strategies adopted for movement in microgravity and the direct effects of deconditioning. Computerized dynamic posturography (CDP) has been used during the first decade of the International Space Station (ISS) expeditions to quantify the initial postflight decrements and recovery of postural stability.

METHODS: The CDP data were obtained on 37 crewmembers as part of their pre- and postflight medical examinations. Sensory organization tests evaluated the ability to make effective use of (or suppress inappropriate) visual, vestibular, and somatosensory information for balance control. This report focuses on eyes closed conditions with either a fixed or sway-referenced base of support, with the head erect or during pitch-head tilts (± 20° at 0.33 Hz). Equilibrium scores were derived from peak-to-peak anterior-posterior sway. Motor-control tests were also used to evaluate a crewmember's ability to automatically recover from unexpected support-surface perturbations.

RESULTS: The standard Romberg condition was the least sensitive. Dynamic head tilts led to increased incidence of falls and revealed significantly longer recovery than head-erect conditions. Improvements in postflight postural performance during the later expeditions may be attributable to higher preflight baselines and/or advanced exercise capabilities aboard the ISS.

CONCLUSIONS: The diagnostic assessment of postural instability is more pronounced during unstable-support conditions requiring active head movements. In addition to supporting return-to-duty decisions by flight surgeons, the CDP provides a standardized sensorimotor measure that can be used to evaluate the effectiveness of countermeasures designed to either minimize deconditioning on orbit or promote reconditioning upon return to Earth.

KEYWORDS: ataxia, vestibular, ISS, postflight, multisensory, unloading.

Wood SJ, Paloski WH, Clark JB. *Assessing sensorimotor function following ISS with computerized dynamic posturography*. Aerosp Med Hum Perform. 2015; 86(12, Suppl.):A45–A53.

The monitoring of sensorimotor readaptation to Earth's gravity is important for flight surgeons to determine when crewmembers can safely return to their activities of daily living, such as driving and exercise. Computerized dynamic posturography (CDP) was implemented to support this assessment as a pre- and postflight medical requirement for International Space Station (ISS) crewmembers. While crewmembers are subjectively evaluated by flight surgeons using standard neurological assessments,[5] CDP provides an objective means of assessing sensorimotor function that can be implemented in a systematic way across individuals. This report summarizes the rationale and results obtained from CDP through the first 10 yr of the ISS.

The rationale for using CDP as a medical assessment tool stems from our understanding of the mechanisms of sensorimotor adaptation to spaceflight, as well as prior data that provide the evidence base for CDP as a clinically relevant measure. As reviewed below, two fundamental mechanisms relevant to sensorimotor control include multisensory integration and gravitational unloading.[39] There is considerable variability in postflight postural ataxia among crewmembers. This variability must be understood in the context of these adaptive mechanisms to ensure that the appropriate countermeasures

From Azusa Pacific University, Azusa, CA; NASA Johnson Space Center, Houston, TX; and the Center for Space Medicine, Baylor College of Medicine, Houston, TX.

Address correspondence to: Jacqueline M. Reeves, NASA Johnson Space Center, Division Resource Support, Biomedical Research & Environmental Sciences Division, 2101 NASA Parkway, MC Wyle/SK/37, Houston, TX 77058; Jacqueline.m.reeves@nasa.gov

DOI: 10.3357/AMHP.EC07.2015

are implemented to maximize performance following transitions across gravitational environments.

Mechanisms of Adaptation

On Earth, gravity provides the static, omnipresent spatial reference needed for fusion of information from different sensory modalities. Postural sway on Earth elicits redundant feedback from vision, somatosensory, and vestibular transducers (semicircular canals and otoliths). Sensory input regarding orientation relative to gravity thus provides the fundamental external reference to facilitate multisensory transformations necessary for motor control and spatial orientation and navigation.[37] Movement in the ISS microgravity environment results in new patterns of sensory cues. Changes in orientation on orbit do not elicit the same otolith or somatosensory cues as on Earth. Adaptive changes require a new reference frame for multisensory integration to maintain spatial orientation. These adaptive changes carry over to the postflight period and are reflected by the perceptual and motor coordination problems, especially during head tilts that become less severe over time.[32]

Hypotheses have been developed that neural adaptation to microgravity involves either a reinterpretation of otolith input[22,31,41] or neglect of low-frequency otolith information that no longer provides reliable information.[11] There is evidence of sensory reweighting, with more reliance in flight on visual and tactile cues for spatial orientation.[42] Increased fall risk postflight can result when astronauts do not realize they are leaning away from upright as a result of adaptive changes in sensory processing. While multisensory integration is important for resolving the tilt-translation ambiguity on Earth,[1,38] we propose that it is also a critical mechanism contributing to postural ataxia following ISS flights.

In addition to multisensory interactions, adaptation during spaceflight also results from direct effects of microgravity. The removal of gravitational loading itself can have profound effects that either negatively impact sensorimotor function or reduce one's capacity to overcome sensorimotor deficits. Gravitational unloading can alter neuromotor skills that depend on accurate proprioception for mass discrimination and force control. The ability to manipulate objects in microgravity or judge forces needed to push off surfaces to navigate must be refined on orbit.[25] Altered proprioception associated with unloading leads to impaired judgment of limb position.[35] Most crewmembers show a compliant response when jumping postflight, consistent with the decreased limb stiffness required in microgravity.[26] Crewmembers often report perceived heaviness of their body and limbs during the early postflight period.[33]

Postural and locomotion control on Earth are constrained by the musculoskeletal strength required to rapidly move one's center of gravity relative to one's base of support.[27] The extent to which musculoskeletal deconditioning from spaceflight contributes to postflight postural ataxia depends on flight duration and available countermeasures. During Shuttle-MIR missions with limited countermeasures, mass in the major postural muscles decreased between 12–20% before reaching a new steady state condition.[20] There is generally a loss of force and power,[9] in part due to changes in motor unit recruitment (alterations in neural drive to contract the muscle).[2,16] The decline in stiffness and force of tonic postural muscles is accompanied by an increasing involvement of phasic muscles.[17] Active exercises intended to recondition musculoskeletal and cardiovascular function also serve to recondition the disrupted neuromuscular activation patterns observed during self-generated perturbations postflight.[19]

Evidence Base for Computerized Dynamic Posturography as a Standard Measure

Clinical applications of CDP include the assessment, rehabilitation, and management of balance disorders.[3] The CDP performance can help identify those at risk of recurrent falls and guide the clinician in the development of a safe exercise program.[36] Before ISS, CDP had been used experimentally to examine postflight postural ataxia following both short and long-duration flights.[4] In particular, the sensory organization tests provided by the EquiTest® System platform (NeuroCom, Clackamas, OR) have been used to assess the relative importance of visual, vestibular, and somatosensory feedback for control of postural stability.[28,32] The greatest decrements occur when the eyes are closed and the support surface rotates in direct proportion to anterior-posterior (AP) body sway (sway referencing). By disrupting somatosensory feedback and removing vision, this condition is sensitive to adaptive changes in how vestibular feedback is used for postural control. We demonstrated that CDP diagnostic performance after short-duration Shuttle flights was enhanced with the addition of dynamic pitch-head tilts.[13] Based on this result, dynamic head tilts were incorporated into the ISS pre- and postflight CDP assessments. Consistent with the Shuttle results, in this report we demonstrate that performing head movements on an unstable support during CDP led to increased incidence of falls with a significantly longer recovery than for head-erect conditions.

METHODS

Crewmembers and Test Schedule

The scope of our report summarizes the CDP results from the first 10 yr or 25 expeditions of the ISS. A separate report[18] describes the outcomes obtained from Russian Space Agency crewmembers (RSA, $N = 25$, of which 7 flew twice) during this same time frame. Therefore this report only includes subjects from the National Aeronautics and Space Administration (NASA, $N = 31$), European Space Agency (ESA, $N = 3$), Japan Aerospace Exploration Agency (JAXA, $N = 2$), and Canadian Space Agency (CSA, $N = 1$). Of the 31 NASA crewmembers, 3 participated in 2 of these ISS expeditions and 12 had no prior spaceflight experience. This protocol is referred to as Medical Requirement MR042L or MedB 1.5 and was approved by the NASA Space Medicine Configuration Control Board and the Multilateral Medical Operations Panel that coordinates International Partner input into ISS Medical Operations.

The CDP protocols performed during this first decade of ISS missions can be subdivided into three phases (see **Table I**). During the first nine expeditions the test conditions were limited to sensory organization tests (SOTs) 1–6 with head erect. Starting with these initial expeditions, each crewmember was tested two times before flight, with the last session occurring between 29–84 d before launch (mean 61 d). To control for any learning effect between the initial familiarization and subsequent sessions, each crewmember's baseline performance was obtained from their last preflight session. The initial postflight test schedule varied, with a first test generally occurring between 2–6 d and a second test between 7–10 d following landing. Resistive exercise during Expeditions 1–9 was limited to use of the interim resistive exercise device (iRED).

During the next 8 expeditions (10–17), pitch head tilts were introduced during SOTs 2 and 5 to sharpen the testing. Motor control tests (MCTs) were also introduced with support-surface translations and toes up rotations (see SOT and MCT descriptions below). The preflight test schedule remained the same; however, the postflight schedule was broadened to include three tests generally occurring at 0–1 d, 2–5 d, and 7–10 d following landing. During these expeditions resistive exercise was performed using the improved iRED, also referred to as the Schwinn resistive exercise device (SchRED).

Beginning with Expedition 18, the postflight schedule was reduced to one measurement between 6–10 d following landing, primarily for the purpose of return-to-duty assessment. Additional data are available on two crewmembers during this phase through their participation in a postflight experiment. The protocol continued to include SOTs 1–5 with head erect, SOTs 2 and 5 with dynamic pitch tilts and MCTs with platform translations. Coincidentally, during these same expeditions, resistive exercise was performed using the advanced resistive exercise device (ARED). As indicated in Table I, each of the three phases had crewmembers returning on both Shuttle and Soyuz vehicles.

Table I. Summary of Crewmembers Included in the Present Report (Excluding RSA Crewmembers).

EXP*	SPACE AGENCY	LANDING VEHICLES	CDP PROTOCOL	RED**
1	NASA, RSA (2)	Shuttle (3)	SOT 1-6	iRED
2	NASA (2), RSA	Shuttle (3)	SOT 1-6	iRED
3	NASA, RSA (2)	Shuttle (3)	SOT 1-6	iRED
4	NASA (2), RSA	Shuttle (3)	SOT 1-6	iRED
5	NASA, RSA (2)	Shuttle (3)	SOT 1-6	iRED
6	NASA (2), RSA	Soyuz (3)	SOT 1-6	iRED
7	NASA, RSA	Soyuz (2)	SOT 1-6	iRED
8	NASA, RSA	Soyuz (2)	SOT 1-6	iRED
9	NASA, RSA	Soyuz (2)	SOT 1-6	iRED
10†	NASA, RSA	Soyuz (2)	SOT 1-5, 2/5M, MCT	SchRED
11	NASA, RSA	Soyuz (2)	SOT 1-5, 2/5M, MCT	SchRED
12	NASA, RSA	Soyuz (2)	SOT 1-5, 2/5M, MCT	SchRED
13	NASA, RSA	Soyuz (2)	SOT 1-5, 2/5M, MCT	SchRED
14	NASA, RSA, ESA	Shuttle (1), Soyuz (2)	SOT 1-5, 2/5M, MCT	SchRED
15	NASA, RSA (2)	Shuttle (1), Soyuz (2)	SOT 1-5, 2/5M, MCT	SchRED
16	NASA (3), RSA, ESA	Shuttle (3), Soyuz (2)	SOT 1-5, 2/5M, MCT	SchRED
17	NASA, RSA (2)	Shuttle (1), Soyuz (2)	SOT 1-5, 2/5M, MCT	SchRED
18	NASA (3), RSA	Shuttle (2), Soyuz (2)	SOT 1-5, 2/5M, MCT	SchRED
20††	NASA (2), RSA, JAXA	Shuttle (2), Soyuz (2)	SOT 1-5, 2/5M, MCT	ARED
21	NASA, RSA, ESA,CSA	Shuttle (1), Soyuz (3)	SOT 1-5, 2/5M, MCT	ARED
22	NASA, RSA	Soyuz (2)	SOT 1-5, 2/5M, MCT	ARED
23	NASA, RSA, JAXA	Soyuz (3)	SOT 1-5, 2/5M, MCT	ARED
24	NASA, RSA (2)	Soyuz (3)	SOT 1-5, 2/5M, MCT	ARED
25	NASA (2), RSA	Soyuz (3)	SOT 1-5, 2/5M, MCT	ARED
26	NASA, RSA (2)	Soyuz (3)	SOT 1-5, 2/5M, MCT	ARED

* Exp refers to the ISS expedition designation upon landing. **The resistive exercise devices (RED) have included the iRED, SchRED, and ARED. †SOT head tilts and MCTs were added during Expedition 10. ††The postflight CDP schedule was reduced beginning with Expedition 20.

Computerized Dynamic Posturography System Description

The CDP was conducted using a modified EquiTest® System. The support surface consisted of a dual forceplate supported by four force transducers (strain gauges) mounted symmetrically to measure the distribution of vertical forces. The subject's feet were centered on the support surface at shoulder width apart (**Fig. 1**). Computer-controlled movements of the support surface and/or visual enclosure were used to modify the sensory conditions or to impose unexpected perturbations. The support surface rotated about the medial malleolus using servomotors linked to the force plates by a lead-screw assembly ($50° \cdot s^{-1}$ maximum). Similar servomotor and lead screws were used to rotate the visual surround ($15° \cdot s^{-1}$ maximum) or translate the support surface forward or backward [$15\ cm \cdot s^{-1}$ ($6\ in \cdot s^{-1}$) maximum]. Subjects wore noise-cancelling headphones through which operator instructions and white noise were supplied to mask external auditory orientation cues.

The subjects were instructed to maintain stable upright posture with arms folded across the chest. The center of pressure (COP) in both AP and medial-lateral directions was obtained from the forceplate strain gauges sampled at 100 Hz. A second order low-pass Butterworth filter (cutoff 0.85 Hz) was applied to the COP to estimate center of mass. The subject's sway angle was then derived from the center of mass, which was assumed to be above the support surface at approximately 55% of total height.[24]

Infrared markers mounted on the headphones were used to quantify head position using an OptoTrak System (Model 3020, Northern Digital Inc., Ontario, Canada). While the subject was standing with head upright, the head position sensor was set to 0° by adjusting the headset frame. Markers were also placed on the upper torso over the spinous process of the T1 vertebra, at the hips parallel with the muscle insertion point at the greater trochanter, at the center of each knee parallel to the center of the medial epicondyle of the femur, and at the center of the back of

Fig. 1. System configuration depicting subject stance with feet at shoulder width and arms folded. Body segment kinematic data was derived from a video-based motion tracking system (OptoTrak, Northern Digital, Inc.) with markers positioned to record movement about the ankles, knees, and hips, as well as movement of the head.

each ankle (Achilles region) parallel to the center of the medial malleolus. These markers thus enabled kinematic analysis of postural strategy using a multisegment model (data not reported here).

Sensory Organization Tests

The SOTs consist of a set of increasingly challenging conditions to assess the subject's ability to make effective use of visual, vestibular, and somatosensory information for maintaining upright stance. During some trials, the support surface and/or visual surround are rotated in direct proportion to the subject's sway, referred to as sway referencing. Sway referencing of the support surface and/or visual surround resulted in disrupted somatosensory and visual input, respectively. Postural sway is measured during 20-s trials, including combinations of two somatosensory conditions (fixed-support, sway-referenced support) and three visual conditions (eyes open, eyes closed, sway-referenced vision). As described in **Table II**, the subject was asked either to maintain their head in a natural upright

Table II. Summary of SOT and MCT Test Conditions.

SOT	SUPPORT SURFACE	VISUAL CONDITION	HEAD CONDITION
1	Fixed Support	Fixed Surround	Head Upright
2	Fixed Support	Eyes Closed	Head Upright
2B	Fixed Support	Eyes Closed	Static Pitch Back 20°
2M	Fixed Support	Eyes Closed	Dynamic Pitch ± 20°
3	Fixed Support	Unstable Surround	Head Upright
4	Unstable Support	Fixed Surround	Head Upright
5	Unstable Support	Eyes Closed	Head Upright
5B	Unstable Support	Eyes Closed	Static Pitch Back 20°
5M	Unstable Support	Eyes Closed	Dynamic Pitch ± 20°
6	Unstable Support	Unstable Surround	Head Upright
MCT	Support Surface	Visual Condition	Head Condition
T	Translations	Fixed Surround	Head Upright
R	Toes Up Rotations	Fixed Surround	Head Upright

orientation, tilted back 20°, or perform continuous ±20° sinusoidal head oscillations paced by an audible tone, transmitted through the headphones, at 0.33 Hz. For dynamic head movements, the test operator monitored the head movement of the subject and gave corrective instruction over several cycles before beginning the trial.

The AP peak-to-peak sway angle, θ (in degrees), was used to compute a continuous equilibrium score, designated as cEQ,[40] as follows:

$$cEQ = \left(1\text{-}\left(\theta/12.5\right)\right) \times \%\,\text{trial completed},$$

where 12.5° is the maximum theoretical peak-to-peak AP sway and the range of normalized values was between 0 and 100. Falls were marked when subjects moved their feet, began to take a step, or raised their arms. While all falls have traditionally been assigned an equilibrium score of 0, the resulting mixed discrete-continuous distribution has compromised inference obtained by standard statistical methods.[8] The slight modification of the equilibrium formula above where "% trial completed" replaced "100" resulted in a continuous distribution. Note that the trials without falls were unchanged from the traditional equilibrium methodology. In addition to ensuring a continuous distribution, the cEQ factors in the time before a fall occurs, thus separating ballistic falls from falls that occurred later in the trial.[40]

Motor Control Tests

The MCTs evaluate one's ability to automatically recover from unexpected support surface perturbations. These consisted of either toes up rotations (8° in 0.4 s) or translations [1.0–1.5 cm (0.4–0.6 in) in 0.25 s, or 4.8 to 6.0 cm (1.9–2.4 in) in 0.4 s] in either forward or backward directions. For the purpose of this report, only the large forward translations are presented. The translation amplitudes were scaled according to height [2.25 × (height ÷ 183 cm)], thus producing similar sway disturbances across subjects. While standing with the head erect and eyes open, these unexpected movements of the support surface elicited automatic stabilizing postural responses analogous to slipping or tripping.

Postural stability during MCTs was characterized by both the initial response (latency and peak COP displacement) as well as the time to recover from the perturbation. The time to stability was based on each subject's COP sway-velocity characteristics during normal stance with eyes open on a fixed surface (from SOT-1 conditions described above) during the same session. The time to stability for each trial was then defined by the minimum time at which the subject's COP velocity remained within 3 standard deviations of this COP sway threshold for 1 s.[12] Both the time to stability and path length (cm) to this time were used.

Modeling Postflight Recovery

Statistical comparison of pre- vs. postflight measurements was limited by the variability in the postflight test schedule across ISS expeditions, especially given the relatively few early postflight measurements. Therefore, both the initial decrement in performance and the time course of recovery were determined by modeling the postflight measurements using a least squares exponential fit with return to preflight mean values. Although we have previously characterized the postflight recovery using double exponential fit to capture both fast and slow recovery dynamics,[29] the number of early postflight data points in this data set limited estimates of the fast recovery phase for most conditions. While the number of trials sometimes varied across subjects, the median value was used from each session. The 95% confidence interval of the amplitude of each exponential fit compared to the corresponding preflight mean was used as the criterion for postflight significance.

RESULTS

Sensory Organization Tests

Consistent with the EquiTest® clinical norms,[24] the preflight cEQ scores for the SOTs decreased when the eyes were closed or the support surface was sway referenced. Neither static nor dynamic pitch head tilts reduced preflight postural performance when the support surface was fixed, but both significantly reduced the preflight cEQ with an unstable support surface.[30] Based on the estimate of cEQ at 0 h after landing from the exponential fits, there was a significant decrement in all SOT conditions. The percentage change in all three head-erect conditions with fixed support was <10% (SOTs 1-3, **Table III**). There was, however, an estimated 25% decrement relative to preflight when dynamic-head movements were introduced with fixed support and eyes closed. SOTs 2 and 3 did not significantly differ from each other; however, both were lower than SOT 1.

The SOT conditions most sensitive to postflight sensorimotor changes used the unstable (sway referenced) support surface (SOTs 4–5), with initial decrements significantly lower than all fixed-support conditions (SOTs 1–3). The initial decrement with unstable support and eyes closed (SOT 5) was estimated at >80% with head erect. As with the fixed-support condition, a static head extension of 20° resulted in postflight decrements similar to the head erect condition. However, most crewmembers tested on landing day did not even attempt dynamic head tilts with an unstable support as this was considered too challenging. When attempted, the overall postflight fall incidence increased from 1.4% (7 of 501 trials) with head erect to 14.7% (52 of 353 trials) with dynamic head tilts. Based on the exponential fit, the fall incidence with dynamic head tilts following flight on the ISS would approach 100%, close to landing with diminished visual inputs and unstable support surface.

Fig. 2 illustrates the recovery dynamics for four SOT conditions characterized by single exponential fits of the median cEQ measures. While the overall decrements were small with the fixed support (Figs. 2A and 2B), the time constant of recovery was typically >4 d (see also Table III). In contrast, the single exponential fit of SOT 5 (Fig. 2C) was dominated by faster recovery dynamics of <1 d. In this condition, a double-exponential fit would provide a better estimate both the fast (days) and slow (weeks) recovery. The variability across crewmembers was also striking during the unstable support conditions, with several crewmembers performing near preflight levels within the first day after landing. As illustrated in Fig. 2D, the majority of crewmembers continued to have difficulty during the first postflight week when required to make dynamic head tilts on an unstable support surface, with several falls during this condition occurring in the second postflight week.

To contrast the recovery dynamics of crewmembers from the three different phases of ISS Expeditions as described in Table I, different symbols have been used to differentiate each group in Fig. 2. The clearest difference was for SOT 5M (Fig. 2D) between the second group that used the SchRED and the last group that used the ARED. Although it is clear that the ARED group included several crewmembers with higher preflight performance, this group consistently outperformed the SchRED group throughout the postflight test period as well (note diamonds > squares).

Table III. Summary of SOT Continuous Equilibrium Scores: Preflight Mean Compared with Estimates of the Initial Postflight Scores (Recovery +0 h) and Time Constant (TC) of Recovery from Single Exponential Fits.

SOT	PRE MEAN (± SEM)	R+0 h (± 95% CL)	% CHANGE @ R+0 h	TC, h (± 95% CL)
1	94.3 (±0.3)	90.0 (±2.2)	4.6%	116.1 (±86.6)
2	89.9 (±0.6)	82.6 (±3.9)	8.1%	99.4 (±74.6)
2B	88.8 (±0.7)	78.2 (±6.3)	11.9%	110.7 (±116.3)
2M	87.8 (±1.2)	65.8 (±13.0)	25.0%	213.7 (±237.3)
3	92.4 (±0.5)	85.9 (±2.9)	7.0%	94.2 (±58.6)
4	87.9 (±0.8)	68.2 (±8.3)	22.3%	44.6 (25.6)
5	74.9 (±1.4)	13.2 (±21.1)	82.4%	19.4 (±10.7)
5B	62.3 (±2.5)	28.2 (±23.2)	54.7%	55.4 (±53.7)
5M	62.3 (±2.8)	< 0 (±25.3)	> 100%	110.6 (±54.4)
6	72.2 (±1.8)	n/a	n/a	n/a

See Table II and text for description of SOT conditions. SEM = standard error of the mean; R = recovery; CL = confidence limits.

Motor Control Tests

The same comparison between the SchRED and ARED expeditions is illustrated for the MCTs

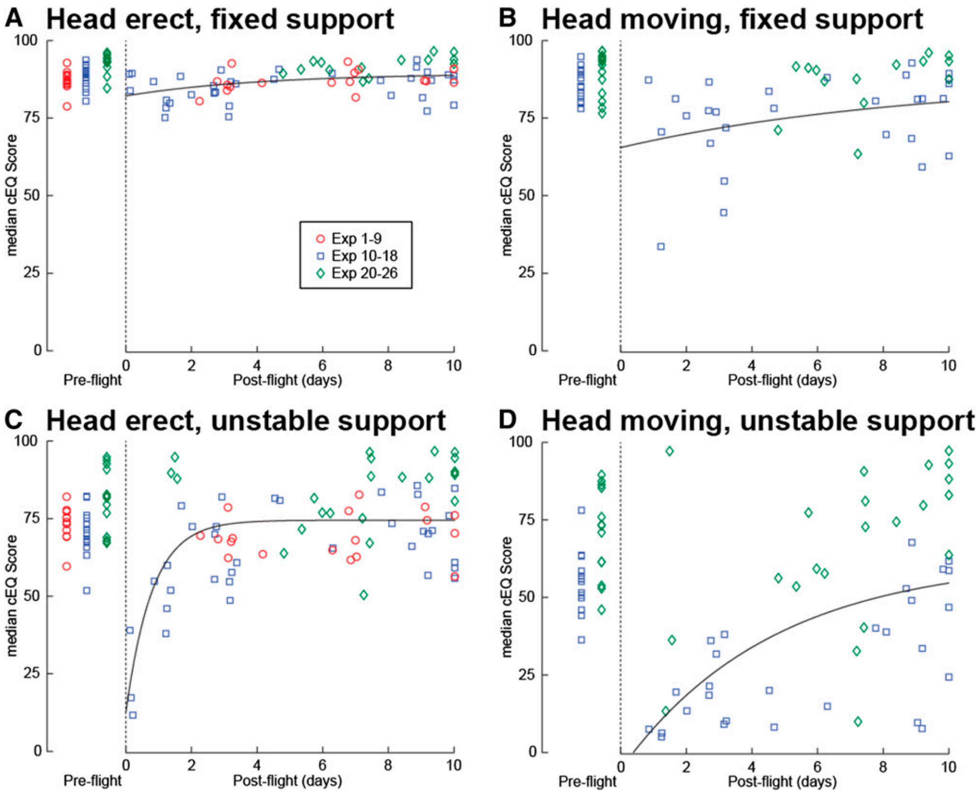

Fig. 2. Comparison of median cEQ scores for A) SOT-2, B) SOT-2M, C) SOT-5, and D) SOT-5M. Each point represents the median of 2–3 trials for one subject's session. The postflight days were determined by the actual hours elapsed since landing, with the exception that sessions occurring later than 240 h were assigned to 10 d. The solid line reflects the best-fit single exponential fit of the postflight data with the preflight mean used as the offset value. Data are separated by ISS phase, with crewmembers from Expeditions 1–9 noted with circles, crewmembers from Expeditions 10–18 noted with squares, and crewmembers from Expeditions 20–26 noted with diamonds.

in **Fig. 3**. While early postflight MCTs were only performed in the SchRED group, there are insufficient data to draw conclusions between these two groups based on the MCTs alone. Note that in contrast to the cEQ measurements, lower times to stability (Fig. 3A) and lower path lengths (Fig. 3B) represent improved performance. Based on the single exponential fits, the MCT recovery dynamics appear very similar to the SOTs 1–3 with the fixed support. The initial time to stability increased by 1.9 s (± 1.5 s, 95% CL), and the corresponding path length increased by 35.6 cm (14 in) [± 25.6 cm (10 in), 95% CL] based on the exponential fits.

DISCUSSION

The CDP performed during the first decade of ISS expeditions has added to an existing evidence base of impaired sensorimotor function following return to Earth. While the primary purpose of the CDP medical requirement is to assist the flight surgeons in return to duty assessments, data obtained during some earlier ISS expeditions have been helpful for estimating the initial decrements and recovery of postural stability following longer duration flights. Dynamic head tilts on unstable support led to increased incidence of falls, significantly greater decrements in performance, and a longer recovery than head erect and fixed-support conditions.

This is consistent with our findings from CDP testing following shorter duration Shuttle flights.[13] Following the Shuttle flights, the standard Romberg condition was also the least sensitive condition. When comparing the performance of astronauts relative to matched ground controls, the greatest diagnostic accuracy was observed in the sway-referenced support condition with head pitched dynamically (94.9% sensitivity, 96.6% specificity). Although the postural decrements are typically less following shorter duration flights,[6] the addition of dynamic head tilts was equally challenging with all 11 first-time Shuttle crewmembers falling during at least 1 trial on landing day.[13] Clearly the postflight clinical examinations are enhanced with the combination of dynamic head tilts and unstable support conditions.

While some crewmembers adopt a pitch-forward head tilt early after long-duration flights,[34] it is interesting to note that static head extension did not increase the sensitivity of the SOT conditions following spaceflight. The recovery of postural stability with dynamic head tilts was

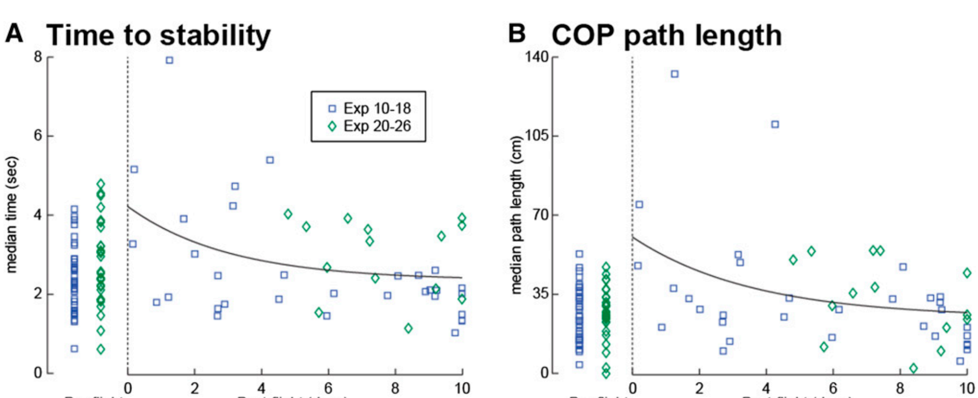

Fig. 3. Comparison of median time to stability and median COP path length obtained during unexpected large forward translations. The postflight days, exponential fit, and symbols are the same as indicated for Fig. 2.

similar to recent measurements of locomotor dysfunction after long-duration spaceflight using a functional mobility test (FMT).[23] In this ISS study, Mulavara and colleagues calculated that a typical subject would recover to 95% of preflight level by approximately 15 d postflight. We hypothesize that adaptive change in the processing of low-frequency otolith input results in a sensory reweighting toward somatosensory cues for balance control. The introduction of dynamic head tilts on an unstable support surface drives the crewmember to use the vestibular cues as during locomotion on the compliant surface during FMT.[23] Cohen and Kimball recently suggested a combination of SOT and FMT has more sensitivity and specificity to detect vestibular impairment than other subjective clinical scales.[7]

The dynamic head tilt condition was also more sensitive in separating out the recovery of balance control across ISS expeditions. Differences in the postflight performance can be attributed in part to the greater preflight levels during the later expeditions (Fig. 2D). A greater level of skill would afford more reserve capacity to compensate for sensorimotor disturbances postflight. However, the differences across expeditions may also be attributable to the enhanced exercise capabilities introduced on ISS during these later missions. Earlier resistive exercise devices had several limitations, including reduced maximal loading, varying resistance, and limited eccentric components. The ARED offered more in-flight exercises and the loading was improved to better simulate the constant mass and inertia of free-weight exercise.[14] We recently demonstrated that crewmembers using the ARED had improved postflight agility scores.[39] The degree of initial postflight decrement in several physiological systems is related to compliance with in-flight countermeasures.[15] In-flight exercises, although targeted primarily to minimize cardiovascular and musculoskeletal deconditioning, may have beneficial effects for postflight sensorimotor function related to mobility, most likely by requiring stable manipulation of external loads during lower-limb exercises (e.g., squats, leg presses).

Although two of the ARED group were on their second ISS expeditions, the increased postflight performance of this group is not likely due to previous flight experience. In fact, there were five first-time flyers in this group as compared to three in the iRED group and four in the SchRED group. Several crewmembers indicated their previous flight experience was most beneficial for the fine motor control skills learned for movement in microgravity. However, it is less clear how previous flight experience benefits postflight sensorimotor recovery. We previously observed that as a group veteran astronauts do not have the same level of sensorimotor impairment as first time flyers.[29] Postflight postural performance has not been consistently improved in crewmembers that have been tested on multiple missions. The best predictor of sensorimotor performance after a mission has been how that crewmember fared during previous flights.[32]

In addition to the improvements attributed to in-flight exercise conditioning, ISS crewmembers have benefited from the supervised reconditioning upon return to Earth.[21] Following landing, 2 h of crew time is reserved each day for postflight reconditioning. Over the course of the first decade of the ISS, this program has incorporated additional exercises that challenge multisensory integration with an increasing level of difficulty customized to the individual's state of recovery. This program also serves to increase crew self-awareness of fall risk.[39] The more mobile a crewmember is following gravitation transitions the quicker the sensorimotor symptoms will be resolved. One of the challenges for future exploration missions will be to provide the tools for crewmembers to self-administer their reconditioning exercises on planetary surfaces in a similar fashion to how the in-flight exercises are administered on the ISS.

Conclusions

The CDP provides a standardized sensorimotor measure that can be used to support both return-to-duty decisions by flight surgeons and evaluation of countermeasure prescriptions that may impact the recovery of sensorimotor function. Therefore, this medical requirement was rescheduled during later ISS expeditions to occur postflight only between 6 to 10 d after landing when postural recovery was presumed to be nearly complete. The absence of the early postflight tests, while perhaps not as critical for return-to-duty decisions, severely limits the second purpose of CDP as a standard measure for countermeasure evaluation. Sensorimotor changes are most profound shortly after gravitational transitions.[39] Therefore, only an epidemiological approach that quantifies the initial sensorimotor decrements can provide the evidence base for how candidate treatment paradigms affect these adaptive changes and allow objective risk-management decisions for future exploration missions.[10] We recommend that a shortened version of CDP incorporating dynamic head tilts, or an analogous sensorimotor measure, should be performed as soon as feasible after landing to define the initial decrements. This shortened protocol can then be tested periodically during the first postflight week to track the dynamics of recovery on both individual and group bases.

The CDP has documented the wide variability in postflight sensorimotor function across crewmembers. The results summarized in this report suggest some exploration crewmembers are likely to exhibit moderate to severe sensorimotor impairment shortly after landing when crew tasks are inherently more risk sensitive. Impairment during dynamic head tilts was often not observed as crewmembers and/or flight surgeons determined these conditions were too challenging to attempt early postflight. The end of the Shuttle program limits access to crewmembers for these critical early postflight assessments. We advocate for the development of field tests of sensorimotor function that should be implemented consistently across expeditions to assess crewmembers returning from ISS in remote landings sites, such as on the Soyuz in Kazakhstan. These field tests would provide an evidence base that could be used during future exploration missions during which crewmembers must self-assess their sensorimotor function following gravitational transitions, administer their own rehabilitation, and determine when they are ready to participate in extravehicular activities.

ACKNOWLEDGMENTS

This report was sponsored by the NASA ISS Program Office with reference to SSP 50260 – ISS Medical Operations Requirements Document (MORD) and SSP 50667 – Medical Evaluations Documentation (MED) Volume B. The authors wish to thank members of the Balance Control Laboratory at NASA Johnson Space Center for data collection and analysis support, the mission integration coordinators for implementation support, and the flight surgeons who advocated for the continued use of CDP as a medical requirement. Finally, we thank the crewmember participants for their willing participation and insightful feedback.

Authors and affiliations: Scott J. Wood, Ph.D., Azusa Pacific University, Azusa, CA; William H. Paloski, Ph.D., NASA Johnson Space Center, Houston, TX; and Jonathan B. Clark, M.D., M.P.H., Center for Space Medicine, Baylor College of Medicine, Houston, TX.

REFERENCES

1. Angelaki DE, McHenry MQ, Dickman JD, Newlands SD, Hess BJ. Computation of inertial motion: neural strategies to resolve ambiguous otolith information. J Neurosci. 1999; 19(1):316–327.
2. Antonutto G, Capelli C, Girardis M, Zamparo P, di Prampero PE. Effects of microgravity on maximal power of lower limbs during very short efforts in humans. J Appl Physiol (1985). 1999; 86(1):85–92.
3. Black FO. What can posturography tell us about vestibular function? Ann N Y Acad Sci. 2001; 942:446–464.
4. Black FO, Paloski WH. Computerized dynamic posturography: What have we learned from space? Otolaryngol Head Neck Surg. 1998; 118(3, Pt. 2):S45–S51.
5. Clark JB, Bacal K. Neurologic concerns. In: Barratt MR, Pool SL, editors. Principles of clinical medicine for space flight. New York (NY): Springer; 2008:361–380.
6. Clément G, Reschke MF. Neuroscience in space. New York (NY): Springer; 2008.
7. Cohen HS, Kimball KT. Usefulness of some current balance tests for identifying individuals with disequilibrium due to vestibular impairments. J Vestib Res. 2008; 18(5-6):295–303.
8. Feiveson AH, Metter EJ, Paloski WH. A statistical model for interpreting computerized dynamic posturography data. IEEE Trans Biomed Eng. 2002; 49(4):300–309.
9. Fitts RH, Riley DR, Widrick JJ. Physiology of a microgravity environment invited review: microgravity and skeletal muscle. J Appl Physiol. 2000; 89(2):823–839.
10. Gray GW, Sargsyan AE, Davis JR. Clinical risk management approach for long-duration space missions. Aviat Space Environ Med. 2010; 81(12):1128–1132.
11. Guedry FE, Rupert AR, Reschke MF. Motion sickness and development of synergy within the spatial orientation system. A hypothetical unifying concept. Brain Res Bull. 1998; 47(5):475–480.
12. Haibach PS, Slobounov SM, Slobounova ES, Newell KM. Aging and time-to-postural stability following a visual perturbation. Aging Clin Exp Res. 2007; 19(6):438–443.
13. Jain V, Wood SJ, Feiveson AH, Black FO, Paloski WH. Diagnostic accuracy of dynamic posturography testing after short-duration spaceflight. Aviat Space Environ Med. 2010; 81(7):625–631.
14. Korth D. Exercise countermeasure hardware evolution on ISS: The first decade. Aerosp Med Hum Perf. 2015; 86(12, Suppl.):A7–A13.
15. Kozlovskaya IB, Grigoriev AI. Russian system of countermeasures on board of the International Space Station (ISS): the first results. Acta Astronaut 2004; 55(3-9):233-237.
16. Kozlovskaya IB, Kreidich Yu V, Oganov VS, Koserenko OP. Pathophysiology of motor functions in prolonged manned space flights. Acta Astronaut. 1981; 8(9-10):1059–1072.
17. Kozlovskaya IB, Sayenko IV, Sayenko DG, Miller TF, Khusnutdinova DR, Melnik KA. Role of support afferentation in control of the tonic muscle activity. Acta Astronaut. 2007; 60(4-7):285–294.
18. Kozlovskaya IB, Yarmanova EN, Egorov AD, Stepantsov VI, Fomina EV, Tomilovaskaya ES. Russian countermeasure systems for adverse effects of microgravity on long-duration ISS flights. Aerosp Med Hum Perform. 2015; 86(12, Suppl.):A24–A31.
19. Layne CS, Mulavara AP, McDonald PV, Pruett CJ, Kozlovskaya IB, Bloomberg JJ. Effect of long-duration spaceflight on postural control during self-generated perturbations. J Appl Physiol (1985). 2001; 90(3): 997–1006.
20. LeBlanc A, Lin C, Shackelford L, Sinitsyn V, Evans H, et al. Muscle volume, MRI relaxation times (T2), and body composition after spaceflight. J Appl Physiol (1985). 2000; 89(6):2158–2164.
21. Loehr JA, Guilliams ME. Physical training for long-duration spaceflight. Aerosp Med Hum Perf. 2015; 86(12, Suppl.):A14–A23.
22. Merfeld DM. Rotation otolith tilt-translation reinterpretation (ROTTR) hypothesis: a new hypothesis to explain neurovestibular spaceflight adaptation. J Vestib Res. 2003; 13(4-6):309–320.
23. Mulavara AP, Feiveson AH, Fiedler J, Cohen H, Peters BT, et al. Locomotor function after long-duration space flight: effects and motor learning during recovery. Exp Brain Res. 2010; 202(3):649–659.
24. NeuroCom International. SMART EquiTest® System Operator's Manual. Clackamas (OR): NeuroCom; 2003.
25. Newman DJ, Amir AR, Beck SM. Astronaut-induced disturbances to the microgravity environment of the Mir Space Station. J Spacecr Rockets. 2001; 38(4):578–583.
26. Newman DJ, Jackson DK, Bloomberg JJ. Altered astronaut lower limb and mass center kinematics in downward jumping following space flight. Exp Brain Res. 1997; 117(1):30–42.
27. Pai YC, Patton J. Center of mass velocity-position predictions for balance control. J Biomech. 1997; 30(4):347–354.
28. Paloski WH, Black FO, Reschke MF, Calkins DS, Shupert C. Vestibular ataxia following shuttle flights: effects of microgravity on otolith-mediated sensorimotor control of posture. Am J Otol. 1993; 14(1): 9–17.
29. Paloski WH, Reschke MF, Black FO, Dow RS. Recovery of postural equilibrium control following space flight (DSO 605). In: Sawin CF, Taylor GR, Smith WL, editors. Extended Duration Orbiter Medical Project Final Report. Houston (TX): National Aeronautics and Space Administration; 1999:5.4-1–5.4-16.
30. Paloski WH, Wood SJ, Feiveson AH, Black FO, Hwang EY, Reschke MF. Destabilization of human balance control by static and dynamic head tilts. Gait Posture. 2006; 23(3):315–323.
31. Parker DE, Reschke MF, Arrott AP, Homick JL, Lichtenberg BK. Otolith tilt-translation reinterpretation following prolonged weightlessness: implications for preflight training. Aviat Space Environ Med. 1985; 56(6):601–606.
32. Reschke MF, Kornilova LN, Harm DL, Bloomberg JJ, Paloski WH. Neurosensory and sensory-motor function. In: Leach Huntoon CS, Antipov VV, Grigoriev AI, editors. Space Biology and Medicine. Reston (VA): AIAA Press; 1996:135–193.
33. Ross HE. Astronaut's perception of heaviness and limb position. Hum Perf Extrem Environ. 1998; 3(1):34–36.
34. Thornton WE, Hoffler GW, Rummel JA. Anthropometric changes and fluid shifts. In: Johnston RS, Dietlein LF, editors. Biomedical Results from Skylab. Washington (DC): NASA; 1977:330–338.
35. Watt DG, Money KE, Bondar RL, Thirsk RB, Garneau M, Scully-Power P. Canadian medical experiments on Shuttle flight 41-G. Can Aeronaut Space J. 1985; 31(3):215–226.
36. Whitney SL, Marchetti GF, Schade AI. The relationship between falls history and computerized dynamic posturography in persons with balance and vestibular disorders. Arch Phys Med Rehabil. 2006; 87(3):402–407.

37. Wiener S, Berthoz A. Forebrain structures mediating the vestibular contribution during navigation. In: Berthoz A, editor. Multisensory control of movement. New York (NY): Oxford University Press; 1993: 427–456.
38. Wood SJ. Human otolith-ocular reflexes during off-vertical axis rotation: Effect of frequency on tilt-translation ambiguity and motion sickness. Neurosci Lett. 2002; 323(1):41–44.
39. Wood SJ, Loehr JA, Guilliams ME. Sensorimotor reconditioning during and after spaceflight. NeuroRehabilitation. 2011; 29(2):185–195.
40. Wood SJ, Reschke MF, Black FO. Continuous equilibrium scores: factoring in the time before a fall. Gait Posture. 2012; 36:487–489.
41. Young LR, Oman CM, Watt DG, Money KE, Lichtenberg BK. Spatial orientation in weightlessness and readaptation to earth's gravity. Science. 1984; 225(4658):205–208.
42. Young LR, Oman CM, Watt DG, Money KE, Lichtenberg BK, et al. M.I.T./Canadian vestibular experiments on the Spacelab-1 mission: 1. Sensory adaptation to weightlessness and readaptation to one-g: an overview. Exp Brain Res. 1986; 64(2):291–298.