Original Research

AMERICAN ACADEMY OF OTOLARYNGOLOGY–HEAD AND NECK SURGERY FOUNDATION

OTO Open
1–8

DOI: 10.1177/2473974X17738767
http://oto-open.org
SAGE

Neurovestibular Symptoms in Astronauts Immediately after *Space Shuttle* and *International Space Station* Missions

Millard F. Reschke, PhD[1], Edward F. Good, MD[2], and Gilles R. Clément, PhD[3]

Sponsorships or competing interests that may be relevant to content are disclosed at the end of this article.

Abstract

Objectives. (1) To assess vestibular changes and related sensorimotor difficulties, especially instability of posture and gait, among astronauts immediately after they return from space and to compare the effects experienced after short- and long-duration space missions. (2) To determine whether any difficulties experienced were severe enough to impair the astronauts' ability to leave the spacecraft in the event of an emergency.

Study Design. Prospective cohort study.

Setting. National Aeronautics and Space Administration's Kennedy Space Center and Johnson Space Center.

Subjects and Methods. Fourteen crewmembers of 3 *Space Shuttle* missions that lasted about 1 week and 18 crewmembers of 8 *International Space Station* missions that lasted about 6 months were given brief vestibular examinations 1 to 5 hours after landing. These examinations focused on the presence of vestibular and motor coordination difficulties, as well as motion sickness and motion sensations. Standardized tests included the observation of abnormal eye movements, finger-to-nose pointing, standing up from a seated position, postural stability, and tandem gait.

Results. Unsteady walking and postural instabilities were observed after short- and long-duration missions. Motion sickness symptoms were observed after long-duration missions but not after short-duration missions. The symptom most frequently reported by the astronauts was an exaggerated perceived motion associated with sudden head movements during reentry and after landing.

Conclusion. The severity of the observed abnormalities would limit the ability of crewmembers during the first 5 hours after landing and increase the time required to leave the spacecraft during this period.

Keywords

vestibular examination, space flight, posture, gait, adaptation

Received July 19, 2017; revised August 22, 2017; accepted October 4, 2017.

Decreased mobility due to vestibular and sensorimotor alterations associated with space flight has been identified by the National Aeronautics and Space Administration's (NASA's) Human Research Program as a potential risk for human Mars missions.[1,2] This risk is the greatest during and immediately after transitions between different gravitational environments, when decrements in locomotion and spatial orientation might have high operational impact, such as emergency egress of the vehicle immediately after landing on a planetary surface.

Postural deficits and sensorimotor performance decrements have been observed in astronauts after they return from short- and long-duration missions.[3-7] Results of these studies showed decrements in postural stability and increased time required for postural recovery, both of which intensified as a function of flight duration.[8,9] However, previous investigations did not include testing during the first few hours after return from long-duration missions onboard the *International Space Station* (*ISS*); the first postflight testing was conducted 1 day after landing, when performance decrements had abated.

[1]Neuroscience Laboratories, Johnson Space Center, National Aeronautics and Space Administration, Houston, Texas, USA
[2]Baylor College of Medicine, University of Texas Health Science Center, Houston, Texas, USA
[3]KBRwyle, Houston, Texas, USA

Corresponding Author:
Gilles R. Clément, PhD, KBRwyle, 2400 NASA Parkway, Houston, TX 77058 USA.
Email: gilles.r.clement@nasa.gov

Symptoms of vestibular disorders have been observed in astronauts immediately after return from short-duration missions onboard the *Space Shuttle* flights.[10] These symptoms were recorded during medical debriefs between the astronauts and crew flight surgeons on the day of return (generally 2-4 hours after landing) and 3 days later. The severity of symptoms had considerably diminished 3 days after landing. Unfortunately, similar reports are not available for the immediate postlanding period of the *Soyuz* vehicle, which returns crewmembers from long-duration space missions on the *ISS*.

Here we report symptoms of vestibular disorders and associated sensorimotor alterations measured in astronauts 1 to 5 hours after they return from short-duration *Space Shuttle* missions or long-duration *ISS* missions. The scientific objective of this study was to assess the effects of mission length on symptoms of vestibular disorders, especially instability of posture and gait. The operational objective was to determine whether the severity of the symptoms would impair the crews' ability to quickly exit the vehicle in the event of an emergency.

Figure 1. The crew transport vehicle approaches the *Space Shuttle Discovery* after landing of the STS-114 mission at Dryden Flight Research Center, Edwards, California. Photo courtesy of the National Aeronautics and Space Administration / Carla Thomas.

Table 1. Time after Landing When the Vestibular Examination of the *Space Shuttle* and *ISS* Subjects Started.

Mission	Crewmembers, n	Time after Landing, min
Space Shuttle		
1	3	110-130
2	7	30-90
3	4	45-75
ISS		
1	2	55-75
2	1	300
3	3	245-280
4	3	75-95
5	3	75-115
6	1	260
7	3	85-290

Abbreviation: *ISS, International Space Station.*

Methods

Subjects

The *Space Shuttle* crewmembers included 12 men and 2 women (mean ± SD age, 42.4 ± 5.0 years) who flew on 3 missions that lasted about 1 week (mean duration, 7.4 ± 0.9 days). Four crewmembers were participating in their first space mission, and the remaining 10 had flown on at least 1 other occasion.

The *ISS* crewmembers included 16 men and 2 women (mean age, 45.5 ± 6.1 years) who were transported to and from the *ISS* on 8 *Soyuz* missions for missions that lasted about 6 months (mean duration, 175.8 ± 13.7 days). Seven crewmembers were participating in their first space missions, and 11 had flown on at least 1 other occasion.

Informed written consent was obtained from all the subjects. The study was conducted in accordance with the Helsinki Declaration of 2004, and ethical approval was obtained from NASA's Institutional Review Board.

Test Conditions

After a *Space Shuttle* mission, crewmembers were tested onboard the crew transport vehicle at the NASA Kennedy Space Center in Florida (**Figure 1**). This mobile clinic typically docked with the *Space Shuttle* within 20 minutes of landing. Astronauts left the *Space Shuttle*, with assistance if needed, via a short ramp to the crew transport vehicle, where they removed their reentry spacesuits and were examined and treated as necessary. The time of exit from the *Space Shuttle* varied considerably but typically ranged from 30 to 45 minutes after landing. All subjects in the present study were examined within 1 to 2 hours after landing (mean duration, 1.2 ± 0.5 hours; **Table 1**).

The crewmembers returned from long-duration *ISS* missions in the *Soyuz* capsule, which landed on the flat steppe of Kazakhstan in Central Asia. Testing was conducted in an inflatable tent at the *Soyuz* landing site or in a quiet room at the Karaganda airport (Kustanai) in Kazakhstan. Within minutes of landing, the astronauts were extracted from the capsule by the recovery teams. The crewmembers then sat in reclining seats before being moved to the inflatable tent for postlanding assessment (**Figure 2**). After all the medical checks were performed, crewmembers were then flown by helicopter to the Karaganda airport. Ten *ISS* crewmembers in the present study were examined in the tent 1 to 2 hours after landing, and 6 other *ISS* crewmembers were examined in the airport within 2 to 5 hours of landing (mean duration, 2.7 ± 1.6 hours; **Table 1**). Two crewmembers could not be tested in the tent or the airport because of severe motion sickness symptoms.

Examination

Because the *Space Shuttle* and *ISS* crewmembers' postlanding examinations were performed several years apart, the

Figure 2. The *International Space Station* crews remove their spacesuits and undergo medical checks in an inflatable tent after they land in a *Soyuz* capsule near the town of Zhezkazgan, Kazakhstan. Photo courtesy of the National Aeronautics and Space Administration.

personnel and procedures differed. Nevertheless, the vestibular and motor function tests used for the present study were comparable, as described in **Table 2**. However, there were some notable differences among the testing protocols. Because of time constraints, saccades and pursuit were not examined in the *ISS* subjects, and pointing tests were performed after only 3 *ISS* expeditions (missions 5-7). Unlike the *Space Shuttle* subjects, the *ISS* subjects were not asked to keep their hands crossed in front of the body during the chair stand test and the postural stability test. In addition, when standing upright, the *ISS* subjects could place their feet at a comfortable position, typically equal to their shoulder width, whereas the *Space Shuttle* subjects were asked to stand upright with their feet together. These conditions were imposed on the *ISS* crew for safety reasons; the sudden transition from a prone position to a standing position just before the testing could cause dizziness and/or faintness due to orthostatic intolerance, so a wide stance was accepted to make the stand tests less challenging. However, the floor of the medical tent was not as flat as that of the crew transport vehicle, and this made the balance and gait tests more challenging for the *ISS* subjects.

In addition to the tests described in **Table 2**, subjects were asked if they had experienced coordination difficulties or perceptions that their body or their surroundings were moving during head and body movements. Subjects were also asked if they had experienced motion sickness during their flight and at the time of the postflight examination. The occurrence of reentry motion sickness was characterized by the presence of pallor, cold sweating, nausea, and vomiting. To mitigate the symptoms, 9 crewmembers who had a history of reentry motion sickness took an oral dose (25 mg) of meclizine or promethazine after the deorbit burn (ie, 2-3 hours before the postflight vestibular examinations started).

Examinations of the *Space Shuttle* crewmembers were performed by 1 of the authors (E.F.G.), who is a neurologist. For the *ISS* crews, the examinations were videotaped and subsequently evaluated by us.

Results

Vestibular and Motor Function Tests

Table 3 shows the number of *Space Shuttle* and *ISS* subjects with positive results for each test. To compare the responses of the *Space Shuttle* and *ISS* subject groups, Fisher's exact test was calculated for 2 × 2 contingency tables. Indeed, for comparing proportions between 2 populations, Fisher's exact test tends to be more accurate than Pearson's chi-square test when samples of 2 small populations are compared.[11]

The main observations are summarized as follows:

- All *Space Shuttle* subjects had normal test results for saccade and pursuit tracking.
- One *Space Shuttle* subject had an upbeating positional nystagmus when sitting upright that was detected through Frenzel goggles but considered to be within reference range. Attempts to induce paroxysmal positional nystagmus were negative for the 2 *Space Shuttle* subjects tested with the Dix-Hallpike maneuver.[12]
- Gaze-evoked nystagmus with prolonged gaze holding at large lateral and upward eccentricities was noted in 29% of *Space Shuttle* subjects and 38% of *ISS* subjects.
- The most common abnormal finding was the incapacity to walk heel to toe along a straight line without stumbling or falling. This difficulty was demonstrated by 79% of *Space Shuttle* subjects and all 9 *ISS* subjects tested (100%). All subjects demonstrated abnormal broad-based gait during normal walking. The typical distance between the feet was 45 cm.
- The next-most common abnormality, dysmetria during the pointing test, was exhibited by 71% of the *Space Shuttle* subject and 57% of the *ISS* subjects during their first few attempts at finger-to-nose testing. All subjects achieved the target by the third to fifth attempts.
- All subjects but 1 reported that standing immediately after landing required extraordinary effort. Fifty-seven percent of *Space Shuttle* subjects and 29% of *ISS* subjects could not stand from a seated position without assistance. Orthostatic intolerance, decrease in muscular strength, and microgravity-induced changes in central muscular coordination contributed to this deficiency.
- Postural instability during the standing test was positive for 36% of the *Space Shuttle* subjects and 31% of the *ISS* subjects. The *ISS* crewmembers who were tested immediately after landing (ie, after the same delay as for the *Space Shuttle* crewmembers) did not have difficulties in maintaining upright balance.

Table 2. Description of the Oculomotor and Motor Tests Performed Immediately after *Space Shuttle* and *ISS* Missions.

	Space Shuttle	*ISS*
Oculomotor tests	Subjects were asked to gaze in various directions or to follow the examiner's moving finger. Gaze-evoked nystagmus, abnormally slow or fast saccades, asymmetry, and inaccurate tracking were assessed qualitatively by relying on direct observation of the subjects' eye movements in visible light. Two subjects were examined for signs of positional nystagmus via Frenzel goggles and the Dix-Hallpike maneuver.[12]	Subjects were asked to gaze in various directions or to follow the examiner's moving finger. Gaze-evoked nystagmus was assessed qualitatively by relying on direct observation of the subjects' eye movements in visible light.
Pointing	The examiner raised a finger in front of the subjects and asked them to touch it with their finger and then touch their nose several times. This showed the subjects' ability to judge the position and distance of a target. Abnormal responses included under- or overshoot of the intended position and lack of coordination of movement.	The subjects were asked to touch their nose alternatively with their right and left index fingers several times. Abnormal responses included under- or overshoot of the intended position and lack of coordination of movement.
Chair stand test	Subjects sat in a chair and placed their hands, crossed at the wrists, on the opposite shoulder. They kept their feet flat on the floor and their back straight. They were then asked to rise to a full standing position while keeping their arms against their chest. Subjects failed this test when they could not stand up without assistance or when they used their arms to complete the test.	Subjects sat in a chair with their arms at their sides. They kept their feet flat on the floor and their back straight. They were then asked to rise to a full standing position without using their arms. Subjects failed this test when they could not stand up without assistance or when they used their arms to complete the test.
Postural stability	Subjects stood with their 2 feet together, their arms crossed in front of their body, and they tried to maintain their balance with their eyes open and subsequently with their eyes closed. Losing balance was defined as large body sway, placing 1 foot in the direction of the fall, or falling.	Subjects stood up from the prone position and tried to maintain their balance with their eyes open. They placed their feet at a comfortable position, about shoulder width apart, arms at their sides. Losing balance was defined as large body sway, placing 1 foot in the direction of the fall, or falling.
Tandem walking	Subjects were walking in a straight line with the front foot placed such that their heel touched the toe of the standing foot. Abnormal gait was characterized by jerky, unsteady motion of the trunk and an unsteady gait, as well as spreading the legs apart to widen the base of support.	Subjects were walking with the front foot placed such that their heel touched the toe of the standing foot. Their arms were crossed in front of the body. A successful test was characterized by completing steps in a heel-to-toe fashion without gaps, side-stepping, or pausing for several seconds to regain balance.

Abbreviation: *ISS, International Space Station*.

Subjective Reports

All subjects reported feeling unstable or unbalanced when walking, particularly when making turns. Four *Space Shuttle* subjects had headaches after landing, and 3 subjects reported having had headaches during the first 2 or 3 days of flight. Postflight headache in 1 of these individuals was related to position (worse when upright, relieved upon lying supine). Only 1 *ISS* crewmember reported headache after landing.

All 16 *ISS* subjects reported being nauseated immediately after landing. In addition to these 16 subjects, 2 other crewmembers could not be tested in the tent or at the airport because of severe reentry motion sickness symptoms. Interestingly, none of the *Space Shuttle* crewmembers had symptoms of reentry motion sickness after landing. However, 7 *Space Shuttle* subjects reported being nauseated, an indicator of space motion sickness, during the first few days of flight. Unfortunately, in-flight reports of symptoms were not available for *ISS* crewmembers.

Fifty percent of *Space Shuttle* subjects and 75% of *ISS* subjects perceived motion of the environment or their body when they moved their head. Translational movements along the fore-aft, lateral, or vertical axis produced a sense of accentuated motion in that direction. One subject bent forward to counteract the sensation of falling in that direction and needed to straighten up abruptly to avoid falling. While *Space Shuttle* subjects stooped during postflight testing, they felt that the floor was "rushing up to meet them," a symptom that has been reported previously.[3,13] This sensation ceased immediately when body or head motion stopped.

Table 3. Subjects Who Displayed Postflight Vestibular Abnormalities after *Space Shuttle* and *ISS* Missions.

	Subjects, n (%)		
	Space Shuttle (n = 14)	*ISS* (n = 16)	*P* Value[a]
Oculomotor tests			
Saccades/pursuit	0 (0)	N/A	N/A
Positional nystagmus	1 (7)	N/A	N/A
Gaze-evoked nystagmus	4 (29)	6 (38)	.709
Motor tests			
Pointing	10 (71)	4 of 7 (57)	.638
Chair stand test	8 (57)	4 of 14 (29)	.251
Postural stability	5 (36)	5 (31)	.999
Tandem walking	11 (79)	9 of 9 (100)	.253
Symptoms			
Reentry motion sickness	0 (0)	16 (100)	<.001
Headache	4 (29)	1 (6)	.157
Space motion sickness	7 (50)	N/A	N/A
Subjective reports			
Motion illusions	7 (50)	12 (75)	.257
Feeling unstable	13 (93)	16 (100)	.467

Abbreviations: *ISS, International Space Station*; N/A, not available.
[a]Fisher's exact test.

Other symptoms described by *Space Shuttle* crewmembers included foot tingling when pressure was applied to the soles of the feet during reentry but not when walking after landing. Skin sensitivity changes have been reported in several other short-duration missions.[14] Although *ISS* subjects did not report a tingling sensation in their feet, they all reported that their head and limbs felt very heavy after landing. None of the subjects reported diplopia, or double vision.

Discussion

The primary purpose of this study was to assess symptoms that might impede an astronaut's ability to exit the vehicle unassisted after landing. Many of the subjects in this study demonstrated vestibular abnormalities that could limit this ability during the first 5 hours of landing.

Although the time required to leave the spacecraft unassisted after landing has not been systematically measured, for obvious safety constraints, there has been casual observations by the crews. For example, during return of *Expedition 6* from the *ISS*, a technical malfunction caused the *Soyuz* spacecraft to land some 460 km away from its planned touchdown point. The 5-hour delay for arrival of the ground support team gave the crew an opportunity to open the hatch, unstrap, and egress the *Soyuz* spacecraft without any outside help. Performing fast, coordinated movements was not possible, and head movement provoked oscillopsia and nausea.[15]

The present study shows that the percentage of crewmembers with symptoms of vestibular disorders was similar after long-duration *ISS* missions and short-duration *Space Shuttle* missions, with the exception of reentry motion sickness. Russian investigators previously reported that motion sickness during reentry affects 27% of the cosmonauts after short-duration missions (4-14 days) and 92% after longer-duration missions (several months to 1 year).[16,17] Our observations following *ISS* missions support these earlier reports.

The percentage of *Space Shuttle* subjects who had symptoms of vestibular disorders in the present study is similar to that reported for studies of 112 astronauts who flew on the *Space Shuttle* between 1996 and 2000.[10,18] In these previous studies, the most frequent symptoms of vestibular disorders were persisting sensation aftereffects (60%), difficulty walking in a straight line (57%), unstable balance (48%), imprecise finger-to-nose pointing (20%), and use of arms for rising from a chair (14%).

Postflight sensory feedback, postural equilibrium, and motor performance have important implications for the success of potential emergency egress from the space vehicle immediately after landing. Our results indicate that *Space Shuttle* and *ISS* subjects would both have serious difficulties egressing a spacecraft without assistance soon after landing in case of an emergency. A previous report estimated that 5% to 15% of *Space Shuttle* crewmembers would be unable to egress the *Space Shuttle* due to neurovestibular symptoms and orthostatic intolerance after landing.[18] Since *ISS* crewmembers have a greater incidence of reentry-induced motion sickness, this might exacerbate performance of an emergency egress after long-duration missions.

We expected, however, that the proportion of subjects who failed the standing and balance tests would be higher after *ISS* than *Space Shuttle* missions, as shown by the results of computerized dynamic posturography,[9,19] but this was not the case in our study. Our results might be affected by the different testing conditions for the *Space Shuttle* and *ISS* subjects. Indeed, the *Space Shuttle* subjects performed tests with their feet together and their arms across the chest, whereas the *ISS* subjects had their feet apart and their arms aligned with their body. Also, the degree of impairment after landing probably reflects factors other than mission duration, such as previous flight experience, in-flight exercise, and the use of other procedures intended to preserve orthostatic function upon return to Earth. For example, the conditions of reentry for the *Space Shuttle* and the *Soyuz* capsule are different. The decelerating gravitoinertial force in *Soyuz* is about 4 Gx (directed along the subject's chest to back), as opposed to 1.2 Gz in the *Space Shuttle* (directed along the subject's head to toe). *Space Shuttle* crews were required to wear a specialized suit weighting about 32 kg; thus, leaving the vehicle, even under nominal conditions, was physically strenuous. Finally, the *Space Shuttle* floor was nearly horizontal after landing (except for a 6-degree forward pitch attitude), whereas the *Soyuz* capsule could land upright on its side and the terrain might not be flat.

Another limitation of this study is that postflight vestibular examinations were performed in some subjects who took meclizine or promethazine. These vestibular suppressants can impair vestibular perception and cause drowsiness,[20] affecting the results of the vestibular examination and limiting the applicability of assessing symptoms that might impede an astronaut's ability to exit the vehicle unassisted after landing.

Vestibular Abnormalities after Space Flight

The 2 most frequent findings in this study were postural instability and reports of illusory sensations that the self or the environment was moving during rapid movements of the head or torso. Postural abnormalities during the immediate postlanding period have been documented[3,4,21] and are generally believed to reflect disturbances in vestibular or proprioceptive function. Numerous anecdotal reports of perceived motion associated with head movements have been noted as well (reviewed by Reschke et al[22]). These illusory movement sensations, particularly oscillopsia, are usually attributed to disturbances in vestibular or cerebellar function[12] and may well have a different etiology from the postural disturbances.

The vestibular system unquestionably plays an important role in postural and locomotor control. Acute injuries to the vestibular system produce imbalance and vertigo, after which subjects (animals, humans with labyrinthine defects) accommodate and regain the ability to walk.[12] The action of antigravity muscles depends on vestibular system activity.[23] Impairments in the ability to identify the direction of discrete whole body linear movements after returning from space could indicate that otolith function may be less sensitive after a space flight than before.[22]

It has been proposed that vestibular, proprioceptive, and visual inputs, which are critical for equilibrium and gait, are redundant (ie, that only 1 is sufficient under normal conditions).[24] Many patients with bilateral vestibular loss do not have normal gait and fall frequently.[25,26] However, some patients with labyrinthine defects learn to walk without difficulty, despite visual blurring with sudden head movements.[27] These individuals also have little difficulty maintaining balance with their eyes closed and their feet together,[28] suggesting that they are mainly using proprioceptive inputs for balance. In addition, individuals with severe sensory neuropathy cannot maintain their balance in the dark or with their eyes closed, despite having normal vestibular systems. Postural instability can be evoked in those without sensory defects by several methods: extending the subject's neck so that visual fixation is impossible and the otoliths are out of their normal plane of function, occluding or perturbing visual stimuli, or minimizing foot proprioception by having the subject stand on a thick surface.[29] Bed rest and dry immersion both produce postural instability that persists for roughly the same period as the postural instability noted after space flight,[30] which implies that proprioception is a likely factor in producing this instability.

Illusory motion sensation has long been thought to depend on an intact vestibular system. Mach[31] demonstrated that sudden acceleration or deceleration produced sensations of movement in the direction opposite that of the acceleration. Illusory motion sensation can be produced through other means, such as visual stimuli or vibrating peripheral muscle spindles.[32,33] Space crewmembers returning to Earth have reported that moving their head in pitch or roll can cause the sensation of an exaggerated translational motion in direction to the head movement. This phenomenon has occurred during reentry and occasionally shortly after landing, and it has been attributed to a reinterpretation of the otolith signals.[34,35] On Earth, otolith signals may be interpreted as linear motion or head tilt relative to gravity. Because stimulation from gravity is absent during spaceflight, interpretation of the graviceptors as tilt is inappropriate. Therefore, during adaptation to weightlessness and shortly after return to Earth, the brain would interpret all otolith graviceptor inputs to indicate translation.

Postflight disturbances in balance and walking control could be due in part to changes in how the central nervous system processes sensory information as a result of prolonged exposure to weightlessness.[22] Investigators have proposed a training program for facilitating recovery of balance and locomotor function after long-duration space flight. Manipulating the sensory conditions during exercise (eg, varying visual flow patterns during walking on a treadmill while watching a moving screen) will systematically and repeatedly promote adaptive change in walking performance and improve the astronaut's ability to adapt to a novel gravity environment. It is anticipated that this training regimen will facilitate neural adaptation to unit gravity (Earth) and partial gravity (Mars) after long-duration space flight.[36]

Impact for Clinical Research

Balance disorders and illusory motion sensations develop in healthy individuals as a result of exposure to microgravity and subsequent reexposure to normal gravity. Space research provides an invaluable opportunity to understand the evolutionary physiology of humans. From a neurologic perspective, the unique aspects of the space flight environment are particularly important for elucidating the mechanisms of spatial orientation, posture, and locomotion.

As people age on Earth, they sometimes experience instabilities when standing and walking. The development of simple walking and balance training procedures like the ones used by the astronauts in orbit can be used to help prevent falling and injury in the elderly population.[37] Also, the abbreviated vestibular examination designed for use aboard the crew transport vehicle and in the medical tent can be used to remotely evaluate elderly or patients with vestibular disorders. Because smartphones have introduced an easy method to record video, patients could record themselves performing stand tests and tandem walking tests at regular intervals in their homes, and otolaryngologists or neurologists could remotely evaluate their recovery.

Acknowledgments

We are grateful to Sam L. Pool, Charles F. Sawin, Denise Baisden, Richard T. Jennings, Larry O. Pepper, Christine Wogan, John B. Charles, and Inessa Kozlovskaya for their enthusiastic support of this work and to Igor Kofman, Liz Fisher, Joel Montalbano, and Jody Cerisano for their help with data collection and analysis.

Author Contributions

Millard F. Reschke, study design, data collection, data analysis, manuscript writing; **Edward F. Good**, study design, data collection, data analysis, manuscript writing; **Gilles R. Clément**, data analysis, manuscript writing.

Disclosures

Competing interests: None.

Sponsorships: None.

Funding source: National Aeronautics and Space Administration, study design and conduct; collection, analysis, and interpretation of the data; and writing or approval of the manuscript.

References

1. Paloski WH, Oman CM, Bloomberg JJ, et al. Risk of sensory-motor performance failures during exploration-class space missions: a review of the evidence and recommendations for future research. *J Gravit Physiol*. 2008;15:1-29.
2. Bloomberg JJ, Reschke MF, Clément G, et al. *Risk of Impaired Control of Spacecraft/Associated Systems and Decreased Mobility due to Vestibular/Sensorimotor Alterations Associated with Space Flight*. Houston, TX: Johnson Space Center; 2016. National Aeronautics and Space Administration report TM JSC-CN-36487.
3. Homick JL, Reschke MF. Postural equilibrium following exposure to weightless space flight. *Acta Otolaryngol*. 1977;83: 455-464.
4. Anderson DJ, Reschke MF, Homick JE, Werness SA. Dynamic posture analysis of *Spacelab-1* crewmembers. *Exp Brain Res*. 1986;64:380-391.
5. Bloomberg JJ, Peters BT, Smith SL, et al. Locomotor head-trunk coordination strategies following space flight. *J Vestib Res*. 1997;7:161-177.
6. Mulavara AP, Feiveson A, Feidler J, et al. Locomotor function after long-duration space flight: effects and motor learning during recovery. *Exp Brain Res*. 2010;202:649-659.
7. Bloomberg JJ, Mulavara AP. Changes in walking strategies after space flight. *IEEE Eng Med Biol Mag*. 2013;22:58-62.
8. Wood SJ, Loehr JA, Guilliams M. Sensorimotor reconditioning during and after spaceflight. *NeuroRehabilitation*. 2011;29: 185-195.
9. Wood SJ, Paloski WH, Clark JB. Assessing sensorimotor function following *ISS* with computerized dynamic posturography. *Aerosp Med Hum Perform*. 2015;86(suppl 12):A45-A53.
10. Bacal K, Billica R, Bishop S. Neurovestibular symptoms following space flight. *J Vestib Res*. 2003;13:93-102.
11. McDonald JH. *Handbook of Biological Statistics*. 3rd ed. Baltimore, MD: Sparky House Publishing; 2014.
12. Baloh RW, Honrubia HH, eds. *Clinical Neurophysiology of the Vestibular System*. 2nd ed. Philadelphia, PA: FA Davis; 1990. Contemporary neurology series 32.
13. Watt DGD, Money KE, Tomi LM. MIT/Canadian vestibular experiments on the *Spacelab-1* mission: 3. Effects of prolonged weightlessness on a human otolith-spinal reflex. *Exp Brain Res*. 1986;64:308-315.
14. Lowrey CR, Perry SD, Strzalkowski NDJ, et al. Selective skin sensitivity changes and sensory reweighting following short-duration space flight. *J Appl Physiol*. 2014;116:683-692.
15. Pettit D. Mars landing on Earth: an astronaut's perspective. *J Cosmology*. 2010;12:3529-3536.
16. Ortega HJ, Harm DL. Space and entry motion sickness. In: Barratt MR, Pool SL, eds. *Principles of Clinical Medicine for Space Flight*. New York, NY: Springer; 2008:211-222.
17. Gorgiladze GI, Bryanov II. Space motion sickness. *Kosm Biol Aviakosm Med*. 1989;23:4-14.
18. Clark JB, Bacal K. Neurologic concerns. In: Barratt MR, Pool SL, eds. *Principles of Clinical Medicine for Space Flight*. New York, NY: Springer; 2008:361-379.
19. Cohen HS, Kimball KT, Mulavara AP, et al. Posturography and locomotor tests of dynamic balance after long-duration spaceflight. *J Vestib Res*. 2012;22:191-196.
20. Diaz-Artiles A, Priesol AJ, Clark TK, et al. The impact of oral promethazine on human whole-body motion perceptual thresholds. *J Assoc Res Otolaryngol*. 2017;18:581-590.
21. Watt DGD, Money KE, Tomi LM, Better H. Otolith-spinal reflex testing on *Spacelab-1* and *D-1*. *Physiologist*. 1989; 32(suppl 1):S49-S52.
22. Reschke MF, Clément G, Thorson SL, et al. Neurology. In: Nicogossian AE, Williams RS, Huntoon CL, et al, eds. *Space Physiology and Medicine: Evidence and Practice*. 4th ed. New York, NY: Springer-Verlag; 2016:245-282.
23. Jones GM, Watt DGD. Muscular control of landing from unexpected falls in man. *J Physiol*. 1971;219:729-737.
24. Nutt JG, Marsden CD, Thompson PD. Human walking and higher-level gait disorders, particularly in the elderly. *Neurology*. 1993;43:268-279.
25. Herdman SJ, Blatt P, Schubert MC, Tusa RJ. Falls in patients with vestibular deficits. *Am J Otol*. 2000;21:847-851.
26. Bessot N, Denise P, Toupet M, Van Nechel C, et al. Interference between walking and a cognitive task is increased in patients with bilateral vestibular loss. *Gait Posture*. 2012;36:319-321.
27. Grossman GE, Leigh RJ. Instability of gaze during locomotion in patients with deficient vestibular function. *Ann Neurology*. 1990;27:528-532.
28. Bles W, deJong JM, Rasmussens JJ. Postural and oculomotor signs in labyrinthine-defective subjects. *Acta Otolaryngol (Stockh)*. 1984;406:101-104.
29. Brandt T, Krafczyk S, Malsbenden I. Postural imbalance with head extension: improvement by training as a model for ataxia therapy. *Ann NY Acad Sci*. 1981;374:636-649.
30. Koppelmans V, Mulavara AP, Yuan P, et al. Exercise as potential countermeasure for the effects of 70 days of bed rest on cognitive and sensorimotor performance. *Front Syst Neurosci*. 2015;9:121.
31. Mach E. *Grundlinien der Lehre von den Bewegungsempfindungen*. Leipzig, Germany: W. Engelmann; 1875. Amsterdam, Netherlands: Bonset; 1967 (translation).
32. Roll JP, Popov KE, Gurfinkel VS, et al. Sensorimotor and perceptual function of muscle propriception in microgravity. *J Vestib Res*. 1993;3:259-273.
33. McDonald PV, Bloomberg JJ, Layne CS. A review of adaptive change in musculoskeletal impedance during space flight and associated implications for postflight head movement control. *J Vestib Res*. 1997;7:239-250.

34. Young L, Oman CM, Watt DGD,et al. Spatial orientation in weightlessness and readaptation to Earth's gravity. *Science*. 1984;225:205-208.
35. Parker DE, Reschke MF, Arrott AP, et al. Otolith tilt-translation reinterpretation following prolonged weightlessness: implications for preflight training. *Aviat Space Environ Med*. 1985;56:601-606.
36. Bloomberg JJ, Peters BT, Cohen HS, Mulavara AP. Enhancing astronaut performance using sensorimotor adaptability training. *Front Syst Neurosci*. 2015;9:129.
37. Buccello-Stout RR, Bloomberg JJ, Cohen HS, et al. Effects of sensorimotor adaptation training on functional mobility in older adults. *J Gerontol B Psychol Sci Soc Sci*. 2008;63:295-300.