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Sensorimotor Disturbances in Astronauts Following Space Flight: Causes, Evaluation, and Countermeasures

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Sensorimotor Disturbances in Astronauts Following Space Flight: Causes, Evaluation, and Countermeasures

by

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Dedication

To my family, for providing the foundation in life that has led to opportunity.

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Sensorimotor Disturbances in Astronauts Following Space Flight: Causes, Evaluation, and Countermeasures

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Spaceflight induces a myriad of changes on the physiology of the human body. A cumulative result of many of these changes is sensorimotor dysfunction whereby small movements at the head level may lead to an exaggerated sense of movement. An astronaut's activities of daily living are directly affected until that time when his/her functional performance has returned to near-baseline, a process that may take up to 15 days post-return. These physiological changes can also affect performance in the foreseeable future during exploration class missions.

This project reviews current areas of research that are investigating possible countermeasures to reduce the time needed to return to baseline functional performance with regards to posture and gait instability. It will also review other strategies that are currently being utilized in the non-astronaut, outpatient rehabilitation setting and present evidence suggesting their potential ability to mitigate postflight sensorimotor dysfunction.

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List of Acronyms

CNS	Central Nervous System
COP	Center of Pressure
EVA	Extravehicular Activity
FMT	Functional Mobility Test
GVS	Galvanic Vestibular Stimulation
ISS	International Space Station
JSC	Johnson Space Center
MRI	Magnetic Resonance Imaging
NASA	National Aeronautics and Space Administration
NTRS	NASA Technical Reports Server
SOT	Sensory Organization Test
STS	Space Transportation System
TCC	Time to Course Completion
TSAS	Tactile Situation Awareness System
VOR	Vestibulo-ocular Reflex
VR	Virtual Reality
WMFT	Wolf Motor Function Test

CHAPTER 1 – INTRODUCTION

An astronaut's central nervous system is adapted to the Earth's gravitational field. Sensory inputs from the proprioceptive, vestibular, visual, and tactile systems are integrated within the brain and allow for harmonized control of movement. The loss of gravity during spaceflight leads to alterations in the body's inertial guidance system both centrally and peripherally. The transition from 0-g to 1-g also leads to sensorimotor dysfunction as the body again tries to adapt to its new environment. The results of these changes include space motion sickness, spatial disorientation, visual changes, manual control disruptions, and – of focus for this project – postural and gait instability.

The impact of such changes varies with setting. In the case of returning to Earth, the risk of injury while performing activities of daily living is apparent. For exploration class missions though, the risk lies during and after gravity transitions (postlaunch and postlanding). The disorientation and imbalance may lead to impaired vehicle egress, loss of vehicular control, and falls during extra-vehicular activity (EVA).[1] Other exacerbating factors to an astronaut's gait and posture include physical deconditioning from spaceflight, poor visual cues, and an altered center of gravity.

A compliant surface may also increase the risk of fall. This notion was investigated by MacLellan and Patla[2], where participants were instructed to walk under four separate conditions: normal ground, normal ground with an obstacle in the path, compliant surface, and compliant surface with an obstacle in the path. Full body kinematics was measured and swing limb kinetics derived. Data revealed that though the "CNS is able to appropriately adjust foot placement in the approach phase over a compliant travel surface, obstacle clearance show maladaptive changes that can potentially threaten stability."[2] There are multiple video clips available from the Apollo era lunar missions in which crewmembers are seen falling and having difficulty regaining their balance during EVAs. If any one of these events were to result in injury to a crewmember, the results could be catastrophic. Figure 1 lists some of the data collated from the Lunar Surface Journal from the NASA website. Of note, there was increase in the number of falls during Apollo 16 and 17 where astronauts logged over 20 hours of two-crew EVAs during each mission.

Mission	Time on Moon (hours)	# of EVAs	EVA Duration (2 crew EVA)	Falls
11	22	1	2.5	0
12	32	2	7.8	2
14	34	2	9.4	0
15	87	3	18.8	3
16	**71**	**3**	**21.3**	**10**
17	**75**	**3**	**22**	**8**
Total	12.5 days	14	81	23

Figure 1: Summary of falls occurring during EVAs (Apollo 11-17). Data Source: Apollo Lunar Surface Journal (www.hq.nasa.gov/alsj/frame.html)[3]

Researchers at the National Aeronautics and Space Administration use a functional mobility test (FMT) to assess locomotor dysfunction in International Space Station crewmembers. The FMT, Figure 2, is an obstacle course with many thick foam pylons and obstacles; the speed at which it is completed is purely dependent upon the astronaut. The various elements of this course force the subject to balance on one foot to step over styrofoam blocks, move their head to avoid hitting hanging pylons, and bend at the waist to maneuver without collision. The ground surface is also made of foam; this causes the subject to depend more upon their vestibular system for sensory input as it does not provide the same stability as a solid surface.

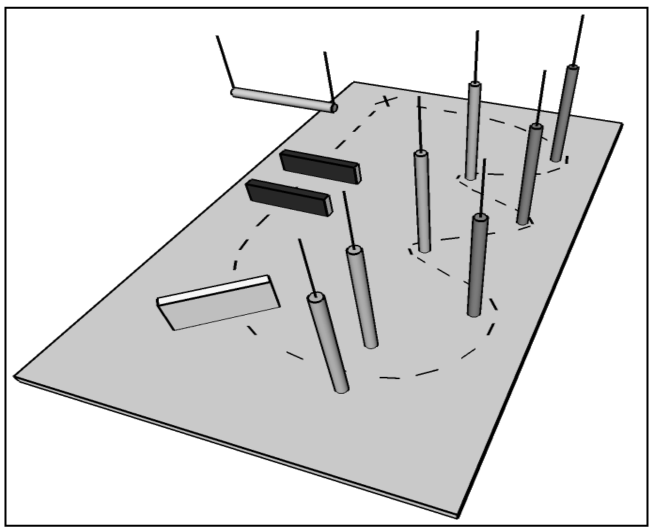

Figure 2: Functional mobility test obstacle course. Vertical pylons on right side suspended from ceiling for "slalom" section and horizontal styrofoam blocks on left side lay on floor as ground obstacles. (Mulavara AP, Feiveson AH, Fiedler J, et al. Locomotor function after long-duration space flight: effects and motor learning during recovery. *Exp Brain Res*. 2010;202(3):649-659.)[4] Image reproduced under license agreement, Springer Science and Business Media.

A study by Mulavara et al.[4] assessed preflight and postflight locomotor dysfunction in 18 ISS crewmembers, with each member experiencing an average of 185 days of flight time. Negotiating the course required a combination of balance, postural/truncal stability, and whole body coordination. The subjects served as their own controls and primary outcome was measured in time required to complete the course in seconds (TCC). All crewmembers demonstrated some form of altered locomotor function postflight, with a median 48% increase in the TCC.[4] The duration for recovery was estimated at 15 days for the typical subject to recover to 95% of his/her preflight score.[4] Time to complete course is represented graphically in Figure 3, and percent recovery in Figure 4.

On an individual basis, this study also analyzed the TCC for all trials from each daily session during the different days of postflight testing. This revealed that functional recovery after a long-duration mission was "comprised of two parts: (a) A rapid on-line strategic change characterized by immediate onset after landing; (b) A slower adaptive change requiring days to complete after landing."[5] (Figure 5) There was a significant positive correlation between long-term recovery and early motor learning parameters [Kendall's *Tau* = 0.69, P<0.001, 95% confidence interval (0.45, 0.92)].

In a separate preliminary study by Glasauer et al.[6], seven shuttle crewmembers were asked to navigate a triangular course with and without vision. Their motion was tracked and then plotted to assess what, if any, deviation could be seen when compared preflight and postflight. Figure 6 shows the intended and actual route of one subject from this study. There was an increase in postflight angular errors; however there was no significant change in reaching the corners and walking the required length. "The significant decrease in walking velocity and a change in head-trunk coordination while walking around the corners of the path observed post-flight may suggest that during re-adaptation to gravity the mechanisms which are necessary to perform the task have to be re-accomplished."[6]

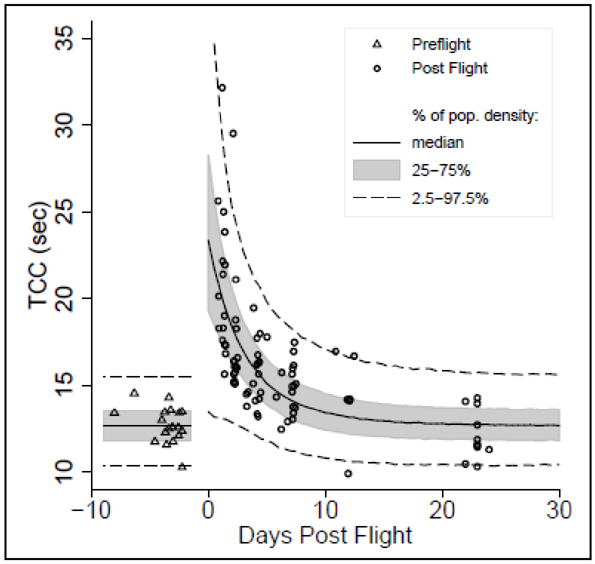

Figure 3: Time to complete course. (Mulavara AP, Feiveson AH, Fiedler J, et al. Locomotor function after long-duration space flight: effects and motor learning during recovery. *Exp Brain Res*. 2010;202(3):649-659.)[4] Image reproduced under license agreement, Springer Science and Business Media.

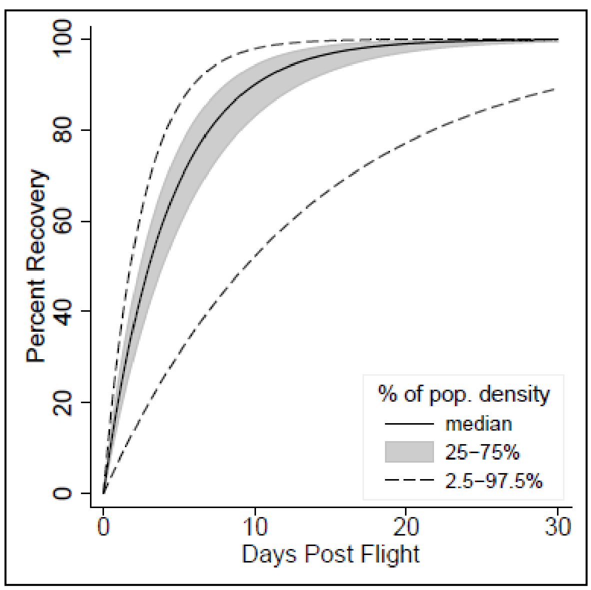

Figure 4: Percent recovery to baseline performance. (Mulavara AP, Feiveson AH, Fiedler J, et al. Locomotor function after long-duration space flight: effects and motor learning during recovery. *Exp Brain Res*. 2010;202(3):649-659.)[4] Image reproduced under license agreement, Springer Science and Business Media.

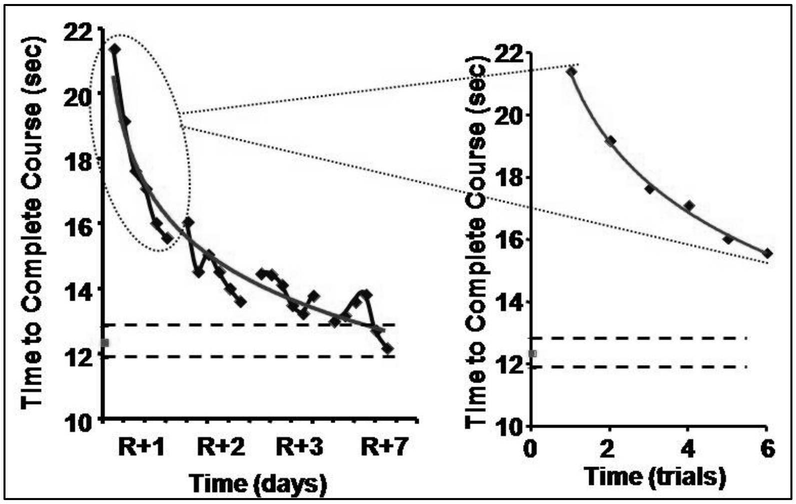

Figure 5: Scatter plot of single crewmember's TCC. Data based on all trials from each session during the different days of post-flight testing. The line-dot curve illustrates the fit to the first trial TCC across post-flight sessions. (Mulavara AP, Feiveson AH, Fiedler J, et al. Locomotor function after long-duration space flight: effects and motor learning during recovery. *Exp Brain Res*. 2010;202(3):649-659.)[4] Image reproduced under license agreement, Springer Science and Business Media.

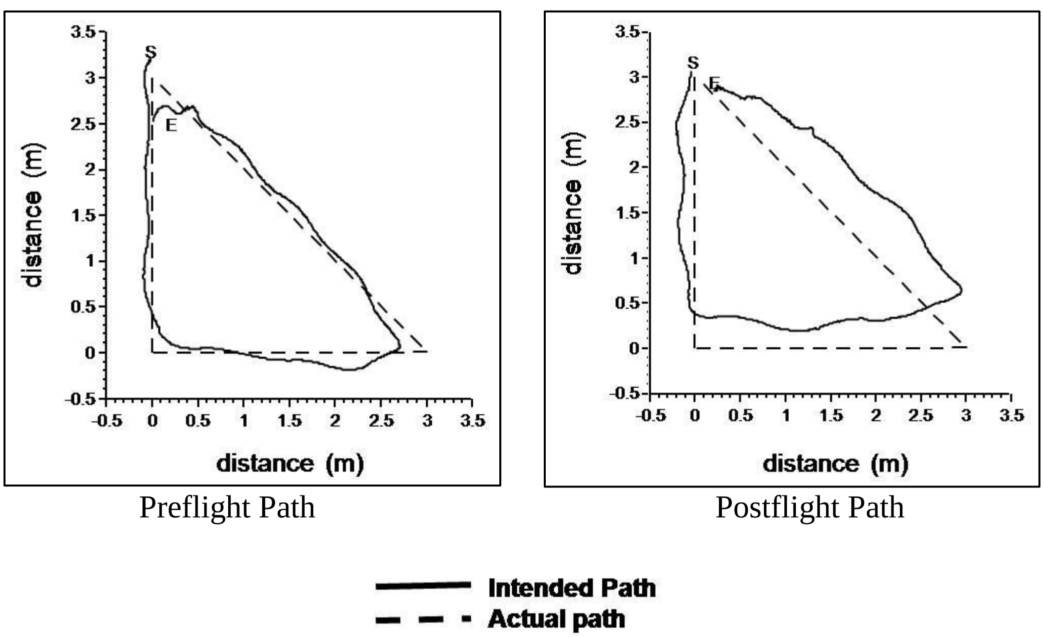

Figure 6: Walking test of a crewmember comparing preflight to postflight patterns.[5] Image reproduced under written permission from Jacob Bloomberg, PhD.

Prior research performed on board space shuttle missions between 1989 and 1995 as part of the NASA Extended Duration Orbiter Medical Project revealed changes to the vestibulo-ocular reflex (VOR) after spaceflight.[7] This reflex relies on sensory input from the vestibular apparatus within the inner ear. The otolith organs comprise the first part of the apparatus and are sensitive to changes in linear motion, head tilt, and the constant effect of gravity on Earth. During spaceflight though, the ability to recognize head tilt is lost and the brain perceives all otolith signals as being linear acceleration. The semicircular canals comprise the second part of the vestibular apparatus. Rotation at the head level is detected by the canals and leads to a compensatory eye movement in the opposite direction that helps stabilize a visual image on the fovea. Results from tests aboard various shuttle missions from 1989 to 1995 showed “there is degradation in the astronauts’ ability to acquire targets with the head and eyes, and to pursue moving targets, even when the location of these targets is known, and the acquisition or pursuit process has been practiced and rehearsed.”[8] Compensatory, in-flight mechanisms included a slower head velocity and an increase in the number of saccades made by the eyes. The return to preflight condition was seen by the fourth day postflight.

The VOR is not dependent upon visual cues and will therefore work in darkness. Nevertheless, exposure to space flight will lead to reinterpretation of existing vestibular information and changes in gaze stabilization. This collectively leads to a reduction in visual acuity during head motion.[5] Small positional changes at the head level, upon return to Earth, were also previously noted to create an exaggerated sense of movement based on early Neurolab Spacelab Mission reports.[9] Figure 7 illustrates some of the unusual sensations reported by crewmembers immediately postflight from the Mercury through shuttle era.[10]

All of the elements from the previous studies demonstrate an imbalance between sensory input and motor output. They help establish that postural and gait stability are directly affected with spaceflight. As such, the development of a plan to facilitate recovery of locomotor and functional capabilities is important. One of the goals of countermeasures is to decrease the time for adaptation to Earth, Mars, the moon or even an asteroid. As this primary goal is achieved, the risk of activity related injuries is reduced. The amount of available time for research and exploration at said destination is then also maximized.

NASA is currently investigating various countermeasure training programs including adaptability training, sensory supplementation, and artificial gravity. All of them engage one or more of the physiologic systems responsible for sensorimotor function. The outpatient rehabilitation sector often times will employ different methods to aid in the recovery or maintenance physical therapy of its patients. These methods have been demonstrated to challenge the body’s senses and postural stability, much like the strategies undergoing study at NASA. Some of the outpatient studies were limited by small sample size, but nevertheless the outcome of interest was within the realm of sensorimotor dysfunction and could lay the framework for further investigation.

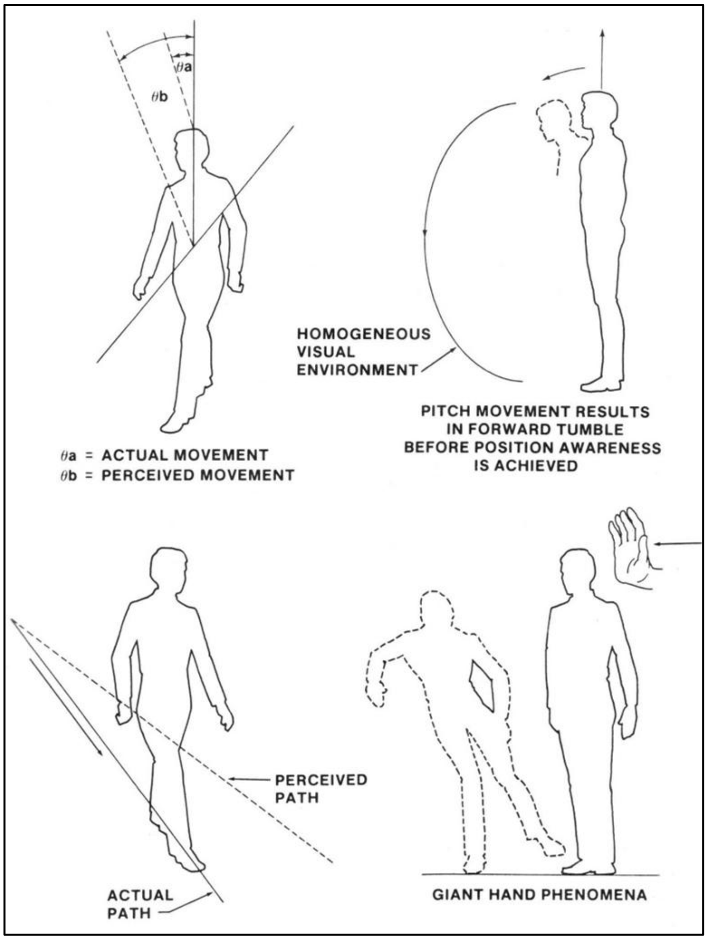

Figure 7: Unusual sensations associated with standing or walking after a flight.
(Nicogossian A, Huntoon CL, Pool S eds. *Space Physiology and Medicine, 2nd Edition*. 2nd ed. Lea and Febiger; 1989.)[10]

CHAPTER 2: METHODS

This capstone is based upon a synthesis of the existing literature and attendance of seminars given by some of the authors of such studies. No individuals were recruited for any invasive procedures or diagnostic studies.

Information was attained from presentations given by Jacob Bloomberg, PhD and William Paloski, PhD at the University of Houston main campus as part of a lecture series for Space Physiology: Systems Physiology. Both lecturers discussed sensorimotor dysfunction with a focus on etiology and countermeasures. The latest research and data from NASA were presented.

Systematic searches were conducted thru the United States National Library of Medicine database and OvidSP using individual keywords followed by various combinations of those keywords to produce phrases. These included but were not limited to: exercise rehabilitation, functional performance, gait disturbance, gait equilibrium, gait postflight, gaming therapy, juggling, locomotor (dys)function postflight, neurolab, Nintendo Wii ©, otolith dysfunction weightlessness, physical therapy, sensorimotor dysfunction, STS 90, vestibular function spaceflight, video coordination, video game rehabilitation, virtual reality posture, virtual reality rehabilitation, weightlessness.

Additionally, reverse searches were conducted to find articles published by Drs. William Paloski and/or Jacob Bloomberg within this particular field of interest. The published results from STS-90, the Neurolab Spacelab Mission, were also reviewed.

Further searches using both keywords and specific author names were conducted on the NASA website through the NASA Technical Report Server (NTRS).

CHAPTER 3: GROUND ANALOGUES

Sensorimotor disturbances experienced by crewmembers postflight have not been successfully replicated with prolonged head-down bedrest, a commonly used ground based analogue for space flight. However, preliminary success has been seen through the aid of galvanic vestibular stimulation (GVS). Normal sensory input from the vestibular system is interrupted in this technique by small electrical currents, typically less than 1-2 milliamps in magnitude.

A study by MacDougall et al.[11] evaluated the effects of galvanic stimuli on subjects' postural control. The subjects were tested under various sensory organization tests, or SOTs. These included variations of three visual conditions – eyes open/closed and sway reference vision, with two proprioceptive conditions – fixed and sway-reference support surfaces. Computerized dynamic posturography was used for analysis. Sway patterns for center of mass were then drawn out as seen in Figure 8. It provides a visual comparison of the sway data between subject and astronaut. It was found that the "SOT scores observed in astronauts on landing day did not differ significantly to that generated by GVS [galvanic vestibular stimulation] in our normal subjects."[11]

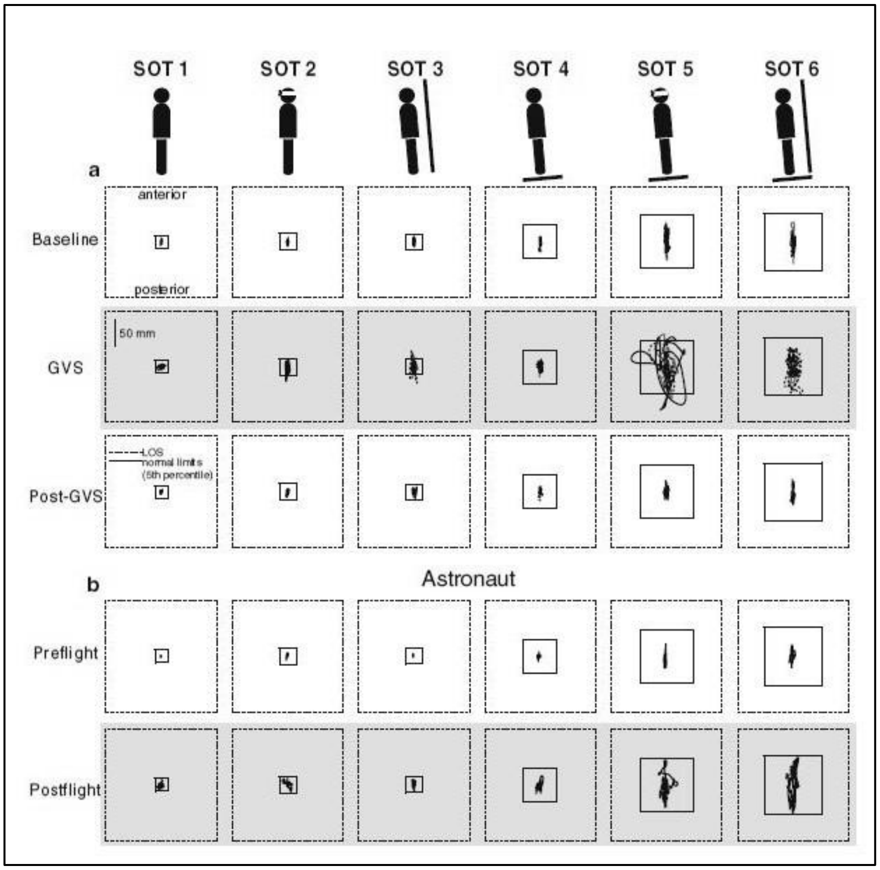

Figure 8: Sway data (projection of the center of mass onto the support surface) from a subject during computerized dynamic posturography. (MacDougall HG, Moore ST, Curthoys IS, Black FO. Modeling postural instability with Galvanic vestibular stimulation. *Exp Brain Res*. 2006;172(2):208-220.)[11] Image reproduced under license agreement, Springer Science and Business Media.

- SOT 1 – eyes open
- SOT 2 – eyes closed
- SOT 3 – eyes open and sway-referenced visual surround
- SOT 4 – eyes open and sway-referenced support
- SOT 5 – eyes close and sway-referenced support
- SOT 6 – eyes open and sway-referenced support and visual surround
- Top row – baseline data
- Middle row – data during GVS exposure
- Bottom row – data recorded without GVS 10 minutes after GVS exposure

In a separate study by Moore et al.[12], current was delivered to the surface of the skin over the mastoid process in 20 subjects with no known history of locomotor or vestibular deficits. It was delivered in either a pseudorandom fashion or head-coupled fashion (proportional to the summed vertical linear acceleration and yaw angular velocity of the head). Their mobility was assessed on an obstacle course of similar size and makeup to that of the functional mobility test course developed by Jacob Bloomberg, PhD for postflight locomotor assessment of astronauts. There was a significant increase in the time for course completion during both pseudorandom and head-coupled galvanic vestibular stimulation; 21% and 14% increase, respectively. This is equivalent to an ISS astronaut's performance at five days post-landing. [12]

The prior studies demonstrate the ability of GVS to help recreate the conditions of postflight locomotor dysfunction. While this ability could ultimately play a role in a countermeasure setting, one limitation is the safe duration for which GVS can be used to induce instability. Only when current is applied do the effects take place. It remains unclear how long such current can be delivered safely without risk of permanent neurological harm to the individual.

CHAPTER 4: RESEARCH AT NASA

Two major categories of practical countermeasures currently being considered at NASA include adaptability training and sensory supplementation. A driving goal is to develop a program that will facilitate and enable a rapid (re)adaptation to an environment with a different gravitational pull. The NASA-JSC motion and neuroscience labs provided information on its current research areas, some of which is not yet available in the public domain.

The purpose of adaptability training is to "determine whether trained subjects could transfer learned skills from one discordant visuo-proprioceptive environment to another."[13] Prior research has demonstrated that motor skills can be enhanced through a process called adaptive generalization when the subject is forced to learn a specific task under repetitive, varying sensorimotor conditions.[14] This formed a premise for a study by Brady et al., whereby 19 subjects started walking on a treadmill naturally and were slowly transitioned to a continuous, lateral oscillation motion for duration of 20 minutes. What emerged were two separate groups: (1) subjects that fixed themselves in space so the treadmill moved below them and (2) subjects that fixed themselves to the base so they moved laterally as the base oscillated. The authors suggest that the participants' preferences vary for "optimizing gait stability, some depending more heavily on vision (group 1) and others on proprioception (group 2)."[15]

This concept was carried to the next experiment, by the same authors, in which ten subjects walked at 2.5 km/hour on a treadmill mounted upon a motion based platform. This was done while a large screen positioned in front of the treadmill displayed an oscillating visual image. Another ten subjects in the control arm of this experiment completed the same training but without any motion in the treadmill or projected film. The hypothesis was that exposure to multiple sensory challenges enhances the ability of the central nervous system to adapt to a novel environment or task.[5] All participants waited for 20 minutes after completing the final training session. They then had to complete a two minute trial with new visual and treadmill motion patterns. Subjects that received sensorimotor adaptability training had faster reaction times and improved composite scores overall (based on heart rate, stride frequency, and reaction time). Quantitative data for this study was not available at the time of writing for this capstone project.

Prior research has provided evidence that exposure to microgravity will lead to a reduction in postural reflexes to the major muscle groups of the lower extremities.[16] It is thus understandable why the Russian Space Agency developed a "Penguin Suit" – an axial loading apparatus designed to counteract these effects. Integrating these different approaches into a single countermeasure system would be optimal; a modality that links together resistive exercise with axial loading as well as sensorimotor challenges.

Another countermeasure category is sensory supplementation. Sub-threshold mechanical noise applied in a tactile fashion to the soles of the feet has been found to reduce the postural sway of participants instructed to stand motionless upon a slightly raised, fixed platform.[17] The use of sub-threshold vestibular stimulus delivered via electrodes over the mastoid process can improve vestibular function. Normal subjects in a heel-toe stance demonstrated an increase in standing time.[5] A current search of the literature found no studies presently investigating the use of this modality in crewmembers. However, an abstract was found on the NASA Technical Reports Server where the use of stochastic resonance was advocated as a means of enhancing the response of a crewmember's neural system. Specifically, its use was highlighted in the event emergency egress from a space vehicle after a water landing was required.[18]

Another form of sensory supplementation is thru the use of a tactile situation awareness system (TSAS). Designed in cooperation between the U.S. Navy and NASA, TSAS is a device worn by the subject that provides vibrotactile stimuli to the torso and/or limbs in response to the user's position. The user then interprets these signals to improve their situational awareness and subsequently make postural corrections as needed. No present-day research studies for this modality were found, however prior research involving pilots of both rotary wing and fixed wing aircraft demonstrated an ability "to fly complex maneuvers with no instruments or outside visual references with less than 20 minutes of [TSAS] training."[19]

CHAPTER 5: RESULTS

There are ongoing research projects, outside of the space industry, whose goal is to aid in the creation of new rehabilitation strategies for patients afflicted by any one of several ailments that impair locomotion. These methods have been demonstrated to challenge the body's senses and postural stability, much like the countermeasures undergoing study at NASA. The following studies are discussed in detail with the intent to help establish proof of principle – that their countermeasure methodologies could carry over into the aerospace realm and are worth investigating.

A. VIDEO GAME TECHNOLOGY:

In "Video Game-Based Exercises for Balance Rehabilitation: A Single-Subject Design," Betker et al.[20] investigated if balance can be improved by using video games. Specifically, standing balance exercises were linked to video games that were controlled by the user's foot center of pressure. The study size was a limitation, with only three subjects: (1) a 20 year old status-post cerebellar tumor excision with residual severe ataxia; (2) a 58 year old status-post right sided cerebrovascular accident with respective leg, foot, and postural scores on the Chedoke-McMaster Stroke Assessment of 3, 2, and 4; and (3) a 41 year old status-post closed traumatic brain injury. The final subject was predominantly wheelchair bound and could stand for exercises in periods of 20 to 30 seconds while full sessions lasted 10-15 minutes.

Pre-intervention assessments were done whereby subjects were instructed to complete various tasks in the standing position, such as turning their head, torso, and raising a bar above their heads. The goal was to determine if a subject did or did not fall during any of those activities. The process was done while standing on the floor and again while on a foam mat so that the increase in surface compliance would introduce a degree of uncertainty.

Video game equipment setup started with a foam pressure mat embedded with piezoresistive sensors. Information about the subject's foot center of pressure (COP) was then relayed via an interface box into a laptop running the exercise game. Each subject participated in eight exercise sessions of 45 minutes each over a three week period. Four main games were played and it was noted if, and how frequently, each subject fell. Therapists were present for all sessions as a safety factor. Each game also had unique attributes:

- Under Pressure, apple drop – the user's goal was to catch objects with a basket whose motion was controlled by foot COP. Speed of the basket and movement in anteroposterior (AP) and mediolateral (ML) directions were recorded.
- Under Pressure, target practice – user goal was to position a bullseye so that it was struck by a moving arrow. Speed and accuracy were measured.
- Memory Match – user goal was to find matching pairs of cards. COP movement range and speed were both noted.
- Tic-Tac-Toe – game was played against the computer. AP and ML motion as well as speed were again noted.

Pre-exercise tasks were repeated after three weeks of game therapy and these results are shown in Figure 9.

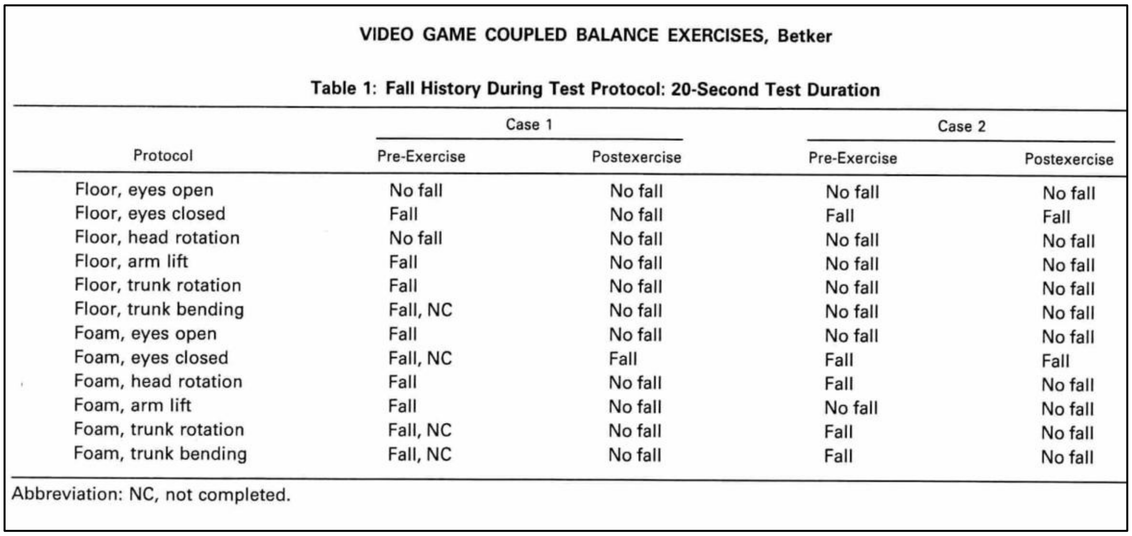
VIDEO GAME COUPLED BALANCE EXERCISES, Betker

Table 1: Fall History During Test Protocol: 20-Second Test Duration

Protocol	Case 1		Case 2	
	Pre-Exercise	Postexercise	Pre-Exercise	Postexercise
Floor, eyes open	No fall	No fall	No fall	No fall
Floor, eyes closed	Fall	No fall	Fall	Fall
Floor, head rotation	No fall	No fall	No fall	No fall
Floor, arm lift	Fall	No fall	No fall	No fall
Floor, trunk rotation	Fall	No fall	No fall	No fall
Floor, trunk bending	Fall, NC	No fall	No fall	No fall
Foam, eyes open	Fall	No fall	No fall	No fall
Foam, eyes closed	Fall, NC	Fall	Fall	Fall
Foam, head rotation	Fall	No fall	Fall	No fall
Foam, arm lift	Fall	No fall	No fall	No fall
Foam, trunk rotation	Fall, NC	No fall	Fall	No fall
Foam, trunk bending	Fall, NC	No fall	Fall	No fall

Abbreviation: NC, not completed.

Figure 9: Fall history during test protocol. (Betker AL, Szturm T, Moussavi ZK, Nett C. Video game-based exercises for balance rehabilitation: a single-subject design. *Arch Phys Med Rehabil*. 2006;87(8):1141-1149.)[20] Image reproduced under license agreement, Elsevier Limited Publishing.

There was an improvement in balance for subjects 1 and 2 as they demonstrated a decrease in their fall rate. Subject 3 was unique because of the baseline need for assistance with standing. Three weeks of therapy were then provided and the subject was able to stand independently on firm ground for up to 20 seconds. Another measurement in this study was each subject's foot COP excursion in the AP and ML planes as measured in centimeters. Where balance was maintained pre- and post-exercise, subject 1 had decreased COP values for all tasks. Subject 2, however, had similar pre- and post-exercise values. In some instances the values increased slightly. For tasks where both subjects fell pre-exercise and maintained standing balance post-exercise, the post-exercise COP values were generally lower.[20]

Overall, all three subjects improved their fall rate and provided positive feedback about the use of video-game based therapy. The feedback, though a qualitative descriptor, is especially important when considering the importance of crewmember participation in the field of countermeasure research.

B. JUGGLING AND NEUROPLASTICITY:

Numerous animal studies have been done to investigate neuroplasticity. This is the brain's ability to create new neural connections as a means of adapting to a novel environment. Researchers have found that training into new environments leads to changes in the cerebral cortex including cortical thickness, size of synaptic contacts, number of dendritic spines, and dendritic branching.[21] The increase in synapse numbers may last for at least 28 days after the completion of training.[22] Earlier work by Black et al. revealed that novel motor learning alone led to synaptogenesis while an increase in regular physical activity did not; instead it led to angiogenesis.[23]

"Neuroplasticity: changes in grey matter" was an experiment that used whole-brain MRI to visualize learning-induced plasticity in the brains of volunteers who were taught how to juggle.[24] A total of 24 subjects (21 female and 3 male), all of whom lacked juggling experience, were matched for sex and age then divided into two groups: jugglers vs. non-jugglers. All subjects received a baseline MRI. The experimental group was given three months to learn a standard 3-ball juggle with a common goal of being able to perform a sustained cascade for at least 60 seconds. At the end of this period all subjects received another MRI. Then, during months 3 thru 6, the jugglers were neither allowed to practice nor expand upon their skills. A third MRI was performed at the end of 6 months. Most jugglers had lost their ability to perform a coordinated 3-ball cascade by that point.

An imaging technique known as voxel-based morphometry was utilized to detect focal changes within the brain's anatomy. Researchers found a temporary and selective structural change in the brain areas associated with the processing and storage of a complex visual motion. In the longitudinal analysis, there was a statistically significant (44 df, $p<0.05$) transient expansion of grey matter in the mid-temporal area and in the left posterior intraparietal sulcus for the juggling group between the 1st and 2nd scans.[24] This was decreased in the third scan. No changes in grey matter were found in the non-juggling control group.

The major changes observed in this study were in motion-based regions of the brain. Given that all of the participants had normal fine-motor skills, however, it was the contention of the study's authors that "juggling, and consequently the perception and spatial anticipation of moving objects, is a stronger stimulus for structural plasticity in the visual areas (used for the retention of visual motion information) than in the motor areas."[24]

This juggling study was revisited to better determine the time involved before structural changes occurred. Driemeyer et al.[25] used the time schedule as seen in Figure 10 for their investigation and also used voxel based morphometry in their analysis.

MRI Scan #	Time	Training
1	Day 0	Learn 3 ball cascade
2	Day 7	Juggle ≥ 1 minute
3	Day 14	Juggle ≥ 2 minutes
4	Day 35	Juggle ≥ 3 minutes
5	Day 60	No juggling
6	Day 120	No juggling

Figure 10: Established intervals for MRI scans and training requirements.
(Driemeyer J, Boyke J, Gaser C, Büchel C, May A. Changes in gray matter induced by learning--revisited. *PLoS ONE*. 2008;3(7):e2669.)[25] Image within public domain and available freely.

A total of 20 subjects, all inexperienced, received six MRI scans over a duration of 120 days. Significant increases ($p<0.001$) were noted bilaterally in the middle temporal area of the visual cortex, frontal and temporal lobes, and cingulate cortex when comparing scans 2 thru 4 (juggling interval) to the baseline MRI scan. Occipital changes were detectable after only 7 days of juggling. These findings were reversed in the scans taken during the latter interval of no activity.

The increase in gray matter was directly linked to the period where subjects were learning a three-ball cascade. Further practice after they learned this skill was not associated with continued changes in brain structure. Thus, an argument is made that the qualitative change of learning a new task is more critical for the brain to change its structure than training of this task once learned.[25] The authors concede, however, that increases in gray matter could very well be a combination of both. What exactly is being measured in the "gray matter increase" is a limitation in these studies. There is debate as to whether this is a quantitative measure of neurons versus a reflection of increased cell size, neural or glial cell genesis, spine density or changes in blood flow or interstitial fluid.[25]

C. USE OF VIRTUAL REALITY:

Microsoft Corporation unveiled its *Xbox Kinect* hands-free motion control system in June 2010 at the Electronic Entertainment Expo (E3) in Los Angeles. Audio and video sensors eliminate the need for a traditional controller or joystick so players use their own body motions to play games.[26] While this technology is brand new, Nintendo Co., Ltd., released their version of virtual reality with the Wii ® console in 2006. It requires the user to interact with a video game thru a wireless controller worn on the wrist. Embedded in the controller are sensors responding to velocity and direction. This information is processed alongside an infrared light sensor mounted on top of the user's television.

"Effectiveness of Virtual Reality Using Wii Gaming Technology in Stroke Rehabilitation" (EVREST) was a pilot, randomized clinical trial that evaluated the safety (primary outcome) and efficacy (secondary outcome) of virtual reality using the Nintendo Wii system.[27] It involved stroke patients with arm motor impairment due to stroke. Intervention included 8 sessions of 60 minutes each over a 14 day period. Games played focused on movements including shoulder flexion/extension, elbow flexion/extension, wrist pronation/supination, and thumb flexion. Parallel recreational activities for the control group tried to focus on similar motions.

Nine of the eleven VR patients completed all training sessions, and eight of the eleven recreational therapy patients completed their sessions. With regards to safety and feasibility, there were a few complaints of fatigue in both groups but otherwise no adverse events. Efficacy was measured four weeks after intervention with the Wolf Motor Function Test (WMFT), Box and Block Test, and Stroke Impact Scale. The WMFT is comprised of 15 timed and 2 strength tasks that vary in complexity – i.e. fold a towel, lift a can, strength task including forward flexion of the shoulder. Subjects in the VR Nintendo Wii ® arm demonstrated a significant improvement of 7 seconds in their WMFT (-7.4 seconds; 95% CI, -14.5, -0.2). The minimal clinically important difference is cited as at least 1.5-2 seconds.[27] Both groups showed improvement in the Box and Block Test.

One limitation of this study is the limited exposure to the intervention. Patient bias is another limitation; the excitement for using the "latest" technology may have influenced a subject's desire to become more active in his/her therapy. On the other hand, patients in the control group who played cards, Jenga ®, and bingo may not have been equally stimulated.[27]

Astronauts returning after spaceflight experience gait and postural instability – not necessarily difficulty in flexion and extension of the shoulder, elbow and wrist. The prior study was the first of its kind in terms of using a VR based gaming system, and was intended to establish proof of principle. Without trials there is no evidence to discount the ability of a similar VR system in assisting in the recovery from postflight sensorimotor disturbances. On that note, there are many strengths to the study that are of relevance to the aerospace community, including size and portability of the gaming unit. Another great advantage is since the Wii ® is computer assisted, large movements on the user's part are not required making it perfect for situations where the user faces physical limitations, i.e. postflight postural instability.

There are instances where other forms of virtual reality have been investigated for rehabilitation benefit in stroke patients. A systematic review article from 2007 found a total of 11 such studies, but only 3 were randomized clinical trials.[28] One in particular was of greater significance to this project in that it focused on gait training with the use of a treadmill linked to a virtual reality head-mounted display.[29] Twenty subjects with post-stroke hemiplegia were recruited. Inclusion criteria of particular interest included: (1) CVA more than 6 months prior to the study; (2) diagnosis of hemiplegia due to the documented lesion; (3) ability to walk independently or with a guard; (4) asymmetric gait pattern; (5) short step-length defined as less than the 95^{th} percentile of normal. The control group stepped over ten separate foam obstacles positioned 15-22 inches apart in hallway. Repeating the task twelve times was the equivalent of one full session; subjects completed six sessions. The experimental group wore a virtual reality headset that projected virtual objects as they walked on a treadmill. In the event a subject's foot "collided" with a virtual object, feedback included an auditory tone and a vibrotactile sensation on the involved limb. They also completed six sessions of approximately one hour each. No subjects fell during any of the training sessions. Figure 11 is a graphical representation of the differences between each group in their various testing parameters.

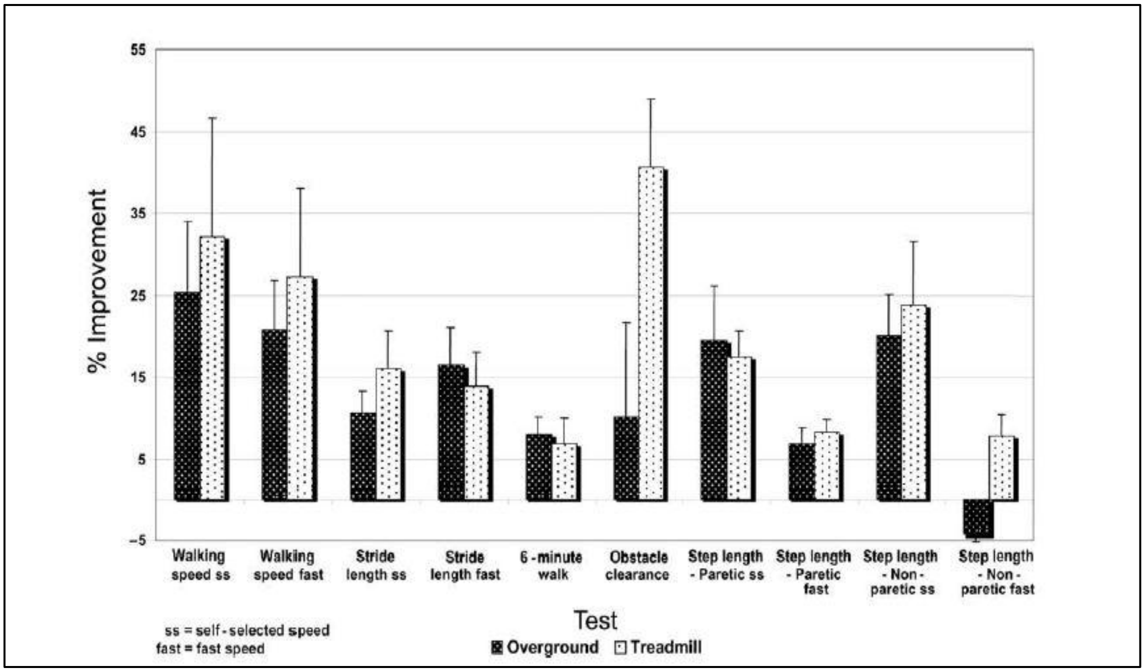

Figure 11: Comparison of % improvement between control and experimental groups based on outcome measure.[29] Image within public domain, published in Journal of Rehabilitation Research and Development, 2004 May;41(3A):283-92.

The virtual arm of the study demonstrated improvements in 7 out of 10 outcome measures. There was a statistically significant improvement in gait velocity for virtual reality training versus real training (20.5% vs. 12.2% improvement, $p<0.01$). Both interventions resulted in clinically important changes overall. It is worth noting that the change in cadence leading to a faster walking velocity, though statistically insignificant, was based on the subject taking longer steps during each session as opposed to taking more steps.[29] This is important because longer steps may suggest greater confidence that developed over the training period. The various forms of sesnory feedback – auditory, visual, tactile – that comes from using a virtual reality system may also influence the user's interest in the system as opposed to ambulating down a hallway which may seem less appealing.

CHAPTER 6: DISCUSSION & CONCLUSIONS

Optimizing a crewmember's environment plays an important role in mitigating the effects of postflight sensorimotor dysfunction. Broadening visibility through the suit visor and increasing the overall range of motion of the suit are two examples of optimizing the environment of a crewmember on EVA. Despite these engineering efforts, other countermeasures must be developed to work in conjunction with them to combat sensorimotor dysfunction. In order for a countermeasure to be effective it must take into account multiple factors – i.e. size of the device if it is to be stowed onboard, cost involved in production, ease and desirability of use by the astronaut, and power consumption. Some of the countermeasures being investigated succumb to one or more of these limitations.

Researchers at NASA use the FMT to assess locomotor dysfunction in International Space Station crewmembers. This current approach pits crewmembers against themselves; there is no reward incentive for completing an obstacle course other than knowledge of improving personal time for completion. It is the opinion of this author that a reward system, or some reflection of advancement for completing a course at a faster time, would be beneficial when developing countermeasures. Such systems are already in place as seen in video gaming. As noted in the study in which foot center of pressure controlled video games were used, that "exercise regime motivated subjects to increase their practice volume and attention span during training … in turn improved subjects' dynamic balance control."[20]

The use of foot-COP linked video games as a countermeasure to mitigate post-flight sensorimotor disturbances and improve balance is worth investigating. The device is portable, and feedback from the patients in the trial was favorable. The power of this study was limited yet the improvement in fall rate for each subject is evident. The study also demonstrated that graded, dynamic balance exercises can be effectively joined to video games on different surfaces, be it with a small foam mat or perhaps one of greater length so long as they are embedded with the same type of piezoresistive sensors. The author of the original study proposed this idea of a larger, walking mat as a means to facilitate stepping; that the use of foot-COP biofeedback coupled to dynamic exercise tasks would lead to an increased awareness of the motor control required to successfully perform that movement.[20]

Of note, a meta-analysis of force platform feedback in post-stroke patients revealed the intervention improved stance symmetry, but did not improve balance performance while walking or moving.[30] The use of a foam surface would therefore be beneficial as it introduced a degree of instability. Whether softer, more compliant materials should be used is also worth investigating.

The idea of juggling in low gravity environments is impractical. However, the idea of juggling under conditions of artificial gravity mid-journey or prior to spaceflight while on Earth is plausible. The duration or "lifespan" of synaptogenesis from learning new activities has shown promise based on animal studies. The neuroplasticity of the human brain has also been demonstrated as a result of such activities. It does, however, remain unclear whether the increase in regional grey matter from juggling will have a direct effect on an individual's ability to complete other tasks.

Current sensorimotor-adaptability training at NASA pairs dynamic treadmill motion with visual oscillation. It results in faster reaction times and better overall composite scores. Whether this form of training affects grey matter in the brain would be interesting information to ascertain. If so, this author conjectures that perhaps linking sensorimotor-adaptability training with juggling is not so far-fetched. A good diagnostic approach would be to perform voxel based morphometry analyses of crewmember MRIs pre- and postflight. It would be important information to gather if indeed there are regional declines in gray matter due to spaceflight. Taken one step further, if there are decreases in the various cortices, where are they located and what is the rate of recovery?

Astronaut candidates in the past have ranged between the ages of 26 and 46, with the average age being 34.[31] Looking down the road, medical advances and better countermeasures might enable NASA to start flying older individuals. Boyke et al. showed that elderly volunteers (mean age = 60 years) who learned how to juggle showed transient increases in gray matter in the hippocampus on the left side.[32] A major function of the hippocampus is to aid in navigation by providing a spatial framework where a person's experiences may interrelate.[33]

The importance of a strong sense of spatial navigation could not be more apparent than when using Microsoft's Xbox Kinect ®hands-free motion control system that was just unveiled. Audio and video sensors eliminate the need for a traditional controller or joystick so players use their own body motions to play games.[26] Virtual reality holds great potential to be an effective and a rather safe way to rehabilitate post-stroke patients. It may also hold promise for astronauts experiencing gait and postural instability postflight. Unfortunately, how it affects the vestibulo-ocular reflex remains to be seen. VR has already been used as a tool to optimize training strategies for emergency egress from spacecraft.[34] But overall, the evidence base for VR is limited by the power of its studies. Further investigation is warranted in both the aerospace and rehabilitation settings.

A common thread between the various activities – treadmill, juggling, etc. – is all of the training improves performance for that particular activity. Again, a valid concern is what degree of skills learned can be transferred over into a new situation as a valid countermeasure for post-flight sensorimotor disturbances. The aerospace community is limited by the lack of a reliable ground-based analogue upon which to base its research. The use of galvanic vestibular stimulation has been tested, but concerns arise about long-term use and its ability to mimic the slow recovery astronauts experience day by day.

There has recently been a shift in focus from lunar missions to exploration class missions by the United States space program. Be it Mars, the surface of an asteroid, or another planetary surface, the transition between gravitational zones will persist and so will its negative effects on the sensorimotor capabilities of astronauts. The Apollo Lunar Module had an autopilot feature but it was not utilized as the crew chose to land manually.[1] Completing this task on a different surface with a different gravitational pull could potentially be even more challenging, perhaps life-threatening.

Countermeasures are needed to reduce the time requirement for returning to baseline functional performance with regards to posture and gait instability. NASA researchers are continually making advances in this area; however, a crucial step forward will come from the development of a ground-based analogue. From virtual reality to juggling to galvanic vestibular stimulation, the next step is to better assess which of those protocols would then bear merit in the space realm while remaining compliant with the constraints of countermeasure design including size, cost, and ease of use. As a demonstrated proof of principle in this capstone, there are ongoing experiments outside the aerospace realm that could be of value to NASA's efforts which must be kept in mind as we continue to investigate this mission critical issue.

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VITA

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