Self-Rotations in Simulated Microgravity: Performance Effects of Strategy Training

Leia Stirling, Dava Newman, and Karen Willcox

Stirling L, Newman D, Willcox K. *Self-rotations in simulated microgravity: performance effects of strategy training.* **Aviat Space Environ Med 2009; 80:5–14.**

Introduction: This research studies reorientation methodologies in a simulated microgravity environment using an experimental framework to reduce astronaut adaptation time and provide for a safety countermeasure during extravehicular activity. ***Methods:*** There were 20 subjects (10 men, 10 women, mean age of 23.6 ± 3.5) who were divided into 2 groups, fully trained and minimally trained, which determined the amount of motion strategy training received. Subjects performed a total of 48 rotations about their pitch, roll, and yaw axes in a suspension system that simulated microgravity. In each trial subjects either rotated 90° in pitch, 90° in roll, or 180° in yaw. Experimental measures include subject coordination, performance time, cognitive workload assessments, and qualitative motion control strategies. ***Results:*** Subjects in the fully trained group had better initial performance with respect to performance time and workload scores for the pitch and yaw rotations. Further, trained subjects reached a steady-state performance time in fewer trials than those with minimal training. The subjects with minimal training tended to use motions that were common in an Earth environment since no technique was provided. For roll rotations they developed motions that would have led to significant off-axis (pitch and yaw) rotations in a true microgravity environment. ***Conclusions:*** We have shown that certain body axes are easier to rotate about than others and that fully trained subjects had an easier time performing the body rotations than the minimally trained subjects. This study has provided the groundwork for the development of an astronaut motion-control training program.

Keywords: astronaut, motion control, human reorientation, workload.

IN ORDER TO REDUCE astronaut adaptation time and provide for a safety countermeasure during extravehicular activity (EVA), this research studied reorientation methodologies in a simulated microgravity environment using an experimental framework. Even though astronauts undergo hundreds of hours of training, the strategies for locomotion and orientation are not specifically prescribed. Typically astronauts' motor-control strategies are developed during training in underwater simulators, such as the Neutral Buoyancy Lab at NASA's Johnson Space Center and the pool in Russia's Star City complex. One major drawback to underwater training is that the viscous drag of the water leads to the use of larger motions, hence recruitment of larger muscles, both of which are inappropriate for optimal microgravity body motions (6). In studies by Newman et al. (17,18), intravehicular activity was analyzed using force and moment sensors in order to quantify the effects of astronaut motion on the surrounding environment. Over an average of 4 wk, the astronauts were seen to adapt their motor-control strategies, including lowering their velocities and reducing their applied forces. Part of this adaptation time was due to neuromusculoskeletal alterations between the different gravity environments, while the rest might be attributed to training and longer-term adaptation.

It is well known that when no external force is present, conservation of linear momentum shows that no translation of the center of mass is possible when starting from rest. However, when no external moment is present, conservation of angular momentum does not rule out a net rotation. The feasibility of self-rotations has been previously studied experimentally in simulated gravity environments (12,21) and computationally (10,23). Since astronauts are not familiar with reorienting without external forces, they will most likely not develop any self-rotation techniques naturally. Several former astronauts mention grabbing anything within reach, such as handholds or latches on lockers, in attempts to externally torque themselves to achieve a net rotation. This study examines how the torso, arms, and legs can be moved with respect to each other to achieve a net rotation such that external torques are not necessary. This reorientation without external torques is termed self-rotation. With the development of appropriate astronaut maneuvers, a training program can be created such that adaptation time upon entering a microgravity environment is reduced.

Yet, reduction of adaptation time to enhance astronaut performance is not the only application of astronaut self-rotation. Another important application is as a safety countermeasure during EVA. Consider an astronaut performing an EVA, and during this period, the astronaut becomes separated from the spacecraft and the thruster backpack incurs a partial failure. If the astronaut has trained with a simple reorientation methodology, a maneuver can be performed such that the remaining thrusters direct the astronaut back to the spacecraft. While there are no flight data for crew sepa-

From the Department of Aeronautics and Astronautics, Massachusestts Institute of Technology, Cambridge, MA.

This manuscript was received for review in May 2008. It was accepted for publication in October 2008.

Address reprint requests to: Dr. Dava Newman, MIT Department of Aeronautics and Astronautics, Room 33-307, 77 Massachusetts Avenue, Cambridge, MA 02139; dnewman@mit.edu.

DOI: 10.3357/ASEM.2355.2009

rations, neutral buoyancy simulations have shown periodic separations that can be extrapolated to 1 every 1000 EVA hours (5).

Even though there has been limited research into astronaut self-rotation, more extensive data does exist regarding other aspects of astronaut motion control. In studies of arm motions in a microgravity environment, several characteristics were seen to adapt, including a reduction in response time, a reduction in hand trajectory curvatures, and final hand position in aimed motions (4,19,20). Further, adaptation is affected by the speed of the motion. Slow movements, which are more dependent on central nervous system afferent feedback, were affected to a greater extent than fast movements, which are more dependent on force feedback. This suggests that muscle spindle activity is reduced in microgravity (7), which is consistent with astronaut reports of a reduction in limb position perception (24) and experimental arm motion tests during parabolic flight (22).

In studies of whole body postural control and adaptation, microgravity was seen to affect simple postural motions. When a foot down stance was requested, the center of mass of the body shifted with respect to the 1-G location (2,3,15). When the foot down requirement was not included, an even greater shift in posture was observed (16). These changes in postural control are thought to be due to the reinterpretation of the muscle spindle activity by the central nervous system (13). During trunk bending motions, when a foot down requirement is included, a reduction in the center of mass motion similar to a terrestrial environment was seen after an initial adaptation period (2,11,14). Translational motion studies have also shown adaptation to the modified environment (1,6,17), including reductions in velocity and applied forces.

There have been several different methods for simulating microgravity in a 1-G setting, including air-bearing floors, underwater scenarios, and body suspension configurations. Each scenario has its advantages and disadvantages. In the underwater scenario one can move about all the rotational axes; however, as previously mentioned, the viscous effects of the water are significant and yield different motion-control strategies than would be obtained in microgravity (6). When using an air-bearing floor, rotations can only be performed about one axis, but there is little friction with the ground so motion control is not as affected as seen underwater. While appropriate for translational motions, the air-bearing floor is not appropriate for performing self-rotations since the floor adds mass and inertia to the body, thus lowering the effect of the limb motions in producing a net rotation. When using a body suspension configuration, the subject is still limited in that only rotations about one axis can be performed during each trial; however, there is a negligible addition to the body mass and inertia. The experiments performed for this research used a suspension system, with the subjects suspended in three different configurations so that rotations about each body axis could be performed.

In this study, we looked to further the understanding of rotational motion control in the microgravity environment by examining three hypotheses. 1) The first hypothesis was that subjects that have had motion strategy training will have a better initial performance with respect to the performance parameters than those that have not received training. 2) Secondly, rotations and motions that are common in an Earth environment (i.e., bicycling, walking, treading water) will have a lower complexity than those that are completely unfamiliar. Further, in cases where no technique is provided, familiar motions will be implemented. For this hypothesis the complexity was analyzed using the NASA Task Load Index (TLX) and the modified Cooper-Harper Rating. By selecting motions that are familiar, we assumed that the control was simpler and we examined whether the rotations were easier to perform. 3) The third hypothesis was that the variation in performance of a group with less training will be greater than the variation in a group with more training. This last hypothesis implies that subjects who are not trained will develop different methods with respect to the other subjects in the same group, yielding a greater variation in time than the subjects in the trained group, which converge to one motion methodology. Through these hypotheses, a better understanding of rotational motion control can be obtained, which could lead to the development of an astronaut motion-control training program.

METHODS

Subjects

This study was approved by MIT's Committee On the Use of Human Experimental Subjects (COUHES) and the participants gave their written informed consent to participate. There were 20 subjects that volunteered to participate in this experiment, 10 men and 10 women, ranging in age from 19 to 29 (mean age of 23.6 ± 3.5).

Experimental Protocol

Each subject performed a series of rotations about the three body axes in both the counterclockwise and clockwise directions. The axes are defined as x (roll), y (pitch), and z (yaw), where x is into the body, y is the axis from finger to finger when the arms are extended, and z is the axis from toe to head. All harnesses were attached via rope to a gymnastics still rings apparatus to achieve the rotations as illustrated in **Fig. 1**. A typical climbing harness was implemented for rotations about x and z, while a sling harness was implemented for rotations about y. While the typical climbing harness gave the greatest freedom of motion, there was not enough stability provided to the subject when rotating about y. Thus, the sling harness was implemented to increase subject stability for these rotations.

During the experiment, the rotations were divided into six blocks as shown in **Table I**. Each block consisted of an equal number of counterclockwise and clockwise rotations and all subjects performed the rotations in the same order. The blocks were placed in this order so that

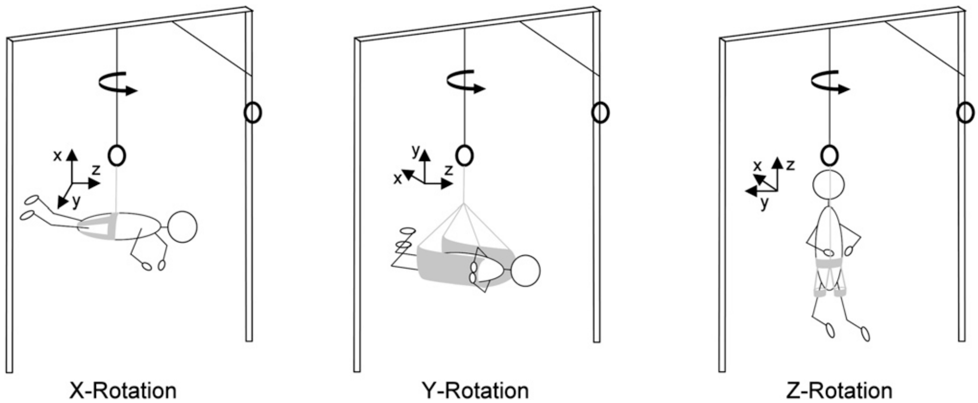

Fig. 1. Configuration of the suspension system for the x, y, and z rotations. Harnesses were attached to a gymnastics rings apparatus, with the extra ring tied off to the side. The rotational axis is indicated with the arrow. Sketch is not to scale; subjects could not touch the sidebars or ground when suspended.

the average age of rotations about each axis would be the same. Fewer rotations were required about x and y than about z as they were more fatiguing for the subject to perform. Our goal was to perform as many rotations as possible without fatiguing the subjects so that their learning patterns and steady state motions could be observed. While rotations about x and z could be performed with the arms and/or legs, subjects were instructed to use only their legs for motions about y as their arms had restricted mobility in this configuration due to the harness implemented.

The subjects were placed in one of two groups, a fully trained and a minimally trained group. Prior to performing the experiment, the subjects went through a training program based on their respective group. The minimal training did not include any motion strategies. The subjects in this group received a theoretical description of momentum conservation. The full training consisted of the same conceptual information along with a motion strategy and video of each rotation. Subjects in the fully trained group were permitted to practice the prescribed motions while unharnessed. No practice in the suspension system was permitted for either group prior to the trials. **Fig. 2** shows the methods provided to the fully trained group for rotating about all three body axes. The rotation about x is a four-part motion where the arms rotate like a windmill. Depending on the desired direction of rotation, either the left or right arm is raised to begin the motion. The raised arm is then rotated downward and the lowered arm is rotated upward in the coronal plane. The arms are returned to the initial positions by bending the elbows and keeping the arms close to the torso. Prior to beginning the cycle again the arms must rotate about z so that the palms are facing in the appropriate direction. When the right arm is initially raised, the rotation will be to the left and when the left arm is initially raised, the rotation will be to the right. The rotation about y is similar to pedaling a bike. As shown in Fig. 2B, the legs are rotated cyclically about the y-axis. A forward pedaling of this motion will cause the body to pitch backward, while a backward pedaling of this motion will cause the body to pitch forward. The rotation about z is performed by an out-of-phase rotation of the legs. In this motion a positive rotary motion (as defined by the right-hand rule) of the legs yields a negative rotation of the body and a negative rotary motion of the legs yields a positive rotation of the body. These strategies were selected as they were simple to perform and were similar to common Earth motions

TABLE I. SELF-ROTATIONS PERFORMED BY EACH SUBJECT.

Block	Descriptor	Rotation Axis	Number of Trials	Rotation Magnitude (degrees)
1	Z_1	z	12	180
2	X_1	x	6	90
3	Y_1	y	6	90
4	Y_2	y	6	90
5	X_2	x	6	90
6	Z_2	z	12	180

The number of trials was split equally between clockwise and counterclockwise motions within each block.

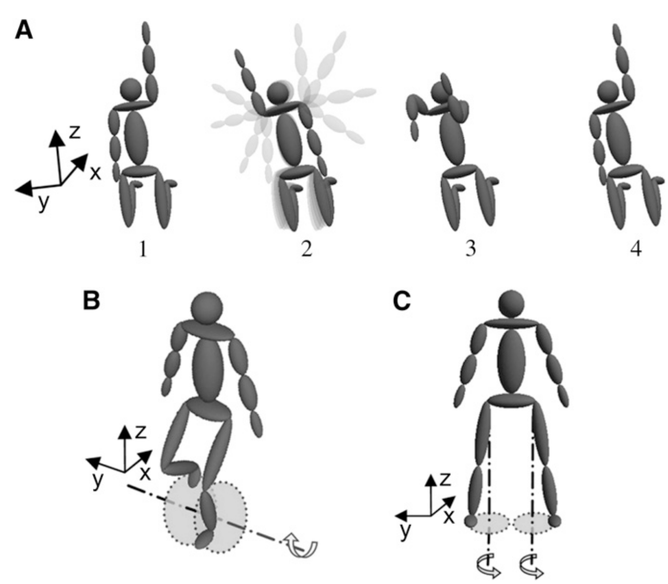

Fig. 2. The methods for rotation about the A) x (roll), B) y (pitch), and C) z (yaw) axes for the trained group. Roll rotations were performed with the arms moving in a windwill-type motion. Pitch rotations were similar to pedaling a bicycle. Yaw rotations were performed with the legs rotating in the same direction, but 180° out of phase.

when possible, such as bicycling and treading water, allowing an evaluation of the second hypothesis. At the completion of the training, the fully trained subjects were asked to explain and demonstrate the rotation strategies while unharnessed to ensure their understanding. The training time allotted for each subject was 20 min, regardless of group.

In order to balance motor control ability between the minimally trained and fully trained groups, i.e., have statistically similar coordination scores between each group, a way to quantify the subjects' motor ability was developed. The Ability Requirements Approach, as presented by Fleishman and Quaintance (8), describes tasks in terms of the human abilities to perform them effectively. Of the human ability definitions given, two were selected as being crucial for self-rotation tasks. They were 1) Gross Body Coordination, which is the ability to coordinate movements of the trunk and limbs and is most commonly found in situations where the entire body is in motion or being propelled, and 2) Gross Body Equilibrium, which is the ability to maintain the body in an upright position or to regain body balance, especially in situations where equilibrium is threatened or temporarily lost. In order to test gross body coordination and equilibrium a jump rope task and balance beam task were administered, respectively. For the jump rope task, the subject was asked to perform a basic jump for the first 90 s, and then for the last 30 s they were to alternate between a basic jump and a crisscross jump. In the basic jump, both feet are slightly apart and the subject jumps over the rope as it passes under him/her. The crisscross method is similar to the basic jump except that the left hand goes to the right part of the body and right hand goes to the left part of the body. The last 30 s was implemented to challenge the subjects and to discriminate between the upper ranges of coordination ability. For the balance beam task, the subject was to: 1) walk to the end of the beam; 2) perform a half-turn; 3) walk to the halfway point of the beam; 4) perform a small jump; and 5) walk to the end of the beam. The subjects were instructed to jump high enough that their feet were off the beam. The jump rope test was scored on a 40-point scale. For the first 90 s, one point was deducted for each time the subject tripped or stopped, with a maximum deduction of five points over 15 s. For the last 30 s, a point was given for each complex pattern completed (basic jump, crisscross jump). The beam task was scored on a 10-point scale, with 5 points given for walking along the beam, 2 points for the turn, and 3 points for the jump. Deductions were made for wobbling and for falling off the beam. The sum of these two tests was termed the subject coordination score. After completion of the coordination test, subjects were assigned randomly to the trained or untrained group such that each group had a similar distribution of coordination abilities.

Experimental Measures

Prior to performing the main experiment, subjects were tested for their coordination score, as previously described. Throughout the experiment, the subjects were videotaped so that motion control strategies could be further analyzed. Performance times and qualitative analyses of the motion strategies were determined from the video data. Following each rotation, subjects were verbally prompted by the test conductor to evaluate the task using a modified Cooper-Harper rating scale. This scale is a modified version obtained from NASA's Johnson Space Center and ranks the motion on a 10-point scale (1 = excellent performance with no improvement needed, 10 = the task cannot be reliably performed). The subjects were also prompted for their fatigue ratings based on a 5-point scale (1 = no fatigue, 5 = extremely fatigued, cannot continue). At the conclusion of each block, cognitive workload measures were determined using the NASA-TLX, which bases workload on mental demand, physical demand, temporal demand, performance, effort, and frustration (9). These results are calculated as a percentage of the total available workload, out of 100, devoted to each workload component. The NASA-TLX was administered on a computer as a two-part questionnaire, where part one had the subject rate magnitudes of the individual factors and part two had the subject perform pairwise comparisons of the factors. Subjects were provided with an information sheet on the workload components so that there was a consistent definition of each term and scoring method.

Statistical Analysis

In order to analyze the effect of the coordination score, least squares linear regressions were used. To analyze the quantitative experimental results between the fully trained and minimally trained groups, a nonparametric Kruskal-Wallis test was used. An F-ratio test on the variance (Levene's test) was implemented to analyze the differences in variance between groups for each rotation for the performance times and workload scores. To examine the difference within groups between rotation blocks, a Friedman test was used. For all statistical tests, significance was set at 0.05.

RESULTS

We first examine the validity of the coordination score as a way to determine rotational motor control ability. Then, we present the effects of training and rotational axis on the performance times and workload measures. Finally, we present the motion-control strategies for the minimally trained group as a way to better understand the motion-control problem.

Coordination Score Analysis

The validity of the pretest coordination score was examined to determine if it predicted rotational motion control as expected. The first performance metric that was considered was the time to perform the task with respect to the coordination score. A linear least squares regression was implemented for each repetition with the log of the performance time as the dependent variable and the coordination score, training group, rotation axis, and rotation direction as the independent variables.

For the first repetition, the linear fit for this model was weak ($R^2 = 0.19$) due to the variance in the subject data, but showed that the coordination score correlated significantly in predicting performance time ($P = 0.025$). As the number of repetitions increased, the coordination score became less significant. As the subjects practiced the motion, they become better at performing it until no significant difference was seen between the lower and higher scoring subjects.

The difference between the log of the initial performance time and the log of the final performance time was defined as $\Delta\log T$. This value can be compared between subjects since a difference in logs is the log of the ratio of times as:

$$\Delta\log T = \log t_i - \log t_f = \log\left(\frac{t_i}{t_f}\right)$$

where the subscript i refers to the initial trial and f refers to the final trial. When a least squares regression was performed on this measure as a function of the independent measures (coordination score, rotational axis, and rotation direction) for the minimally trained group, the linear fit was again weak ($R^2 = 0.25$), but had a statistically significant effect of coordination ($P = 0.044$). However, when this same regression was performed for the fully trained group, the relation was weaker ($R^2 = 0.08$) and the coordination was no longer significant ($P = 0.385$). The loss of significance of the coordination score with respect to $\Delta\log T$ between groups was reasonable as the trained group had additional information to use in order to improve performance, while the minimally trained group had to rely only on their innate ability.

While the linear fits were highly variable, significant effects of coordination score were seen. We concluded that the coordination score gave a good enough indication of performance ability and was an appropriate method for balancing the two groups. Improvements to the coordination score are discussed further in the Discussion. The average coordination score of each group was 38 out of a possible 50, with standard deviations of 5.8 and 8.0 for the minimally trained and fully trained groups, respectively.

Performance Times

When an astronaut performs an EVA in an emergency scenario, the first attempt of a particular type of motion is likely to be different from later attempts. Therefore, it is important to know how different it may be, and perhaps reduce the initial performance times in the space environment through training. **Fig. 3** shows histograms of initial performance times about the three rotational axes for both groups, fully and minimally trained. It is clear from Fig. 3 that training is helpful for z and y rotations. The effects of training are statistically significant ($P = 0.020$ and $P < 0.0005$ for z and y, respectively) under the nonparametric Kruskal-Wallis test. Incomplete motions were excluded. Had this been an emergency scenario and a rotation about y was necessary, an untrained astronaut would have had great difficulty in performing the task. Subjects who were challenged by rotations about z were also challenged by y rotations. A few had difficulty with rotations about y and not with z.

There was no significant difference between the two groups in rotations about x. The minimally trained group tended to use simple sweeping leg motions that created the required net rotation, but their strategies would have resulted in off-axis motions in a true microgravity environment. The trained group followed the recommended strategy that yielded planar motions, but it took longer to perform. This is why the performance times were similar between groups.

These initial data, however, do not tell the whole story. While we might expect subjects to have similar learning curves, we observed very different learning patterns among our subjects. **Fig. 4A and B** show learning curves for two different subjects performing rotations about z. The subject presented in Fig. 4A has a relatively short time of 14 s; but repetition of the task increased performance times in trials 4, 6, and 9. In post-experiment interviews, we found that subjects initially tried a technique, but did not understand why it worked. Therefore, when the task was repeated, it was executed slightly differently, and no more efficiently. It was not until the fourth repetition that the subject understood which aspects of performance were essential to their success. At this point performance time begins to asymptote to a steady state value. Nevertheless, some subjects did capture the essence of the task with fewer repetitions. Although the subject in Fig. 4B had a higher initial time, he reached steady-state performance after the second repetition without ever showing a dramatic increase in performance time. Of the 10 minimally trained subjects, 5 showed an increase in performance time in either the counterclockwise direction, clockwise direction, or both within the first few trials. On the other hand, only one fully trained subject showed a significant increase in performance time and that was because he started the trial in the wrong direction and had to correct his mistake.

With varying efficiency, a majority of the subjects reached a steady state as shown in **Table II**, where steady state includes the trials after the subject has attempted the task five times. The steady state parameters for the clockwise rotation about y were calculated based on nine subjects. The 10th subject never reached steady state. The groups' steady-state average performance times were compared by (nonparametric) Kruskal-Wallis test. Only the counterclockwise performance of the y rotation showed a significant difference ($P = 0.006$).

From the third hypothesis, it was expected that the steady-state response of the minimally trained group would show greater variance than those of the fully trained group. The clockwise and counterclockwise rotations about both z and y showed significantly different variances by Levene's test ($F = 2.87$ with $P < 0.0005$ and

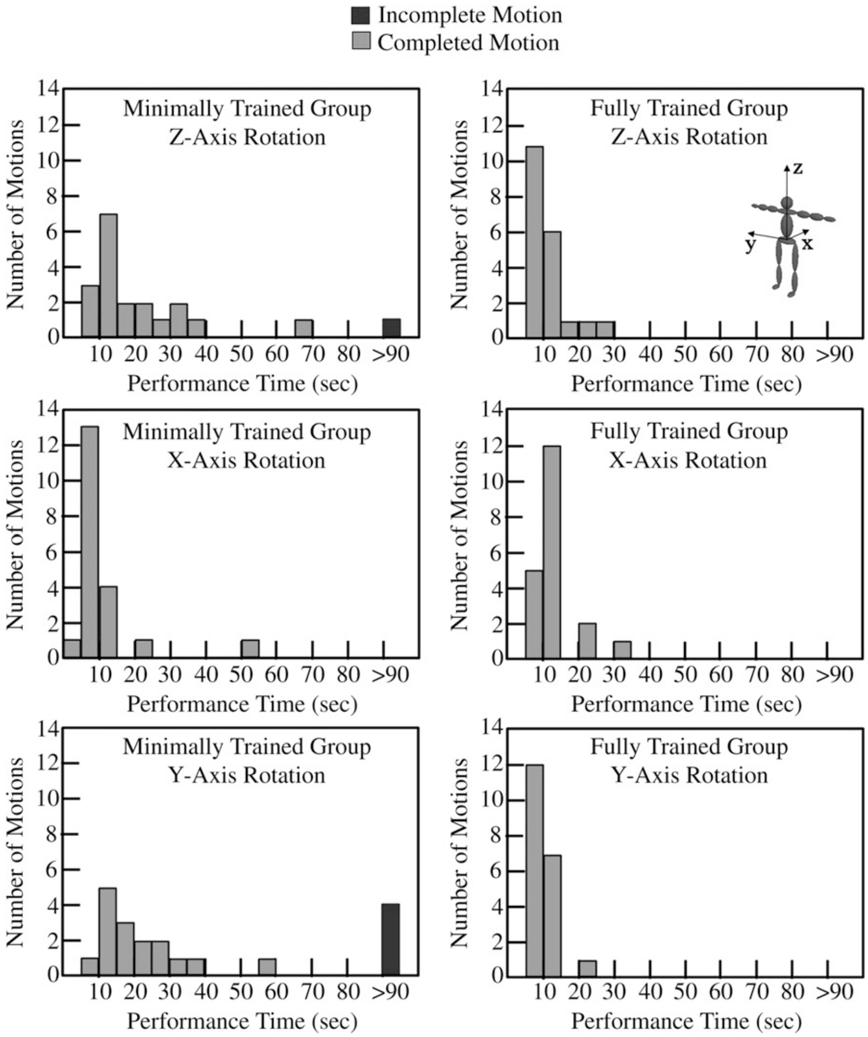

Fig. 3. The distribution of the performance times for the first trial for each axis ($N = 20$).

F = 7.70 with $P < 0.0005$, respectively). Rotations about x did not show significant differences in variances (F = 0.88, $P = 0.69$). Since the subjects in the trained group were all performing the same maneuver, they converged to similar performance times. The minimally trained group had no information about the rotation to be performed and each subject created their own method. An increase in variation for the minimally trained group corresponds to that difference in technique. The lack of significant difference seen in the variance about x aligns with the rotation techniques developed and discussed previously. A significant difference ($P = 0.047$, by Kruskal-Wallis test) in rotation direction was found only in rotations about y for the fully trained group.

Modified Cooper-Harper Test

Since the Cooper-Harper rating provided by the subject is subjective, it is not always indicative of their actual performance. While some subjects gave ratings that were correlated with time performance (higher Cooper-Harper ratings for longer performance times), other subjects had fairly consistent times across all trials but had decreases in Cooper-Harper ratings. Despite showing similar times over all repetitions, the subject may have understood the process better in later trials. This could explain the Cooper-Harper ratings. This important aspect of motion usability is discussed when the workload results are presented further on.

Workload Assessment

A difference in workloads between groups is to be expected for rotations about y and z for two reasons. First, the initial performance times were significantly different between training groups for rotations about y and z. Second, the fully trained subjects performed motions that were familiar from Earth environment motions. As there was no significant difference between times for rotations about x and the trained motion about this axis was not as common to Earth environment motions, no difference in workloads was expected for rotations about x. In addition, the expectation is that the workload would decrease between rotational blocks as the subjects acquire additional practice in performing the motion. **Fig. 5** shows the box plot of the NASA-TLX scores for each rotational block for both groups.

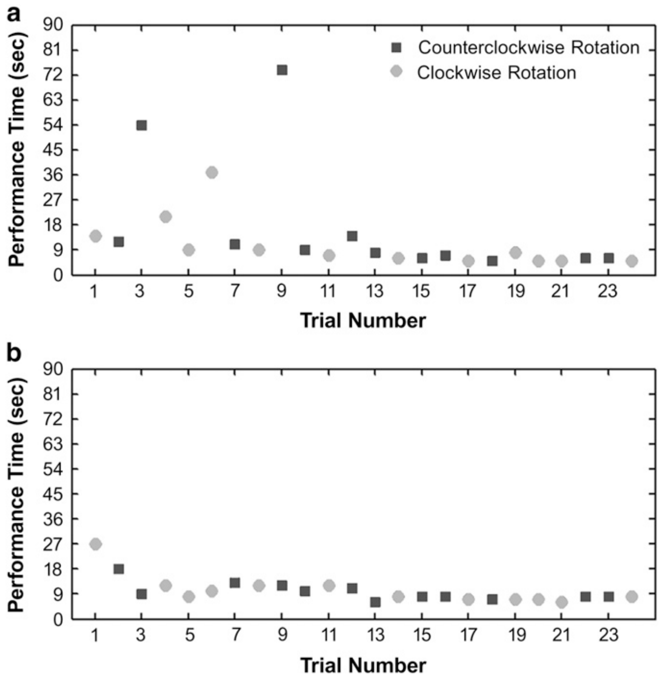

Fig. 4. Two example learning patterns for rotations about z. The subject in A shows increases in performance time with repetition, which is indicative of a minimally trained subject, and the subject in B shows fewer repetitions before the steady state is achieved, which is indicative of a fully trained subject.

A significant difference was seen between groups for Y_1, Y_2, and Z_1, with P-values of 0.002, 0.023, and 0.023, respectively, by Kruskal-Wallis test. The minimally trained group reported a much higher workload than the fully trained group in each of these cases. For the minimally trained group, the y rotations had the highest workload, while the x rotations were perceived to be the most difficult by the fully trained group.

For each group, the perceived difficulty of the rotation decreased significantly after the second block (Friedman test, $P < 0.01$) for all cases. The ratio between values for the first and second block of each rotation axis measures the decrease in workload as:

$$W_{norm} = \frac{W_2}{W_1}$$

where W_1 and W_2 are the workload scores after blocks 1 and 2. These data indicate an average decrease of 20–35% between the first and second blocks. Similar decreases were seen between experimental blocks regardless of group.

In the second hypothesis, rotations that were common in an Earth environment were expected to show lower workload scores than those that were uncommon. This is evident in comparing rotations about y for the fully and minimally trained groups. While the fully trained group was given the description of bicycle motions, the minimally trained group had no reference and instead tried to use familiar motions in an unfamiliar way. The observed workloads correspond to this hypothesis as well, with the fully trained group having significantly lower workloads than the minimally trained group. Examining rotations about x also supports this hypothesis. Unlike the rotations about y, the technique provided for rotations about x was composed of motions that are not common in an Earth environment. Thus, having higher workloads for rotations about x than those about y is consistent with expectation.

Motion Techniques

The motion techniques developed by the minimally trained subjects can be used to examine the second hypothesis and to clarify the motion control problem. Of the 10 minimally trained subjects, 8 initially started the rotations about z by using only their arms. The arm motions developed were generally sweeping motions, similar to that used when treading water, except that the arms traveled in the same direction. Only two subjects began the initial trial using leg motions. Once subjects modified their strategy to include their legs, they never reverted to using arm motions alone. Of the 10 minimally trained subjects, 7 used legs in their steady state motion. Although using the legs requires more energy than the arms—their moments of inertia and mass are greater—the task time decreased in response to the added effort. These results emphasize the value of selecting a solution that balances performance time with energy expended.

During the initial performance of the rotations about z, two of the minimally trained subjects struggled a great deal. One spent time twisting and untwisting the upper body with respect to the lower body. Since no

TABLE II. STEADY STATE PERFORMANCE TIMES (SECONDS) FOR THE CLOCKWISE (CW) AND COUNTERCLOCKWISE (CCW) ROTATIONS (N = 10 FOR ALL BUT THE STARRED ENTRIES, IN WHICH N = 9).

		X-Rotation		Y-Rotation		Z-Rotation	
		cw	ccw	cw	ccw†	cw	ccw
Minimally Trained	Median	6.0	5.0	7.0*	9.0†	7.0	7.0
	Mean	6.9	5.1	20.2*	11.0†	8.1	7.7
	SD	3.5	1.4	26.0*	9.1†	3.8	2.8
Fully Trained	Median	6.5	6.5	7.0	5.0†	7.0	7.0
	Mean	8.2	6.5	7.0	5.3†	6.9	6.9
	SD	4.2	2.1	1.9	0.9†	1.4	1.7

† A statistically significant difference between groups was observed.

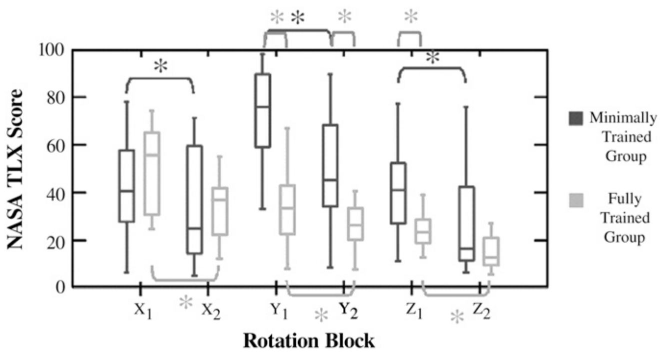

Fig. 5. The distribution of the NASA-TLX workload scores for all subjects (N = 20). Significant differences between groups and within groups are indicated by stars.

change in inertia was obtained after the initial twist, no net rotation was achieved when the subject untwisted. The other subject that experienced difficulty performed sweeping arm motions similar to those of the other subjects. That subject, however, did not pull the arms toward the body after the sweep. Instead the arms oscillated in the same path and thus did not create any net rotation. While this conceptual information was provided during training, these results show that pure conceptual information is not always enough to support efficient performance.

The suspension environment significantly affected the motions developed by the minimally trained subjects for rotating about x. In general, they developed large kicking motions despite instructions that told them to keep the body planar. In a true microgravity environment, these motions would have incurred large off-axis rotations. Many subjects developed these large kicking motions since use of the legs proved to be effective in the rotations about z, which all subjects performed prior to rotations about x. These kicking motions were similar to those used while swimming, which illustrates the tendency to revert to familiar motions.

Rotations about y proved to be the hardest for the minimally trained group, as inferred from the after-experiment interview and the NASA-TLX workload scores. Only 1 out of the 10 subjects in this group began with a strategy that worked. Of the remaining nine subjects, different kicking methods were tried, including a modified freestyle, butterfly stroke, and scissor kick. At the conclusion of the experiment, only three subjects were found to understand why their technique worked. One subject never developed a strategy for rotating clockwise. A second was able to perform the task only intermittently (this subject did not understand which strategies did and did not work). The remaining subjects did not understand why their techniques worked, but could explain their strategy. In general, they had developed ways to execute their kicks such that their feet traced an elliptical trajectory in the xz-plane without their knowing it. To perform this rotation in the ways developed by the subjects was not natural and thus incurred high workload scores, which is consistent with the second hypothesis. Further, the subjects did attempt to use motions they were familiar with in new ways to achieve the desired rotation.

DISCUSSION

The purpose of this study was to investigate self-rotation maneuvers in a microgravity environment. The first research hypothesis was that subjects that had motion strategy training would perform better initially than those that had not received training. The differences in initial performance times and subjective ratings support this hypothesis for rotations about y and z. No direct performance conclusions could be made for rotations about x with respect to this hypothesis. The minimally trained group did not perform rotations that would work in a true microgravity scenario since they would have been non-planar. The lesson learned from this rotation was that subjects take advantage of the environment they are placed in (e.g., the extra stability that was given by the suspension configuration) even if they are attempting to follow the guidelines. This has implications for using simulated environments in training and will be important in determining how the training is to be designed. Our second hypothesis stated that rotations and motions that were common in an Earth environment would have a lower complexity than those that were completely unfamiliar; further, in cases where no technique was provided, familiar motions would be implemented. This hypothesis was confirmed through motion observation along with the NASA-TLX scores. Our final hypothesis, that stated the variation in performance of a group with less training would be greater than the variation in a group with more training, was confirmed using nonparametric statistical tests on the performance time data.

In the development of plausibly difficult motions, it is important to understand their usability. The modified Cooper-Harper rating and the NASA-TLX implemented in this study have been beneficial in showing perceived difficulty of a motion. Even when the subject performs a task with consistent efficiency, the perceived difficulty changed over the trials. This shows that practice of a motion technique is important if multiple tasks are to be performed. More attention can then be devoted to the other tasks. This is especially important, for example, for an astronaut whose jet pack has had a partial failure.

When balancing the groups for this experiment, the subjects were randomly placed into either the trained or untrained groups using a coordination score that was developed by the authors based on the Ability Requirements Approach of Fleishman and Quaintance (8). While this score showed a statistically significant effect for the explicitly investigated time metrics (log T at the first repetition and Δlog T between the first and last repetition), the variability was high and caused a weak linear fit. The high variability seen in the regressions can be partly attributed to the difference in motion components between the tasks comprising the coordination score and the rotations performed in the simulated microgravity. Many studies have shown the importance of specificity of training to the ability to perform a task. Therefore, for future rotational studies it is suggested that the coordination score be evaluated using motions that have a higher degree of similarity to the motions being studied.

We minimized the limitations of the suspension system by focusing on single-axis rotational motions. This has implications for the applicability of simulated environments to train astronauts for an inherently three-dimensional environment. However, as these simulations are low cost, there are situations for which they are appropriate. If we consider training as a tiered system, the first stage could involve implementing motions in a suspension system to obtain an increased mental understanding of how self-rotations are performed. The second stage could occur during parabolic flight training where the astronaut becomes familiar with the perturbations that can occur to the single-axis motions. The final stage could occur in the true microgravity environment. This training need not be time intensive. During this study, we observed learning and reduction of complexity after a few repetitions. Thus, motion training could easily be added to the existing astronaut-training framework without significantly affecting total training time. This tiered training strategy thus compensates for any mis-training (i.e., development of inappropriate movements) that could occur due to simulated environments. Regardless of environment, any motion strategy training must consist of simple repeated trials that reduce cognitive complexity, not merely performance time. While we only considered rotational motions in this study, a motion-control training program should include translational maneuvers as well so that a full repertoire of movements can be sampled.

The motions defined in this study for the fully trained group are not the only possible rotations, but were the simplest to perform and similar to common Earth motions. Certain strategies and modifications to the methods developed by the subjects during the experiment proved very interesting. For example, instead of rotating the feet in circles for the rotation about y and z, subjects created more of an elliptical shape that yielded larger changes in inertia than possible for a pure circle, thereby making each cycle more effective. While the motion training should provide information on techniques, it is important to let natural modifications occur so that each person obtains a technique they are comfortable performing. While we examined performance times between groups, we did not try to design minimum time motions. Other techniques do exist that can achieve larger rotations in shorter periods of time. Our goal was to create simple-to-perform motions that could occur in a reasonable amount of time that had minimal complexity.

This study was the first to examine rotational motion control from an untrained astronaut's perspective. It is also the first to examine the usability of predetermined and self-developed rotational motions. In this study, we developed a way to quantify rotational motor control ability using the concepts of gross body coordination and equilibrium. Further, we have shown that certain axes are easier to rotate about than others and that trained subjects have an easier time performing the body rotations than those that have not been trained. This study has provided groundwork for the development of an astronaut motion control training program.

ACKNOWLEDGMENTS

The authors would like to thank Dr. Alan Natapoff for his help in performing the statistical analysis. This research has been funded by NASA Johnson Space Center Cooperative Agreement NNH04H103A.

Authors and affiliations: Leia A. Stirling, M.S., Ph.D., Children's Hospital Boston and Harvard Medical School, Boston, MA; Dava J. Newman, M.S., Ph.D., Professor of Aeronautics and Astronautics and Engineering Systems, and Karen E. Willcox, S.M., Ph.D., Associate Professor of Aeronautics and Astronautics, MIT, Cambridge, MA.

REFERENCES

1. Amir AR, Newman DJ. Research into the effects of astronaut motion on the spacecraft: A review. Acta Astronaut 2000; 47:859–69.
2. Baroni G, Ferrigno G, Anolli A, Andreoni G, Pedotti A. Quantitative analysis of motion control in long term gravity. Acta Astronaut 1998; 43:131–51.
3. Baroni G, Pedrocchi A, Ferrigno G, Massion J, Pedotti A. Motor coordination in weightless conditions revealed by long-term microgravity adaptation. Acta Astronaut 2001; 49:199–213.
4. Bock O, Howard I, Money K, Arnold K. Accuracy of aimed arm movements in changed gravity. Aviat Space Environ Med 1992; 63:994–8.
5. Brody AR, Jacoby RH, Ellis SR. Extravehicular activity self-rescue using a hand-held thruster. J Spacecr Rockets 1992; 29:842–8.
6. Ferguson P. Quantifying and modeling adaptive astronaut movement: motion strategies for long-duration spaceflight missions [doctoral thesis]. Cambridge, MA: Massachusetts Institute of Technology; 2006.
7. Fisk J, Lackner J, DiZio P. Gravitoinertial force level influences arm movement control. J Neurophysiol 1993; 69:504–11.
8. Fleishman E, Quaintance M. Taxonomies of human performance: the description of human tasks. Orlando: Academic Press; 1984.
9. Hart S, Staveland L. Development of NASA-TLX (task load index): results of empirical and theoretical research. In: Human mental workload. Amsterdam: North Holland Press; 1988:239–50.
10. Kane T. Self-rotation of astronauts by means of limb movements. Transactions of the Second National Conference on Space Maintenance and Extra Vehicular Activities. Wright-Patterson AFB, OH: Air Force Aero Propulsion Lab; 1968.
11. Kingma I, Toussaint H, Commissaris D, Savelsbergh G. Adaptation of center of mass control under microgravity in a whole-body lifting task. Exp Brain Res 1999; 125:35–42.
12. Kulwicki P, Schlei E, Vergamini P. Weightless man: self-rotation techniques. Wright-Patterson AFB, OH: Air Force Aerospace Medical Research Lab; 1962. Technical Documentary Report No. AMRL-TDR-62-129.
13. Lackner JR, DiZio P. Human orientation and movement control in weightless and artificial gravity environments. Exp Brain Res 2000; 130:2–26.
14. Massion J. Movement, posture, and equilibrium: interaction and coordination. Prog Neurobiol 1992; 38:35–56.
15. Massion J, Popov K, Fabre J, Rage P. Is the erect posture in microgravity based on the control of trunk orientation or center of mass position? Exp Brain Res 1997; 114:384–9.
16. NASA. Man-Systems Integration Standards. Houston, TX: NASA-Johnson Space Center; 1995. Report No.: NASA-STD-3000.
17. Newman DJ, Amir AR, Beck SM. Astronaut induced disturbances to the microgravity environment of the *Mir* space station. J Spacecr Rockets 2001; 38:578–83.
18. Newman D, Beck S, Amir A, Baroni G, Ferrigno G, Pedotti A. Measuring astronaut performance in microgravity: loads and modeling. In: Proceedings of the First Biennial Space Biomedical Investigators Workshop; Jan. 11-13, 1999; League City, TX. Hampton, VA: Langley Research Center; 1999.
19. Papaxanthis C, Pozzo T, McIntyre J. Kinematic and dynamic processes for the control of pointing movements in humans revealed by short-term exposure to microgravity. Neuroscience 2005; 135:371–83.
20. Papaxanthis C, Pozzo T, Popov K, Schieppati M. Trajectories of arm pointing movements on the sagittal plane vary with both direction and speed. Exp Brain Res 2003; 148:498–503.

21. Parin V, Gazenko O. Weightlessness (medical and biological research). Houston, TX: Johnson Space Center; 1975. NASA TTF-16105.
22. Patron J, Stapley P, Pozzo T. Human whole-body reaching in normal gravity and microgravity reveals a strong temporal coordination between postural and focal task components. Exp Brain Res 2005; 165:84–96.
23. Scher M, Kane TR. Pitch and yaw motions of a human being in free fall. NASA-CR-97902, 1968. Available at http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19690003892_1969003892.pdf.
24. Schmitt HH, Reid DJ. Anecdotal information on space adaptation syndrome. In: Proceedings of the Space Adaptation Syndrome Drug Workshop; July 1983. Houston, TX: University Space Research Association Division of Space Biomedicine; 1985.