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Subject Effects Exhibited in Human Posture in Neutral Buoyancy and Parabolic Flight

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ABSTRACT

Neutral buoyancy (NB) and parabolic flight (PF) are the only available human-scale three-dimensional spaceflight simulation environments. As such, both environments are used extensively for both research and mission operations purposes despite a lack of quantitative (or even qualitative) characterization of the fidelity of either environment to the spacelfight analog. The present study was undertaken as part of a larger research effort to begin to build such characterizations. Eight healthy adults (4 men and 4 women) were asked to adopt relaxed postures while 'standing' in space shuttle middeck standard-type foot restraints, in NB and during the 0g periods of PF. Subjects were tested in NB in 9 orientations, 3 trials each: Upright; tilted 45° Front, 45° Back, 45° Right, 45° Left; and tilted 90° Front, Back, Right, and Left. PF limitations prohibited 90° testing; consequently the PF test protocol included only Upright and 45° orientations. NB testing was performed at the bottom of a 25' deep NB facility, using SCUBA certified, experienced test personnel. PF testing was performed during four flights on the NASA KC-135. Subjects were fully informed of the test protocol prior to and during testing. Reaction loads were recorded for each foot independently and normalized to subjects' masses; hip, knee, and ankle angles were measured from photographs. Trunk and shank angles (defined respectively by hip-shoulder ray and ankle-knee ray angles to the foot restraint plane) were also recorded. All subjects completed all trials for NB; however, some trials were lost during PF, due to subject motion sickness. Nonetheless, statistically significant ANOVA (analysis of variance) outcomes ($p<.05$) were found between subjects for both postural angles and reaction loads, and also between test conditions for each subject. These results indicate that individual posture maintenance strategies vary in both environments, and do not represent a single consistent neutral posture model in either.

INTRODUCTION

The best — and only — terrestrial “zero-gravity” simulation environments for human applications are neutral buoyancy (NB) and parabolic flight (PF). At first glance both seem to provide reasonable representations of the on-orbit microgravity environment they seek to model. Qualitatively at least, subjects seem to ‘float’ in both environments in much the same way they do in space, and after all there aren’t any foreseeable alternatives for simulating spaceflight conditions on Earth.

Anecdotal evidence from astronauts trained in neutral buoyancy for on-orbit tasks indicates that the training prepares the astronauts well for performing their prescribed tasks, but not for feeling acclimated to the on-orbit environment. In fact, many astronauts have reported a temporary sense of spatial disorientation during the first several minutes of performing a highly practiced task on orbit (particularly during extravehicular activity, or EVA), in direct conflict with an equally strong sense of familiarity with the task protocols and the objects in their visual fields. Furthermore, parabolic flight experience is not a predictor for space motion sickness (SMS), as there is no correlation between motion sickness episodes experienced by astronauts on the KC-135 and on orbit. These and other fragments of information suggest after fairly superficial examination that there is no strong correlation between the sensory landscapes of either NB or PF and spaceflight, or their respective interpretations by human sensory systems.

Under NB conditions, the subject’s body is balanced in the water such that his or her buoyancy is compensated exactly by his or her weight. The subject ideally has no preferred orientation, and neither sinks nor rises. During PF, an aircraft is flown in a Keplerian trajectory, producing periods of “zero gravity” (0g) alternating with periods of up to twice-Earth gravity accelerations. Several studies using different experimental approaches, and performed over a period of multiple decades [e.g., 1-6], demonstrated that human subjects evidence asymmetric responses to neutral buoyancy conditions, particularly with respect to orientation; similarly, Lackner and colleagues [e.g., 7, 8], among others, have also shown that human subjects experience a wide variety of perceptual effects during exposure to PF, and that these effects arise in response to both internal and external cues. However, the implications of these effects for the successful simulation of spaceflight conditions in NB and PF are not explicitly understood. Those implications must be clarified in order to improve the fidelity of human subject research and training exercises performed in these two environments.

We have previously reported on some vision and orientation effects [9,10, respectively] on NB and PF posture. The purpose of the present study is to examine the measurable effects of subject orientation on relaxed human posture in NB and PF environments, and determine if possible whether asymmetries similar to those previously reported for NB are also present in PF.

METHODS

In this study, quiescent, or neutral, restrained posture was studied during both restrained and unrestrained conditions in NB and PF. Tandem space shuttle middeck-type intravehicular activity (IVA) foot restraints were used, one under each foot. Each of these restraints consists of a flat nylon web strap attached to an aluminum plate. The plate is in turn attached to a sensor described below. The restraint is used by sliding the foot under the strap and then either dorsiflexing, plantarflexing, or rotating the ankle to exert an anchoring load on the restraint. Users may choose any or all of the available ankle or subtalar motions to hold themselves in position, and may alternate from one method to another during extended use or to adjust lower or upper body configurations.

Eight subjects (4 men, 4 women), all experienced NB test divers, volunteered to take part in the study. All subjects were fully informed of the test protocol and goals prior to giving their consent to participate. The average age of the subjects was 30.4 [range 26- 39]; average height 1.7m [range 1.6m – 1.9m]; and average weight 72.5kg [range 56.7kg – 94.3kg]. None of the subjects had any history of vestibular or other sensory dysfunction. After completing the NB testing, and all NASA-required training, medical clearances, and paperwork, all subjects reported for testing on the KC–135, and all were authorized for flight.

Prior to each test in either NB or PF, each subject was reminded of the protocol and goals for that test. All subjects were given the opportunity to familiarize themselves with the foot restraints prior to participating in the test. Subjects were instructed for each trial to adopt the most comfortable and relaxed posture for their own bodies and not to attempt to consciously adhere to any particular postural configuration, including either erect or compact posture. They were informed that the test conductor and subject handler would be responsible for providing them cues to enter or exit the foot restraints and also assisting them in moving safely and smoothly onto and off of the experiment apparatus. The subjects were asked to remain in the foot restraints for the duration of each trial unless they felt symptoms of disorientation or motion sickness interfering with their ability to continue. If they became fatigued, disoriented, or ill, they were instructed to notify the test conductor or subject handler for assistance in pausing or terminating their trials. Subjects were asked to exit the foot restraints at the end of each trial in the KC-135, to prevent risk of falling during the transitional and increased gravity periods.

In each environment, 3 successive trials were conducted for each condition. These were: in NB, 0° (not tilted with respect to the local horizontal), tilted 45° front, back, right, and left, and tilted 90° front, back, right, and left; in PF, 0° (not tilted with respect to the local horizontal), tilted 45° front, back, right, and left. The PF set excludes 90° cases because of volumetric constraints imposed by the aircraft cabin. Each trial lasted 30 seconds (NB) or for the maximum available reduced gravity period after subjects were positioned comfortably (PF). Additionally, each subject also completed three trials totally unrestrained, or 'free-floating' in NB. As the subjects were all experienced NB test divers, they did not float to the surface. This case was included to correspond to the Skylab data [11, 12] and more recent studies [e.g., 13] of purely 'neutral' posture.

Joint angle data were collected from still photographs taken during testing in both environments. The photographer was instructed to position himself as accurately as possible 3 meters from the subject and facing the subject's sagittal plane[1] (side view). One photograph was taken from this perspective for each trial. Postural angles were measured from the side view frames by locating the malleolus, (upper) head of the tibia and greater trochanter on the subject, comparing those locations with the subject's swimsuit and dive socks, and then marking and connecting the ankle, knee, hip, and shoulder joint centers on each still print. The error in this angle measurement method is estimated to be ±7°, based on results from a preliminary study [(unpublished)10]. The same method was used for collecting joint angle data on the KC-135, with the following exceptions: due to the limited dimensions of the aircraft cabin and the extremely short duration of each parabola, the photographer used a 28mm lens and

[1] Under the lighting conditions present in the NBRF, 3m is an optimal focal distance of the Nikonos II underwater 35mm still camera used in this study. At that distance, the subject fills approximately 75-80% of the length of the frame.

positioned him/herself approximately 1-2 meters from the subject; due to the limited time available on the KC-135, the photographer was instructed to take two frames per parabola in an attempt to guarantee the availability of joint angle data.

The foot restraints were attached to Assurance Technologies Gamma model sensors, which were in turn anchored to the test stand. Subjects were permitted to wear cotton socks during KC–135 testing and dive socks or booties during NB testing. This is consistent with astronaut use of the IVA foot restraints, as astronauts typically wear socks during on-orbit middeck activities.

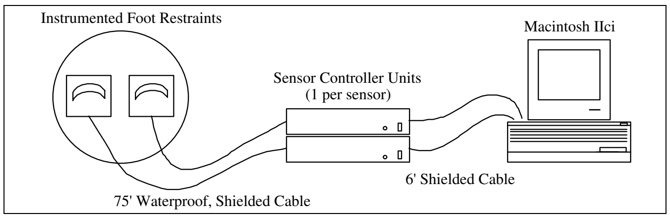

Figure 1. Data Collection System

A total of 12 channels of data were recorded through two controller units connected to the printer and modem ports on an Apple Macintosh IIci™, using a specially developed C language program. The data files were subsequently reduced using original MatLab® language programs.

RESULTS

Neutral buoyancy tests were conducted in the Space Systems Laboratory Neutral Buoyancy Research Facility (SSL NBRF) during one two-week period. All subjects completed all trials satisfactorily. Parabolic flight tests were conducted on the NASA JSC KC-135 during one four-day mission. All subjects participated in at least one flight each. The author took part in three of the four flights. During one flight, the sensor data collection system failed; this means that for two subjects, there are only joint angle data and no reaction loads data. These are admittedly non-trivial holes in the data set. However, this outcome represents a realistically successful human subject parabolic flight campaign.

ANGLE RESULTS

Angle measurement conventions were defined to be consistent with the Skylab model [11, 12], as illustrated in Figure 2. In addition to the hip, knee, and ankle measures, two other angle measures were also tabulated: trunk and shank angles were defined by the intersection between the foot restraint plane and the trunk and shank (ankle-knee) rays, respectively.

Individual subject postural angle values were found by calculating the mean of each three-trial measurement series.

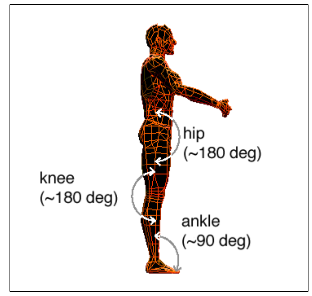

Figure 2. Postural Joint Angle Measurement Conventions

Hip, knee, and ankle angles are defined as shown here, to concur with the Skylab angle reporting convention. Trunk and shank angles are defined by the intersection between the foot restraint plane and the trunk and shank rays, respectively, such that both would be approximately 90° for an upright, erect figure such as the one shown here.

First we examine the NB Unrestrained case. Recall some photographs were not useful for angle measurements, and some trials were not completed at all due to equipment failure or subject discomfort. For each subject angle plotted here, the number of frames used to calculate the mean is reported under the subject's initials; standard deviations are plotted as error bars.

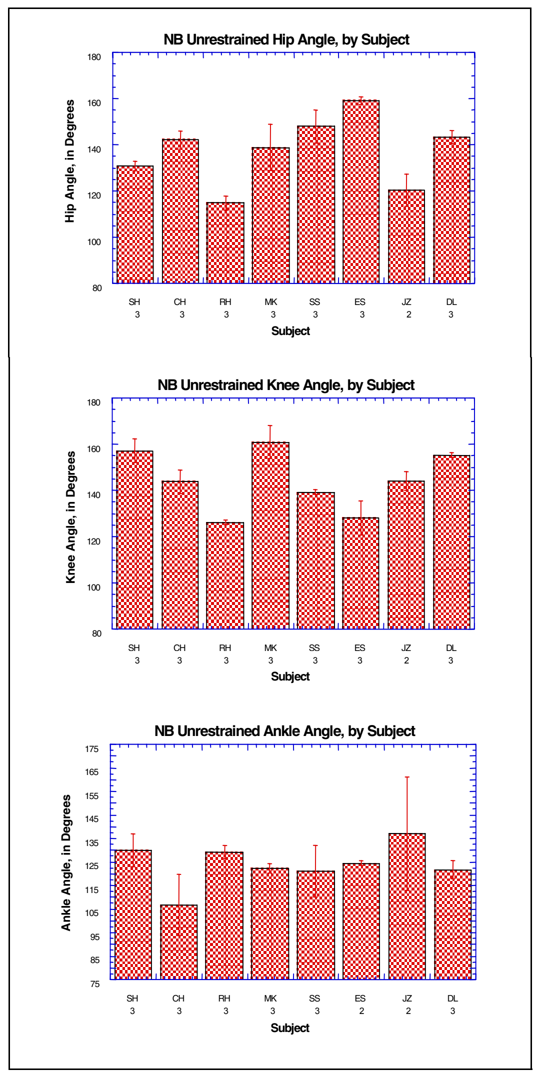

Figure 3. Individual Subject Postural Angles, NB Unrestrained

We tabulated group results by calculating the average for each joint angle across all eight subjects for comparison to the Skylab model and to McDade's [13] results. As shown in Table 1, it appears that the three sets of results are *similar*, but perhaps not the same.

Table 1. NB Unrestrained Joint Angles, Compared to Previous Findings

Angle Measured	Present Study	Skylab Model	McDade Study
Hip	137.6° ± 13.8°	128° ± 7°	117.8° ± 5.2°
Knee	142.7° ± 13.4°	133° ± 8°	133.0° ± 12.9°
Ankle	124.3° ± 9.4°	111° ± 7°	117.0° ± 5.5°

We cannot say whether these differences between the earlier findings and the present data are statistically significant, as we do not have access to the original Skylab data. However, we can conduct statistical comparisons on our own data. To begin, we first examined our unrestrained joint angle data for consistency across subjects. To determine whether the angle values presented in Figure 3 represent individually distinct postural patterns, or whether they are merely examples of postural arrangements which surround a single mean posture, we calculated ANOVA (analysis of variance) measures[2].

Table 2. ANOVA Outcomes for Unrestrained Joint Angles

Angle Measured	Between-subject p-values
Hip	<.001
Knee	<.001
Ankle	.005

So even before foot restraints are introduced, we see that there is some individuality in subjects' 'neutral' postures. Next we averaged each subject's angle measurements over all orientation cases for NB Restrained conditions (we previously examined vision and orientation effects in [9 and 10], respectively). The results are provided in Figure 4.

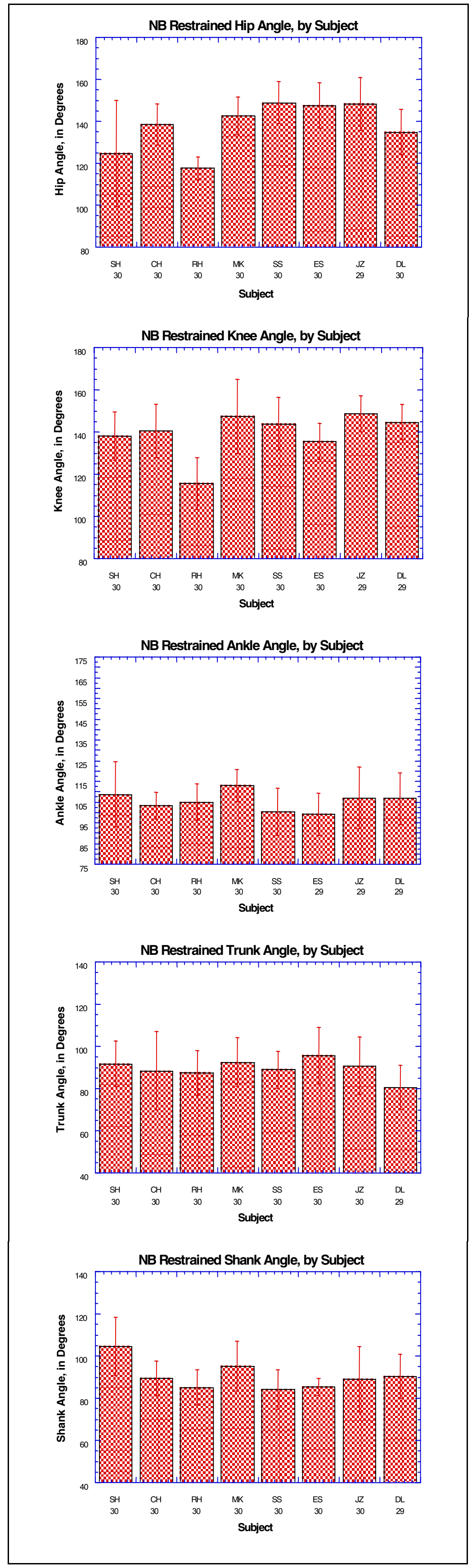

Figure 4. Individual Subject Postural Angles, NB Restrained

Note that for the ankle and trunk angles plotted here, there appears to be an approximately consistent value for the group, whereas large disparities are immediately apparent for the hip and knee angles.

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[2] Normally, results of $p \leq .05$ would be considered compelling for human subjects. However, for this study, because so many comparisons are performed, and the number of samples per test case is not constant, experiment-wise error is assessed to be greater than in the ideal case. For this reason, results of $.04 \leq p \leq .05$ are interpreted as statistically significant but perhaps not meaningfully so (marginally significant), and values of $p < .04$ are accepted to be not only statistically significant but also meaningful. Marginally significant outcomes are considered weak results and are denoted by an asterisk.

Inter-subject differences for the Restrained postures are clearly pronounced: hip, knee, and shank angle measures all produced statistically significant differences, as shown in Table 3. Furthermore, the composite angles formed by the joint pairs hip plus knee, hip plus ankle, and knee plus ankle all produced statistically significant outcomes, indicating that the subjects were not simply finding different individual solutions to achieving a common 'overall' posture.

These inter-subject differences demonstrate that "group means" do not really exist for the NB Restrained cases. The NB Restrained angle values are strongly subject dependent, and these angle values do not appear to represent the same mean, with the exception of the trunk and ankle angles.

Next we turn to the parabolic flight (PF) results. Recall that there is no Unrestrained case in the PF data set; Restrained case joint angle results are shown in Figure 5.

Table 3. Outcomes of Inter-Subject ANOVAs for NB[3] (All Restrained Orientations)

Angle Measured	Between-subject p-values
Hip	<.001
Knee	<.001
Ankle	—
Trunk	—
Shank	<.001
Hip Plus Knee	<.001
Hip Plus Ankle	<.001
Knee Plus Ankle	<.001

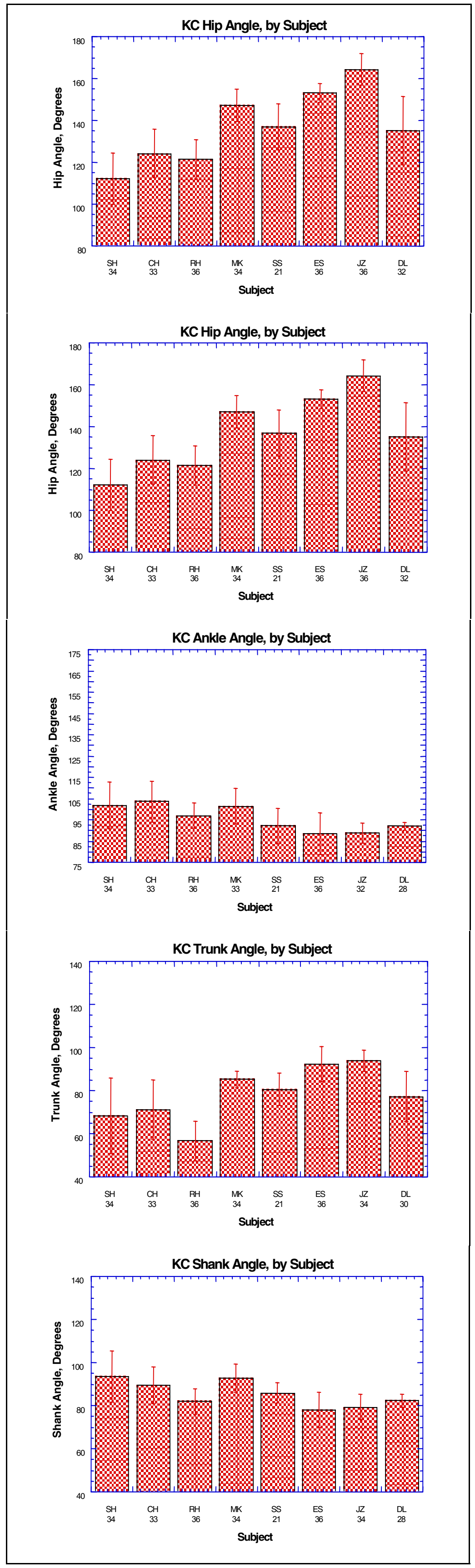

Figure 5. Individual Subject Postural Angles, PF

As in the previous two figures, the number of photographs used to calculate each mean angle value is reported under the corresponding subject's initials. Note the relatively large standard deviations and group-wide disparities among trunk angles, for example.

[3] Note that here the test cases are treated as samples of the subject's joint angles: these comparisons were constructed by considering each NB orientation result as a data point in a subject's NB joint angle data set, so that the ANOVA determines the likelihood that the subject data *sets* (not individual orientation cases) represent a common mean. Please see [10] for orientation results.

Here again subject effects are clearly present across all postural angles and composite angles, as evidenced by the ANOVA results presented in Table 4.

Table 4. Outcomes of Inter-Subject ANOVAs for PF[4]

Angle Measured	Between-subject p-values
Hip	<.001
Knee	.019
Ankle	.006
Trunk	<.001
Shank	.002
Hip Plus Knee	<.001
Hip Plus Ankle	<.001
Knee Plus Ankle	.005

Next we compare the subjects' postures in the two environments. These results are summarized in Table 5, and represent disparities between each subject's neutral buoyancy and parabolic flight postural angles.

Table 5. Outcomes of NB v. PF Postural Angle ANOVAs, by Subject

	Hip	Knee	Ankle	Trunk	Shank	Hip Plus Knee	Hip Plus Ankle	Knee Plus Ankle
ES	—	—	.017	<.001	.027	—	—	—
RH	—	<.001	.033	—	—	.004	—	.0045
JZ	.019	—	.0029	—	—	—	—	.043*
DL	—	<.001	—	—	—	—	—	—
SS	—	—	—	—	—	—	—	—
MK	—	—	.046*	—	—	—	.04*	—
CH	.014	—	—	—	—	.033	—	—
SH	—	—	—	.022	—	—	—	—

Note that although this comparison is constructed to assess postural differences associated with the two *environments* (NB v. PF), it is included here because it also illustrates that the subjects responded variously to those environmental differences: some subjects' postures were significantly different between the two environments, while others' were hardly or not at all distinguishable between NB and PF.

[4] These comparisons were performed in the same manner as those for Table 3, but for PF data only.

REACTION LOAD RESULTS

Next we consider the reaction loads applied by subjects to maintain their postures in the IVA foot restraints. To remove subject mass effects, we normalized reaction loads to subject mass. Again beginning with NB, the group mean reaction load values are presented in Table 4.

Table 6. Normalized Group Mean RMS Values for Neutral Buoyancy Reaction Loads
*** All Subjects ***

		Fx	Fy	Fz	Mx	My	Mz
Left	Normalized Group Mean Reaction Loads	.3967 ± 1.009	1.985 ± 5.514	2.239 ± 6.076	.0877 ± .2392	.3110 ± .8387	.0971 ± .2660
Right	Normalized Group Mean Reaction Loads	.4092 ± 1.029	1.973 ± 5.395	1.601 ± 4.243	.0737 ± .1922	.2342 ± .6176	.1077 ± .2940

Note that the standard deviations for these mean values are quite large relative to the means themselves. Because the load values have already been normalized to each subject's body mass before being averaged into group means, these standard deviations reflect in part the tremendous range of exertion levels employed to maintain stance in the foot restraints. However, one subject in particular, DL, employed substantially larger reaction loads than the rest of the subjects — sometimes more than an order of magnitude greater than the rest of the group. We examine the impact of this subject's results on the group means in Table 6a and 6b.

Table 6a. Normalized Group Mean RMS Values for Neutral Buoyancy Reaction Loads
*** Excluding DL ***

		Fx	Fy	Fz	Mx	My	Mz
Left	Normalized Group Mean Reaction Loads	.0400 ± .0082	.0357 ± .0143	.0911 ± .0524	.0032 ± .0013	.0145 ± .0095	.0031 ± .0021
Right	Normalized Group Mean Reaction Loads	.0452 ± .0117	.0659 ± .0290	.1009 ± .0588	.0058 ± .0026	.0158 ± .0098	.0038 ± .0017

Table 6b. Normalized Group Mean RMS Values for Neutral Buoyancy Reaction Loads
*** DL Only ***

		Fx	Fy	Fz	Mx	My	Mz
Left	Normalized Group Mean Reaction Loads	2.894 ± 1.234	15.63 ± 3.534	17.27 ± 9.800	.6797 ± .3679	2.387 ± 1.317	.7556 ± .1672
Right	Normalized Group Mean Reaction Loads	2.957 ± 1.714	15.33 ± 5.445	12.10 ± 9.118	.5493 ± .1858	1.762 ± 1.046	.8355 ± .3952

Clearly this subject employed a dramatically different self-stabilization strategy than did the other subjects (however, by marked contrast, DL's postural *configurations* were not dramatically different from the other subjects). We examined this assessment by comparing subject reaction loads across the group; the results are summarized in Table 8.

Table 7. ANOVA Outcomes for Comparisons between NB Subjects

	Left Foot, All Subjects	Right Foot, All Subjects
Fx	—	—
Fy	<.001	<.001
Fz	<.001	.002
Mx	.002	.004
My	<.001	<.001
Mz	<.001	<.001

These results confirm the intuitive interpretation that the subjects maintained their postures using distinct self-stabilization patterns. Left and right foot reaction loads also do not appear to be equivalent. 'Footedness' effects are addressed in the following section. Continuing with PF results, the group mean values are shown in Table 8, 8b and 8c (as in Table 6).

Table 8a. Normalized Group Mean RMS Values for Parabolic Flight Reaction Loads
*** All Subjects ***

		Fx	Fy	Fz	Mx	My	Mz
Left	Normalized Group Mean Reaction Loads	.0470 ± .0052	.0966 ± .0505	.2137 ± .0515	.0093 ± .0029	.0273 ± .0083	.0078 ± .0055
Right	Normalized Group Mean Reaction Loads	.0478 ± .0097	.0989 ± .0658	.2166 ± .0409	.0111 ± .0049	.0322 ± .0063	.0078 ± .0055

Table 8b. Normalized Group Mean RMS Values for Parabolic Flight Reaction Loads
*** Excluding DL ***

		Fx	Fy	Fz	Mx	My	Mz
Left	Normalized Group Mean Reaction Loads	.0469 ± .0080	.1028 ± .0172	.2130 ± .0990	.0098 ± .0022	.0270 ± .0122	.0028 ± .0011
Right	Normalized Group Mean Reaction Loads	.0486 ± .0110	.1390 ± .0656	.2175 ± .0510	.0122 ± .0031	.0336 ± .0061	.0094 ± .0014

Table 8c. Normalized Group Mean RMS Values for Parabolic Flight Reaction Loads
*** DL Only ***

		Fx	Fy	Fz	Mx	My	Mz
Left	Normalized Group Mean Reaction Loads	5.023 ± 2.400	54.46 ± 12.26	21.16 ± 8.169	.9532 ± .2343	2.865 ± .8913	2.069 ± .3007
Right	Normalized Group Mean Reaction Loads	4.644 ± 1.699	53.57 ± 14.74	22.21 ± 5.807	1.235 ± .4029	2.559 ± .5812	2.374 ± .6273

Comparing reaction load patterns across the subject pool, we once again find widespread differences between subjects. However, these outcomes are less replete than the NB results.

Table 9. ANOVA Outcomes for Comparisons between PF Subjects

	Left Foot, All Subjects	Right Foot, All Subjects
Fx	—	.029
Fy	<.001	<.001
Fz	.013	.017
Mx	*	.009
My	—	—
Mz	<.001	<.001

Footedness

As noted in the previous section, left and right foot reaction loads also do not appear to be equivalent. We tested this apparent pattern by comparing Left and Right foot reaction loads for each NB test condition; the results are summarized in Table 7. The same assessment was performed for KC; the results are summarized in Table 8.

Table 10. Left v. Right ANOVA Outcomes by NB Test Condition

	Fx	Fy	Fz	Mx	My	Mz
45F	<.001	—	.046*	—	—	—
45B	—	—	—	—	—	—
45R	—	—	—	.012	—	—
45L	—	.002	—	*	—	—
90F	*	—	—	—	—	—
90B	—	—	—	—	—	—
90R	—	—	—	—	—	—
90L	—	.002	—	.006	—	—
0	—	—	—	—	—	—
Blind	—	—	—	—	—	—

Here there is clear evidence of reaction load application inequalities between right and left feet on three axes, and the specific test conditions for which statistical differences were found are also asymmetric: right and left foot loads are unequal in Fx for 45F, but not at all for 45B; both the 45R/45L and 90R/90L pair have significant outcomes in Fy and Mx for one condition, but only in Fy for the other, and the 45R/45L pattern is mirrored by the 90R/90L pattern. These are not the cases for which right/left differences would be expected to arise from buoyancy management issues; indeed, they are often orthogonal or at an oblique angle to the buoyancy vector

However, by contrast there were no statistically significant differences between left and right foot reaction loads in PF.

Table 11. Left v. Right ANOVA Outcomes by PF Test Condition

	Fx	Fy	Fz	Mx	My	Mz
45R	—	—	—	—	—	—
45L	—	—	—	—	—	—
45F	—	—	—	—	—	—
45B	—	—	—	—	—	—
90F	—	—	—	—	—	—
0	—	—	—	—	—	—
Blind	—	—	—	—	—	—

Furthermore, we also found no statistically significant results when we compared reaction loads across subjects as a group or for each subject individually, as summarized in Tables 12, 13, and 14.

Table 12. ANOVA Outcomes for Comparisons between Left and Right Foot Loads, for All Subjects

	NB	PF
Fx	—	—
Fy	—	—
Fz	—	—
Mx	—	—
My	—	—
Mz	—	—

Table 13. ANOVA Outcomes for Comparisons between NB Right and Left Foot Reaction Loads, by Subject

	Fx	Fy	Fz	Mx	My	Mz
SH	—	—	—	—	—	—
CH	—	—	—	—	—	—
RH	—	—	—	—	—	—
MK	—	—	—	—	—	—
DL	—	—	—	—	—	—
SS	—	—	—	—	—	—
ES	—	—	—	—	—	—
JZ	—	—	—	—	—	—

Table 14. ANOVA Outcomes for Comparisons between PF Right and Left Foot Reaction Loads, by Subject

	Fx	Fy	Fz	Mx	My	Mz
SH	[no reaction loads]					
CH	—	—	—	—	—	—
RH	—	—	—	—	—	—
MK	[no reaction loads]					
DL	—	—	—	—	—	—
SS	—	—	—	—	—	—
ES	—	—	—	—	—	—
JZ	—	—	—	—	—	—

This is in keeping with studies going back as far as 1928 [6], which have found subject-dependent orientation effects unique to underwater studies.

DISCUSSION

In both NB and PF, we found marked particularity to each subject's postural configuration; we further found intra-subject variabilities, indicating that subject postures and self-stabilization strategies were not necessarily self-consistent. In essence, we found that this group of subjects does not represent a statistically coherent single population as regards their postural angles (with the exception of the trunk angle in NB). They may, in fact, each represent a distinct population, implying that neutral posture in NB and KC conditions, at least as measured by this study, is individually determined, and not collapsible across multiple subjects. This is a very different perspective than either the Skylab data or any other studies of human posture in reduced gravity conditions have suggested. Although we cannot test for agreement between the present results and the Skylab model, it seems reasonable to also expect variability between individuals on orbit, particularly during the early phases of the zero-g adaptation process. Intra-subject variability likewise seems reasonable to anticipate, and also seems likely to diminish with adaptation. In fact neither of these extrapolations should be controversial, as both agree with anecdotal evidence. However, further study could be beneficial in defining the sources and implications of these differences.

One of our more peculiar findings also agrees conceptually with earlier immersion studies (particularly [1] and [6]), but suggests no ready conclusions: we found persistent clues in the subject reaction loads which seem to suggest some interesting right/left asymmetries; however, our comparisons of right versus left foot reaction loads produced no new insights. The good news for operational researchers appears to be that there is substantially less inter-subject variability in the KC-135 test environment, at least with regard to neutral posture maintenance. Whether PF is the environment best suited to any particular simulation study is nonetheless determined by a great many other factors besides neutral posture consistency.

Admittedly, the technique we employed to gather joint angle data is somewhat coarse, and a source of potential error. However, photographic measurement is consistent with the past literature, and unlike the available alternatives, acceptable for both underwater and parabolic flight use.

Unlike the Skylab results, which were recorded from three male subjects adapted to weightlessness, the present results were gathered using 8 male and female subjects submerged in water for relatively brief periods, and exposed to even briefer cyclic loadings in an aircraft. Although we do not here examine gender differences, some may possibly exist. By contrast, there is ample evidence in the literature — as well as in casual observation — that there exists a wide range of solutions to the postural maintenance problem, regardless of genger. We suggest that although there is quite likely a wholly relaxed ‘neutral posture’ solution for each individual body, (a) that posture may rarely be exhibited by a conscious subject, and (b) even an ideally neutral posture would vary from subject to subject, and over time as well. This is either frustrating or promising, depending on whether one wishes to establish a usable standard for designing zero-g workstations (for example, [13]) or one is intrigued by the tremendous adaptability of the body.

CONCLUSIONS

In summary, then, individual subjects did not exhibit a common posture configuration or maintenance strategy in either NB or PF, and clearly did not exhibit one consistent posture common to both environments. Furthermore, although subjects exhibited somewhat different patterns in the reaction loads applied by their left feet than by their right feet, the right and left foot reactions loads were only sporadically descriminable in NB, and not at all in PF.

Collapsing measurements across subjects and test conditions thus may provide illuminating information about environment-specific effects, but may also be somewhat misleading, as this simplification could obscure or ignore the existence of potentially meaningful subject-dependent effects.

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The following are cited explicitly in this paper. For a more extensive bibliography, please contact the main author.

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