USING TRI-AXIAL ACCELEROMETERS TO ASSESS THE DYNAMIC CONTROL OF HEAD POSTURE DURING GAIT

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ABSTRACT

Long duration spaceflight is known to cause a variety of biomedical stressors to the astronaut. One of the more functionally destabilizing effects of spaceflight involves microgravity-induced changes in vestibular or balance control. Balance control requires the integration of the vestibular, visual, and proprioceptive systems. In the microgravity environment, the normal gravity vector present on Earth no longer serves as a reference for the balance control system. Therefore, adaptive changes occur to the vestibular system to affect control of body orientation with altered, or non-present, gravity and/or proprioceptive inputs.

Upon return to a gravity environment, the vestibular system must "re-incorporate" the gravity vector and gravity-induced proprioceptive inputs into the balance control regime. The result is often a period of postural instability, which may also be associated with "space motion sickness" (oscillopsia, nausea, and vertigo). Previous studies by the JSC Neuroscience group have found that returning astronauts often employ alterations in gait mechanics to maintain postural control during gait. It is believed that these gait alterations are meant to decrease the transfer of heel strike shock energy to the head, thus limiting the contradictory head and eye movements that lead to gait instability and motion sickness symptoms.

We analyzed pre- and post-spaceflight tri-axial accelerometer data from the NASA/MIR long duration spaceflight missions to assess the heel to head transfer of heel strike shock energy during locomotion. Up to seven gait sessions (three preflight, four postflight) of head and shank (lower leg) accelerometer data was previously collected from six astronauts who engaged in space flights of four to six months duration. In our analysis, the heel to head transmission of shock energy was compared using peak vertical acceleration (**a**), peak jerk (**j**) ratio, and relative kinetic energy (KE). A host of generalized movement variables was produced in an effort to isolate those that best highlighted vestibular adaptation due to spaceflight.

Data suggest that astronauts used either head or body centered control to reduce the effects of heel strike shock on head position during normal walking at self-selected speeds. Moreover, the form of that control appears to fall under one of two categories: homeostatic or adaptive. Homeostatic control refers to tight constraint (small error) over the value of a given variable before and after spaceflight with little or no "adaptive" changes. Adaptive control refers to lesser constraint over a given movement variable with clear adaptation to earth gravity upon return from spaceflight.

Heel strike shock absorption (ratio of heel to head peak acceleration) best-discriminated head and body centered control strategies. Further, peak jerk data was useful for illustrating pre- and postflight differences in segmental (shank versus head) movement energy. Results from kinetic energy analysis show high consistency between subjects and across test dates. Whether this result highlights a control strategy or is an artifact of approximating body segments using anthropometric tables is, at this point, unclear.

METHODS

Data Collection

Data for this study was collected from six NASA astronauts who flew on long duration space flights aboard the MIR space station. The experimental protocol involved a total of seven test sessions. Three preflight and four postflight gait sessions (see Table 1) were scheduled. Not every astronaut participated in each of the seven test sessions.

Subjects were instrumented with reflective markers for 3-D kinematic analysis, electromyography electrodes to monitor leg muscle activity, and tri-axial accelerometers to measure head and shank accelerations. While kinematic (movement), electromyographic, and dynamic (force, acceleration) data were being collected, subjects walked across the test floor at their self-selected gait speed. Accelerometer data was synchronized to force plate and kinematic data for accurate timing of individual subject gait cycles and stored for later analysis using Bioware software (Kistler Instruments). Data was also collected at both 80% and 120% of self-selected speed, but that data was not analyzed for this project.

Table 1. Key for NASA/MIR Gait Test Sessions

A	practice session	60+ days preflight
B	preflight session 1	30+ days preflight
C	preflight session 2	7+ days preflight
D	R + 0	day of return from spaceflight
E	R + 1	one day after return
F	R + 4	3-6 days after return
G	R + 8	7-9 days after return

Signal Processing

For the present study, the time trace, vertical force plate data, and accelerometer (up to six channels) data were imported from Bioware into a novel signal-processing algorithm written by Dr. Lawrence for use under the Matlab (Mathworks, Inc.) environment. The time trace was converted into millisecond units based upon the data sampling frequency (500-1020 Hz). Vertical force and accelerometer data were filtered at 50 and 100 Hz, respectively. The temporal onset of heel strike was calculated from the vertical force trace. From this, a "heel strike window" of approximately 65 ms (15 ms before heel strike, 50 ms after) was set for subsequent analysis of head and shank accelerometer waveforms (Fig. 1). All data was analyzed over the established heel strike window (different for each data trial) to model the transmission of heel strike shock energy to the head during walking.

Data Analysis

A series of previously defined movement variables was produced from head and shank accelerometer waveforms falling within the designated heel strike window. Figure 1 provides a generalized description of the heel strike window. Note the heel strike window begins prior to the actual heel strike event as peak shank acceleration usually preceded heel strike. The algorithm calculated the peak head and shank accelerations, peak head and shank jerk and head and shank kinetic energy (see Appendix). Jerk, the time rate of change of acceleration, was calculated by taking the derivative of the head and shank acceleration traces (vertical and 3-D magnitude) over the heel strike window. Kinetic energy for the head and shank was modeled as proportional to mv^2, where subject mass m equaled subject weight divided by the acceleration of gravity and velocity v was calculated as the integral of the head and shank acceleration traces over the heel strike window (see Appendix for equations). Anthropometric data (Winter, 1990) was used to approximate head mass for HKE calculation.

Vertical Ground Reaction Force

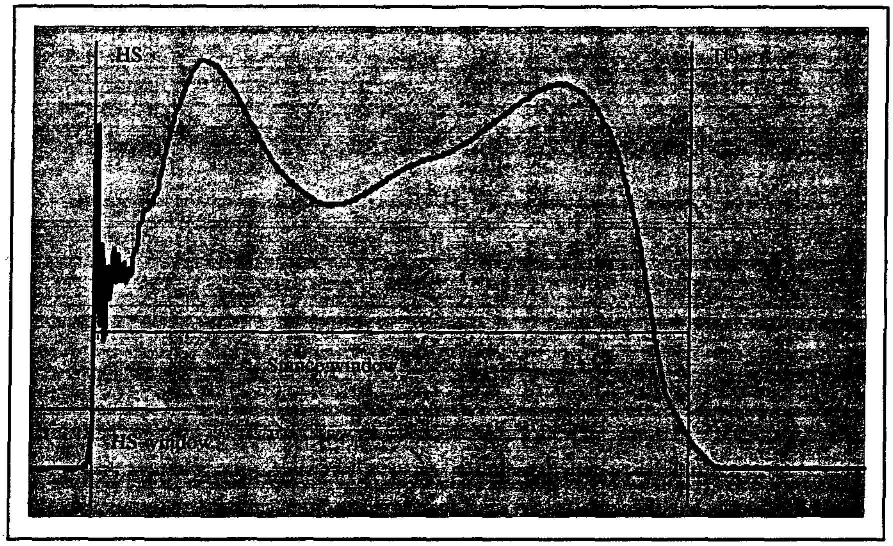

Figure 1. Typical vertical ground reaction force trace illustrated with key epochs in the gait cycle. Horizontal lines approximate the interval set for the heel strike analysis window. This window corresponded temporally to accelerometer traces. HS denotes the heel strike; TO denotes toe-off. The time interval between heel strike and toe-off defines the stance phase of gait.

The algorithm also calculated energy absorption values for acceleration, jerk, and kinetic energy. Absorption values were expressed as either ratios or percentages, modeling the proportion of heel strike shock that was "absorbed" by the body tissues prior to reaching the subject's head. Note the latency between peak shank and head vertical accelerations was calculated to accurately determine absorption values (Smeathers 1989). Peak absorption expressed the ratio of shank to head peak acceleration. Jerk absorption denoted the ratio of shank to head jerk, while RMS jerk ratio denoted the percentage of shank or heel strike jerk reaching the head. Kinetic energy absorption values expressed the percentage of heel strike kinetic energy manifested in head kinetic energy.

Generalized Gait Control Models

Analysis of shock energy variables over the heel strike window suggests the utilization of two generalized models for the control of head position during walking. The first of these control models is the head-centered strategy. Subjects most concerned with minimizing changes in head positioning during walking utilized this strategy. On the other hand, subjects most concerned with minimizing changes in energy transfer throughout the body during walking utilized the body-centered strategy.

Within each strategy, variables were further stratified based upon whether homeostatic or adaptive control was employed. Homeostatic control refers to resisting change in the value of the movement variables with changing environmental conditions. Adaptive control refers to alteration in the value of movement variables during environmental change.

RESULTS

Preliminary results suggest that two of the six astronauts employed a body-centered strategy based upon adaptive control. Figure 2 shows the peak absorption across test sessions (four trials per session) for the two astronaut subjects (9104 and 9015). Note the much higher absorption of heel strike shock upon return from spaceflight (session E) compared to pre- and postflight sessions. Moreover, these astronauts appeared to actively control the magnitude and variability (decrease the error) of shock absorption through the body during Earth-g locomotion.

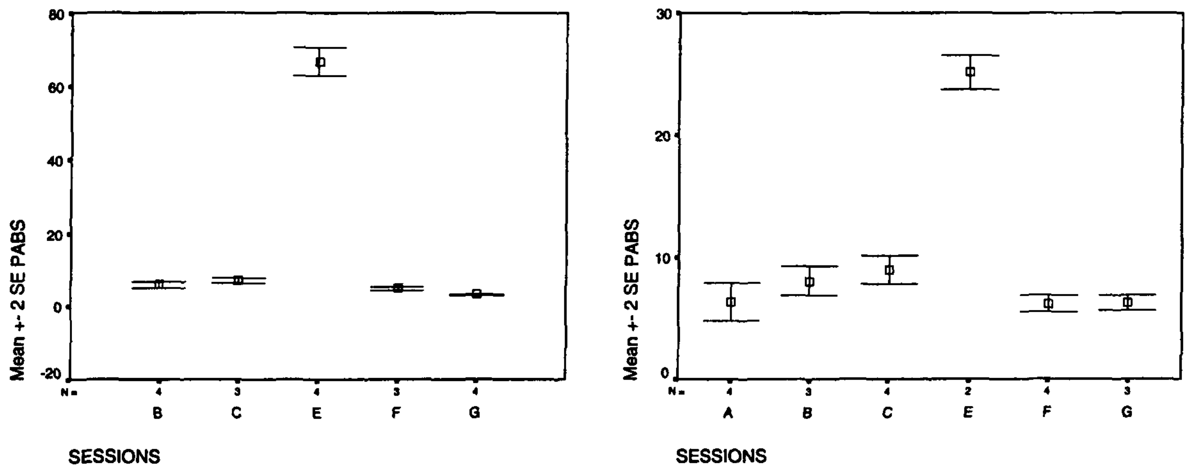

Figure 2. Plots of peak shock absorption across test sessions for two of the MIR astronauts (*l*-9014, *r*-9015). Values are *mean ± standard error (n=4).* Note the higher heel strike shock absorption at one day after return (session E, or R+1) as compared to preflight (A-C) and later postflight sessions F and G.

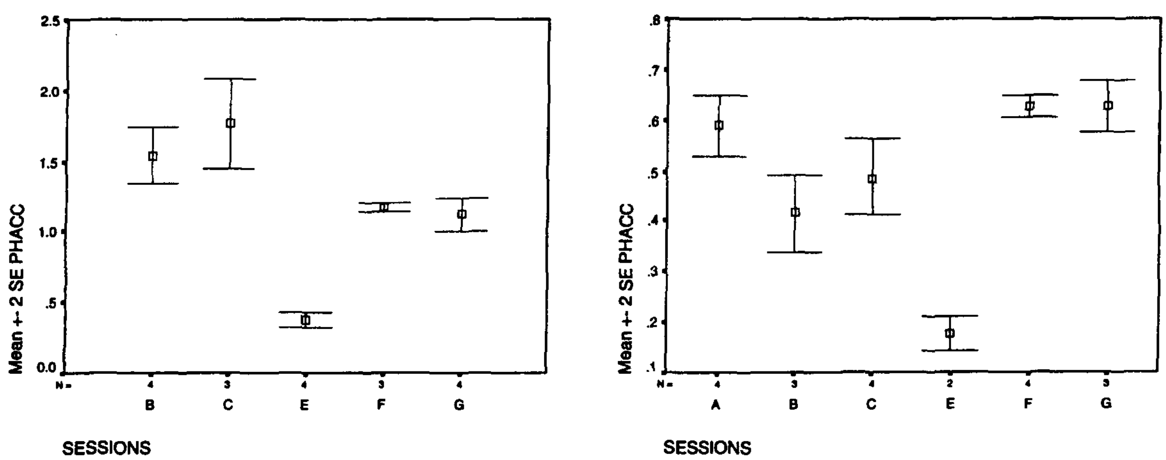

Figure 3. Peak head accelerations resulting from heel strike for astronauts 9014 (*left*) and 9015 (*right*). Note the much-reduced values recorded one day after return (session E). By session F, astronauts had re-adapted to preflight levels. Values are mean ± standard error (n=4).

The interplay between peak head and shank acceleration further illustrate head-centered adaptive control by astronauts 9014 and 9015 (Fig. 3). Note in Figure 3 how both subjects adapted to long duration spaceflight with vast reductions in head acceleration at heel strike (session E), returning to preflight levels upon re-adaptation. Shank acceleration data (not shown) suggests that these astronauts varied lower limb kinematics at heel strike to offset variability in head vertical accelerations; thus minimizing changes in absorption values.

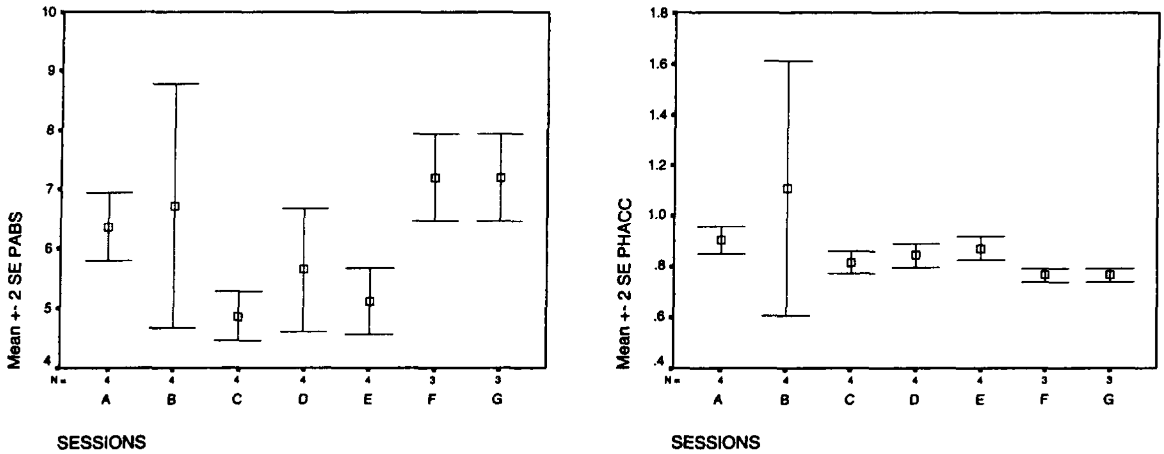

Figure 4. Interplay between shock absorption (left) and head acceleration (right) for NASA/MIR astronaut 1120. Values represent peaks over the heel strike time window (mean ± standard error, n=4).

The control strategy shown utilized by astronaut 1120 (Fig. 4) contrasted with that seen for the above astronauts. Note the absence of a distinct alteration in absorption upon return from spaceflight (sessions D/E vs. C and F. This astronaut appears to utilize a homeostatic head-centered strategy, sacrificing control of total body absorption to instead control peak head acceleration across test day (A-C, E-F) and against changes in environmental condition (pre- vs. post-flight). Data suggest that variations in peak absorption were related to alterations in peak shank acceleration (not shown).

DISCUSSION

One of the principal goals of the JSC Neuroscience Group is to design countermeasures to spaceflight induced gait instability. A series of studies developed to address that issue centers on the role of adaptability in reducing the effects of spaceflight on gait control. In this regard, researchers posit that the ability of a person to adapt to changing circumstances, as well as the form of that adaptation, defines how well that person will re-adapt to gravity environments after prolonged space flight. An example of this can be seen in the responses modern athletes make to variable stimuli. A good soccer player may utilize a simple control regime to standardize motions when performing a sport. Yet she also responds, or adapts, well to unexpected perturbations imposed on those desired movements either by other athletes or playing conditions. Similarly, astronauts must physically adapt to changing environmental conditions to adequately perform spaceflight missions.

Vertical and rotational head oscillations naturally occur during normal walking (Reschke at al. 1994c). Recent evidence shows the vestibular system to play an integral part in assuring gaze stabilization during such head movements (McDonald at al. 1997, Reschke at al. 1994b). Heel strike shock analysis suggests that one method utilized by astronauts to control head position during gait is regulation of shock transmission. Heel strike shock can be modeled a number of ways: using either dynamic (acceleration) or state (energy) functions. We chose to investigate head control regimes by analyzing the dynamic regulation of shock energy transfer by NASA/MIR long duration spaceflight astronauts.

Our analysis results led us to focus on absorption (translation and vibration) and head acceleration as variables most indicative of an astronaut's chosen method for controlling head movements after spaceflight induced gait instability. Lower leg or shank acceleration (and therefore jerk) was linked to either absorption or head acceleration control. Kinetic energy data was impressive in its consistency, but was likely an artifact to use of anthropometric approximations. Evidence that two astronauts showed striking re-adaptation to preflight levels of shock absorption illustrates well the body-centered approach to adaptive control. They varied head and/or vertical shank acceleration during heel strike to control/maintain shock transmission characteristics both preflight and postflight (after re-adaptation). These astronauts greatly increased shock absorption during the re-adaptation phase (sessions D and E or up to 3-4 days after return) to limit head movements that can lead to instability and space sickness symptoms.

Although preliminary results are promising, further analysis of long-duration space flight results is warranted to refine characterization of astronaut adaptive control strategies. A common control theme might emerge for the other four astronauts once rigorous analysis using the absorption variables is applied. Anecdotally, jerk analysis also shows potential as an adaptive gait control assessment tool as. Finally, a study of possible interactive relationships between some of the heel strike shock variables calculated here might prove beneficial.

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APPENDIX

Analysis variables calculated over the heel strike interval:

peak head acceleration (PHACC)
peak shank acceleration (PSACC)
head kinetic energy HKE
shank kinetic energy SKE
peak head jerk (PHJ)
peak shank jerk (PSJ)

Absorption variables calculated over the heel strike interval:

peak absorption: heel strike shock energy absorbed by the body (PABS)
kinetic energy absorption: heel strike kinetic energy absorbed by the body (KEABS)
jerk absorption: heel strike vibration energy absorbed by the body (JABS)
RMS jerk ratio: percentage of heel strike jerk reaching the head (JRAT)

Mathematical techniques for calculating variables:

Acceleration:	**a** , measured directly using a tri-axial (3-D) array of linear accelerometers
Jerk:	$\mathbf{j} = {}^{da}/_{dt}$, time rate of change of acceleration
Kinetic Energy:	proportional to mv^2, where velocity $\mathbf{v} = \int \mathbf{a} \cdot dt$ (over the heel strike interval)
PABS:	$\mathbf{a}_{shank}/\mathbf{a}_{head}$, ratio of peak shank to peak head heel strike acceleration
KEABS:	$(KE_{shank} - KE_{head})/KE_{shank}$, percentage of heel strike KE absorbed by the body
JABS:	$\mathbf{j}_{shank}/\mathbf{j}_{head}$, ratio of peak shank to peak head heel strike jerk
JRAT:	$(jRMS_{shank} - jRMS_{head})/jRMS_{shank}$, percentage of heel strike jerk (root mean square) reaching the head