

Using the Enhanced Daily Load Stimulus Model to Quantify the Mechanical Load and Bone Mineral Density Changes Experienced by Crew Members on the International Space Station

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Introduction

Despite the use of exercise countermeasures during long-duration space missions, bone mineral density (BMD) and predicted bone strength of astronauts continue to show decreases in the lower extremities and spine (1). This site-specific bone adaptation is most likely caused by the effects of microgravity on the mechanical loading environment of the crew member (2). There is, therefore, a need to quantify the mechanical loading experienced on Earth and on-orbit to define the effect of a given "dose" of loading on bone homeostasis.

Carter et al. (3) proposed that a routine of daily mechanical loading could be modeled with an empirical relationship called the daily load stimulus (DLS) (Eq. 1), which is a scalar value resulting from multiple individual loading events of various magnitudes and is expressed as follows:

$$DLS = \left[\sum_{j=1}^k n_j (Gz_j)^m \right]^{1/2m} \quad (\text{Eq. 1})$$

Where Gz = peak magnitude of the vertical component of the ground reaction force (GRF), j = number of loading conditions, n = number of loads in each loading condition, k = number of different loading conditions and m = weighing factor (typically 4) that still requires validation in human subjects. Genc et al. (4) recently proposed an enhanced DLS (EDLS) model that, when used with entire days of in-shoe forces, takes into account recently developed theories on the importance of factors such as saturation, recovery, and standing and their effects on the osteogenic response of bone to daily physical activity. This algorithm can also quantify the timing and type of activity (sit/unload, stand, walk, run or other loaded activity) performed throughout the day.

The purpose of the current study was to use in-shoe force measurements from entire typical work days on Earth and on-orbit in order to quantify the type and amount of loading experienced by crew members. The specific aim was to use these measurements as inputs into the EDLS model to determine activity timing/type and the mechanical "dose" imparted on the musculoskeletal system of crew members and relate this dose to changes in bone homeostasis.

Methods

Four male astronauts (age: 49.5 ± 4.7 years) who flew on long-duration missions aboard the International Space Station (ISS) (mean mission duration: 181 ± 15 days) provided written informed consent before participating in this study. The study protocol was approved by the Committee for the Protection of Human Subjects at NASA's Johnson Space Center, Houston, TX, and by local investigator IRBs.

Capacitance-based insoles (Novel GmbH, Munich, Germany) placed inside the shoes of the crew member were used to measure the in-shoe foot forces. These insoles were part of the equipment for the E318/Foot experiment which is described in greater detail by Cavanagh et al. (5).

After calibration at the start of their work day, the crew members resumed their normal daily activities while data were continuously recorded on a wearable computer at 128 Hz for an average of 8.04 ± 0.63 hours on Earth and 8.74 ± 1.30 hours on-orbit.

Pre- and post flight BMD measurements of the hips, lumbar spine, and total body were obtained from the crew members using DXA scans (QDR 4500, Hologic, Waltham, MA, USA).

Using a method based on that described by Whalen et al. (6), r_1 , the relative ratio of the mean EDLS before and during space flight was compared to r_2 , the relative BMD before and after space flight (Eq. 2).

$$r_1 = \frac{\text{Mean Flight EDLS}}{\text{Mean Pre-Flight EDLS}} \quad r_2 = \frac{\text{Mean BMD Post-Flight}}{\text{Mean BMD Pre-Flight}} \quad (\text{Eq. 2})$$

Results

Mean percentages of activity type performed during typical days are presented in Figure 1A and Table 1. The mean EDLS ratio (r_1) for crew members was 0.74 ± 0.062 , and the mean BMD ratios (r_2) for the femoral neck, trochanter and total hip were 0.95 ± 0.014 , 0.96 ± 0.02 and 0.96 ± 0.031 respectively (Figure 1B). BMD losses in the left femoral neck, trochanter and total hip were $-0.71 \pm 0.34\%$, $-0.71 \pm 0.53\%$ and $-0.81 \pm 0.21\%$ respectively per month. The mean post-

flight change in Z-scores of the femoral neck, trochanter and total hip were -0.25 ± 0.13 , -0.25 ± 0.17 and -0.35 ± 0.06 respectively.

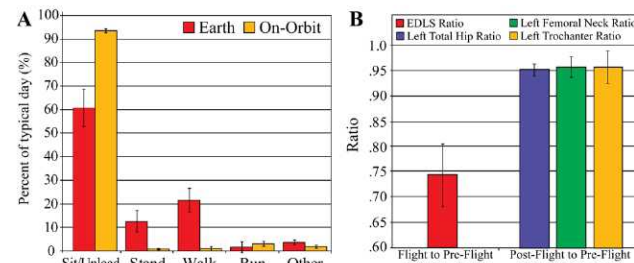


Figure 1: (A) Mean percentage of activity type performed by crew members during typical days. (B) EDLS ratio r_1 and BMD ratios r_2 for ISS crew members.

Table 1: Mean percentage (SD) of activity type performed by crew members during typical days on Earth and on-orbit.

	Sit/Unload (%)	Stand (%)	Walk (%)	Run (%)	Other (%)
Earth	60.7 (8.0)	12.0 (4.7)	21.5 (5.0)	1.61 (2.3)	3.60 (1.2)
On-orbit	93.5 (1.1)	0.79 (0.2)	0.96 (1.0)	2.94 (1.2)	1.83 (0.73)

Discussion

In microgravity, crew members experienced a decrease in both the amount of time spent loaded and the magnitude of the loading dose achieved (Figure 1). Over 93% of a typical crew member's day was spent completely unloaded when on-orbit, versus 60.7% on Earth. The magnitude of the loading dose also decreased by about 26%. Preliminary data from an ongoing bedrest study (7) has shown that, on average, maintaining an r_1 of 1.0 when prescribing doses of treadmill exercise countermeasures can prevent total hip region bone loss during prolonged periods of bedrest (84 days). However, in the current study crew members only achieved an r_1 of .74 while the value for r_2 was .95.

Little is known about the timing of BMD loss and its steady state with prolonged exposure to microgravity, but we assume that bone loss was still occurring at 6 months and that r_2 may have been tending towards r_1 . Comparisons with data from immobilized spinal cord injury (SCI) subjects may provide some insight. Eser et al. (8) predict that it would take 1.34 years to reach 74% of original BMD in the proximal femur using exponentially fitted equations of cross-sectional data from SCI subjects. Zehnder et al. (9) predict a Z-score of -0.378 in the femoral neck after 6 mo of immobility in SCI subjects, which is more loss than observed in the current experiment (-0.25), possibly indicating a positive effect from the countermeasures used.

The loading magnitude and duration during typical days on ISS compared to Earth appears to be insufficient to provide the loading stimulus needed to completely prevent bone loss. We recommend that future generations of exercise equipment for the ISS be designed to provide higher loads of longer duration and that exercise doses be prescribed in a manner so as to obtain r_1 closer to a value of 1.0.

References

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