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Techniques for Determination of Impact Forces During Walking and Running in a Zero-G Environment

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Techniques for Determination of Impact Forces During Walking and Running in a Zero-G Environment

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ABSTRACT

One of the deleterious adaptations to microgravity of space flight is the loss of bone mineral content. This loss appears to be at least partially attributable to the minimal skeletal axial loading concomitant with microgravity (3,5,7). The purpose of this study was to develop and fabricate the instruments and hardware necessary to quantify the vertical impact forces (Fz) imparted to users of the space shuttle passive treadmill during human locomotion in a three-dimensional zero-G environment. The shuttle treadmill was instrumented using a Kistler forceplate to measure Fz. To verify that the instruments and hardware were functional, they were tested both in the one-G environment and aboard the KC-135 reduced gravity aircraft. The magnitude of the impact loads generated in one-G on the shuttle treadmill for walking at 0. m/sec, and running at 1.6 and 2.2 m/sec were 1.1, 1.7, and 1.7 G, respectively, compared with loads of 0.95, 1.2, and 1.5 G in the zero-G environment.

INTRODUCTION

Long duration space flight has been shown to have a deleterious effect on the human musculoskeletal system (3,5,7). These effects include muscular atrophy and bone demineralization (calcium loss). Bone demineralization occurs shortly after entry into weightlessness. Because it is the metabolically more active trabecular bone that is probably depleted, such loss rates can only be sustained for several months before irreversible damage to bone formation occurs (6). Currently, the detrimental influence of microgravity is being studied in hopes of finding a way to decrease or eliminate its effect on human performance and health in space and upon return to Earth.

Exercise countermeasures (e.g., bike ergometer, treadmill, resistive devices) have been used in reducing some of the deleterious effects of weightlessness (4). Some exercise devices which load the muscles of locomotion have been used in manned space flight. These devices include the space shuttle passive treadmill which has been hypothesized to elicit the greatest Fz when compared to the other modalities (e.g., bicycle ergometer) (1). Based on cross-sectional investigations indicating that periods of impact will modify skeletal size and development, Fz are thought to be an important factor in stimulating bone growth and preventing the bone mineral loss associated with space flight (2, 4). In this study, the zero-G peak Fz were compared with the peak forces obtained in the one-G environment.

Currently, the space shuttle passive treadmill employs a harness/bungee system to restrain the astronaut and apply vertical forces. The harness is worn over the shoulders and has fore and aft waist buckle attachment points for the four bungees (fig. 2). The astronaut can tighten or loosen these buckles to vary the load during locomotion. It is not known what load the current harness/bungee system provides or the load necessary to elicit a one-G vertical impact response in the zero-G environment. The quantification of Fz has not previously been measured in the current in-flight passive treadmill system. Because it is believed that impact is a critical factor in maintaining bone mineral integrity (2,4), it is important to quantify the impact loads generated by locomotion on the space shuttle passive treadmill so that more adequate countermeasures can be developed to possibly reduce the deleterious effect of bone demineralization associated with space flight. The purpose of this study was to develop and test the instruments and hardware necessary to quantify the Fz imparted to the space shuttle passive treadmill during human locomotion in a three-dimensional zero-G environment.

METHODS

Instrumentation. To successfully quantify the Fz on the shuttle treadmill in a zero-G environment, it was necessary to design a number of hardware items and combine them with several off-the-shelf components. The principal components included:

- a mounting system for securing the force plate
- the forceplate
- a new system for the bungee attachments
- a means for securing the treadmill to the forceplate
- a system for measuring the harness/ bungee forces.

All components had to meet the requirements for zero-G flight on the KC-135 Reduced Gravity Aircraft (JSC-22803 manual). Thus, the components were designed and chosen for flight integrity as well as functionality. The following paragraphs briefly describe the key parts of the apparatus.

A commercially available forceplate (Kistler Instrument Corporation, Amherst, NY) was bolted to the floor via a custom designed interface plate. The three components Fx, Fy, and Fz of the resulting force F, the coordinates ax and ay of the point of force application, and the z-component of the free moment vector M' were determined with an electronics package (Kistler) (fig. 1). The force across the treadmill is defined as Fx, Fy is the force along the treadmill, and Fz represents the perpendicular (vertical) force to the treadmill surface. The electronic unit contained eight charge amplifiers for converting the electrical charges yielded by the piezoelectric force transducers into proportional voltages and two summing and one dividing amplifier which constituted a small analog computer and calculated the required six output variables from the eight output voltages of the charge amplifiers. The forceplate measured the impact load forces and was mounted between the bolted floor interface plate and the shuttle treadmill interface plate.

One consideration in the selection of the forceplate was the response of the plate to dynamic loading. The mass of the treadmill and interface plate were included in the chosen configuration so it was necessary to examine both the peak force requirements and the frequency response. The unloaded natural frequency of the system was found to be basically flat up to 30Hz, and up to 60 Hz when loaded with an 84 Kg subject (R. Smith, personal communication). Since the frequency of a barefoot runner would be only about 40Hz, the loaded natural frequency response of approximately 65Hz was more than adequate to accommodate the measurements of this study.

It was necessary to relocate the pulleys which attach the harness/bungees to the treadmill and attach them to side pulley plates so that a closed-loop system could be maintained. This arrangement allowed the forceplate to measure the net vertical impact loads produced by an astronaut in the harness/bungee system. The exact shuttle treadmill spacing dimensions were preserved. The side pulley plates were mounted on top of the floor interface plate and the bungee cord clasps were hooked to the plates by small bracket attachments. When in use, the four bungees were threaded through the pulleys and attached to the astronaut to comprise the restraint system. A second interface plate was designed to attach the treadmill to the forceplate. Detailed descriptions and figures of the key hardware items fabricated for this study are in Appendix A.

The space shuttle treadmill was a passive (i.e. non-motorized) system with a 2.5m by 30cm roller track. The overall dimensions of the treadmill were 109 x 48 x 52 cm (with handle folded down) with a 30 x 71 cm available tread area. The treadmill weighed 32 Kg. Using the designed treadmill mounts and interface plate, the shuttle treadmill was mounted to the forceplate. In all cases where bolts were used as fasteners, it was critical that the bolts were tightened so that there was no slippage to possibly give false impact data. To prevent this, the bolts were checked for tightness before each test was conducted.

The experimental protocol employed the current in-flight harness/bungee system developed in 1973 by Gause and Spier (9). To determine the load that the bungees imposed on an astronaut, four forcelinks (Kistler) were placed in series with each of the four bungee cords at the harness connection. This was accomplished by attaching custom clasp-bolt connections on either end of the forcelinks. Determination of the bungee forces was necessary to interpret the forceplate information.

As a part of the system, it was necessary to incorporate a data collection instrument. A biomechanics analysis system (Ariel Performance Analysis System, Ariel Corporation, 6 Alicante, Trabuco Canyon, CA 92679) served as the data collection device. Using this system, data was acquired from all data input channels at a rate of 250Hz/channel. The biomechanics analysis system was also used to analyze and graph the results by its ability to display the impact and forcelink data analog waveforms.

The instrumentation and hardware designed and fabricated for this study were tested as a system to ascertain that the system worked as a whole, and verified that impact forces were measurable in both one-G and zero-G environments using this apparatus. The Anthropometry and Biomechanics Lab at the Johnson Space Center served as the one-G laboratory environment.

The zero-G environment was obtained with a specially modified KC-135 turbo jet transport which flies parabolic arcs to produce short periods of zero-G. This parabolic maneuver is initiated and terminated with a pull-up and pull-out of 1.8 - 2.0 Gs. The length of the zero-G period is typically 23-25 seconds; the 1.8-2.0G duration is approximately 50 seconds. The fact that the KC-135 work space is fully padded may have had a slight effect on the measurement of the Fz.

Test Procedure. To evaluate the design and verify that the equipment was operational, a series of one-G and zero-G studies were conducted. Astronaut volunteers walked and ran on the shuttle treadmill apparatus in one G and zero G. The one-G environment data was acquired before the KC–135 flights.

Five people were needed to conduct the experiment: a front and back spotter, data collector, timer, and subject. The astronaut subject and forcelink cables were monitored by the front and back spotters while the data collector operated the biomechanical analysis system for acquisition of the forceplate and forcelink data. The timer marked when the data was to be taken during the test.

In the one-G laboratory environment, the in-flight timing schedule was followed with a simulated "zero-G parabola" of 25 seconds and the "two-G pull-out" of 50 seconds. The subject walked or ran on the treadmill for the 25-second period and rested during the 50-second period, just as the subject did in the KC-135.

One-G training bungees (bungees with a low pulling force) were used:

- so that the subject would have to execute the one-G locomotion within the same bungee-restrictive dimensions that would be encountered in zero-G,

- so that imposed bungee forces were minimal and the subject could comfortably and safely execute the one-G locomotion wearing the full harness/bungee system. (This would not be possible if the subject used the zero-G flight bungees as described below.)

The bungees used in zero G were flight hardware bungees (bungees with a high pulling force) identical to the bungees used on the shuttle. To establish the correct flight harness/bungee placement, the bungees were adjusted preflight (one-G) in the following manner.

(1) The subject donned the harness and stood on the treadmill with the training bungees unattached to the subject. The forceplate value (lbs) was used as the subject's one-G weight (BW).

(2) The harnessed subject stood on the treadmill with the training bungees and forcelinks attached to the subject. The forceplate value (lbs) was used as the subject's attached weight (AW). The forcelink values (lbs) were obtained and summed to give a total forcelink pull value (PV).

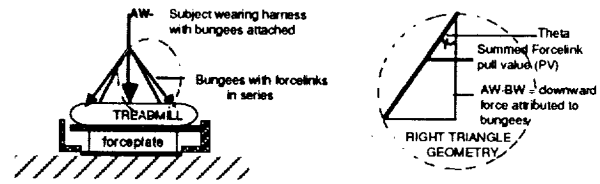

Figure 1. Force diagram for calculating bungee pull forces

(3) Using a simple geometric relation {(AW-BW) = PV cos (theta)}, the angle theta was determined (see fig. 1). Theta represents the average angle between the bungees and the vertical direction. The assumptions were made that the subject stood perfectly in the center of all four bungees, and each bungee pulled with an equal amount of force relative to the other cords. With theta known, the values the forcelinks should yield to produce a one-G pull on the subject was calculated. This information was used to approximate bungee placement for the flight bungees.

(4) The subject then changed to the flight harness/bungee system and stood on the treadmill. The bungees were adjusted so that the proper summed forcelink value for a one-G pull-down was obtained. The forceplate was used to verify that the final bungee adjustment yielded a load equivalent to body weight (fig. 2).

The same measurement protocol was observed for simulated parabolas (one G) and flight parabolas (zero G). Before the test, the subject donned either the training harness/bungee system (one G) or the flight harness/bungee system (zero G). On the first two parabolas, instruments were checked; on the next three, static data was taken and the bungee forces set. On the next four parabolas, forceplate and forcelink data were collected for 10 sec, 10 sec after the onset of weightlessness for the subject walking at 0.9 m/sec (2 mph). The next four parabolas, force measurements were made for 10 sec while the subject jogged at 1.6 m/sec (3.5 mph) and at 2.2 m/sec (5 mph), 10 sec after the onset of zero G .

The data collector used a remote control device to initialize both the forcelinks and the forceplate. The forcelinks were initialized during the 50-second period by having the two spotters hold the bungee cords so that there were no forces acting on the forcelinks. Initialization of the forceplate occurred at the beginning of the 25-second period by having the subject straddle the treadmill.

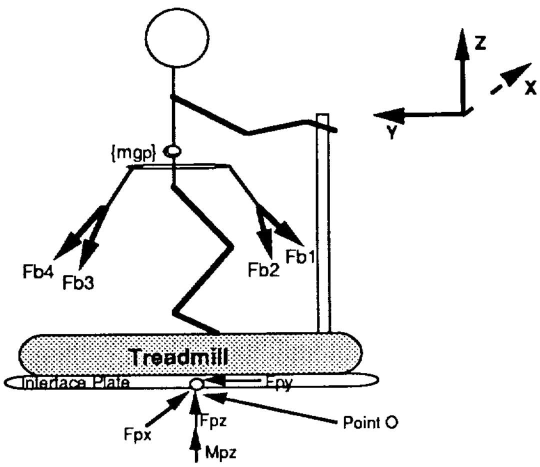

Figure 2. Free Body Diagram with Subject

DISCUSSION

The purpose of this study was to develop and fabricate the instruments and hardware necessary to quantify the Fz imparted to the space shuttle passive treadmill during human locomotion in a three-dimensional zero-G environment. This was accomplished using the treadmill apparatus and the biomechanics analysis system described. The results from this study on a single subject showed that impact loads can be successfully measured in a zero-G environment.

One of the principal determinants of the vertical forces resulting from ambulation in zero G is the pull force of the bungees. If the pull force is increased, the vertical force should increase. In the present study we attempted to establish bungee pull such that we were replicating the one-G environment. We were not able to exactly accomplish this because of the limitations inherent in our one-G simulation. In zero G, subjects must supply a YForce (see fig. 2) to propel the tread of the passive treadmill. This was accomplished by orienting the long axis of the body at an angle to the tread such that the rear bungees are lengthened and the front bungees shortened. In the future we hope that video-analysis of astronauts using the treadmill in flight will permit accurate simulation of this posture. Additional questions which should be answered are:

1) How much impact load is needed to sustain bone integrity?

2) How does locomotion change with experience at zero G?

3) What bungee pull forces are astronauts willing to use in space?

4) Can bungees be successfully replaced with lower body negative pressure?

5) Can other exercise modes be used to obtain significant impact loads?

It is hoped that the techniques developed in this study will be useful in answering these and other questions.

RESULTS

The instrumentation and hardware designed and fabricated for this study were tested as a system to ascertain that the system worked as a whole, and verified that impact forces were measurable in both one-G and zero-G environments using this apparatus. The collection of one-G data in the Anthropometry and Biomechanics Laboratory at the Johnson Space Center took place before zero-G data collection in the KC-135 aircraft. A single astronaut performed the test protocol.

The forceplate graph (Graph 1) shows walking velocity of 0.9 m/sec. The average peak value for the one-G walk was 964 N (217 lbs). The zero-G average peak value for walking was 768 N (173 lbs). It is obvious that approximate one-G loading is possible in zero-G. The subject's one-G weight (BW) without the training bungees was 807 N (181.5 lbs). The zero-G standing baseline for the subject with the flight bungees was 811 N (182.5 lbs). The lateral Fx forces and the fore-aft Fy forces were close to zero in both environments as expected.

The peak values obtained from these graphs were entered into a computer statistical analysis package according to velocity and environment (i.e., all footfall range values of zero-G walking were entered in one column, all footfall range values of one-G walking were entered in a different column, etc.). To account for the additional one-G training bungee pull, the following approach was taken.

The subject's weight was obtained in one-G (via the forceplate) with and without the training bungees. If the weight (z forceplate value) without the training bungees (BW) is subtracted from the weight (z forceplate value) with the training bungees (AW), a cumulative bungee pull value is obtained for the z direction (BPz): AW - BW = BPz. This value (BPz) was assumed to remain relatively constant as the subject executed one-G locomotion. If this value is subtracted from all footfall values obtained in the one-G environment, the one-G baseline returns to the subject's body weight value (versus the subject's attached weight value). This allowed a comparison to be made between the subject's zero-G locomotion and one-G locomotion.

Using the mean values, average differences between one-G and zero-G Fz impact data were calculated for walking, jogging and running. The one-G mean impact force was used as the control.

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APPENDIX A

Equipment Specifications

The following paragraphs and figures describe the entire apparatus beginning with the floor-to-forceplate interface and ending with the subject on the treadmill.

The first interface plate (fig. 3) was designed to bolt to the floor of the KC-135 aircraft with four 3/8" 20 bolts. The 3/8" 16 threaded holes centered on 15.75" by 9.45" were for securing the force platform to the interface plate.

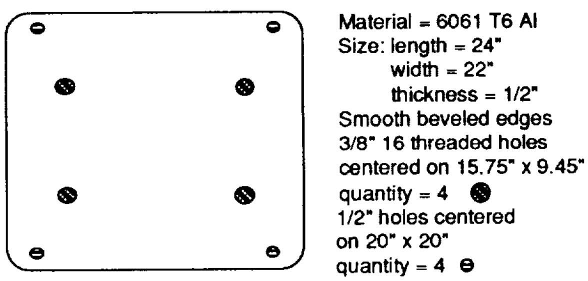


Figure 3: Interface Plate Dimensions-Floor to Forceplate

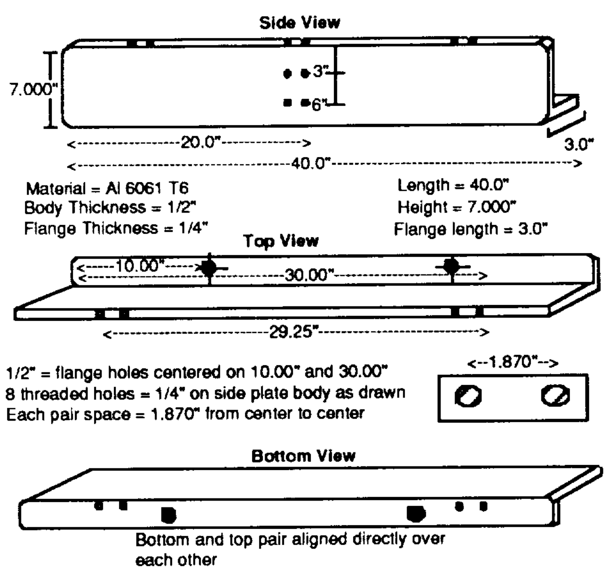


Figure 4: Side Pulley Plate Dimensions

A second interface plate (Figure 5) was designed to attach the treadmill to the forceplate. Four metric 8.8 B bolts were used to secure the interface plate to the force platform (Figure 5).

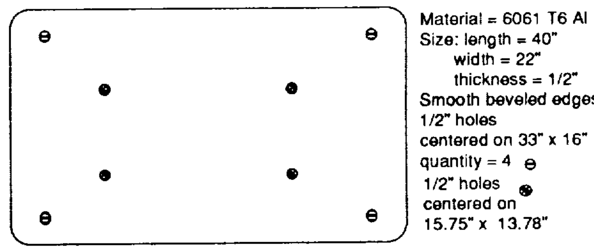


Figure 5: Interface plate Dimensions-Forceplate to Shuttle Treadmill

Treadmill mounts (Figure 6) were designed which could be bolted to the interface plate with 3/8" 16 bolts and used to fasten the space shuttle passive treadmill to the interface plate. These mounts replaced the current Brownline fittings which are used to mount the shuttle treadmill to the orbiter floor in flight.

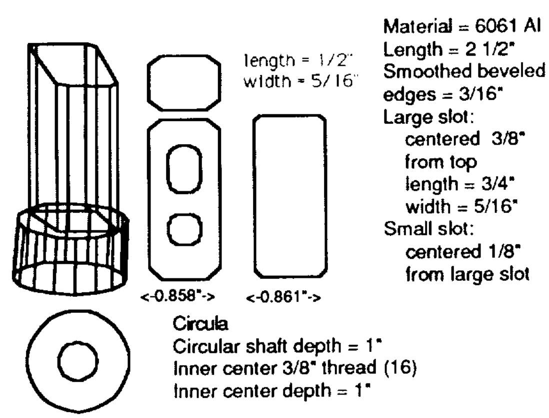


Figure 6: Shuttle Treadmill Mount Dimensions

The space shuttle treadmill is a passive (self-propelled versus motor-driven) system with an 8' by 1' roller track. Using the designed treadmill mounts and interface plate, the shuttle treadmill was mounted to the forceplate.

The experimental protocol employed the current in-flight harness/bungee system developed in 1973. To determine the load that the bungees imposed on an astronaut, four forcelinks (Kistler) were placed in series with each of the four bungee cords at the harness connection. This was accomplished by designing clasp-bolt connections on either end of the forcelinks (Figure 7). Determination of the bungee forces allowed better interpretation of the forceplate information.

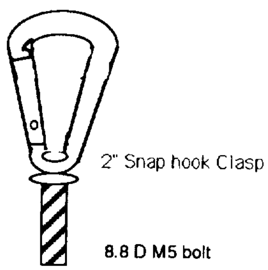


Figure 7: Clasp-Bolt Connection

The forcelinks use a single axis piezoelectric force transducer. The charge signal of the forcelink is transformed into an output voltage directly proportional to the applied force through the use of a charge amplifier. The entire apparatus including the astronaut subject is shown in fig. 2.

As a part of the system, it was necessary to incorporate a data collection instrument. A biomechanics analysis system (Ariel Performance Analysis System, Ariel Corporation, 6 Alicante, Trabuco Canyon, CA 92679) served as the data collection device. Using this system, data was acquired from all data input channels at a rate of 250 samples/channel/second. A ruggedized hardware cabinet had to be obtained to encase this system and the other associated electronics equipment before they could fly on the KC-135 aircraft. A KC-135 floor-to-cabinet interface plate, a backplate, and cabinet insertion plates had to be designed and created for mounting the equipment inside the hardware cabinet. The cabinet backplate and the hardware insertion plate are shown in Figure 8.

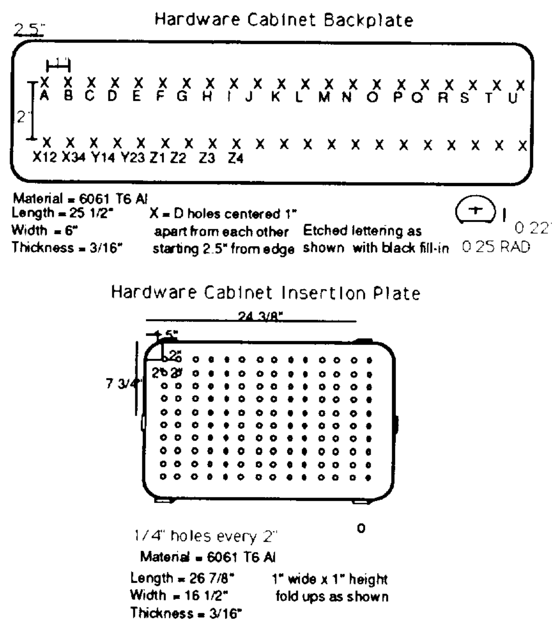


Figure 8: Hardware Cabinet Plate Designs

Securing straps with sewn endplates and aircraft cam devices were fabricated for tying down hardware items in the cabinet. The biomechanics analysis system was also used to analyze and graph the results through its ability to display the impact and forcelink data analog waveforms.

The only difference in the one-G laboratory set-up was that the forceplate was bolted to the floor of the lab with four 3/8" 16 bolts rather than the floor of the KC-135 aircraft.

The entire KC-135 floor has rows and columns of 20" by 20" holes to secure equipment. Except for the locking bolt holes in the floor and a few small windows, the KC-135 is completely padded with a wrestling mat material. This may have a slight effect on the measurement of the Fz, but this was not studied in this project. Stress and hazard analyses were required for the system for flight on the KC-135.

APPENDIX B

Another approach to comparing the dynamic effects of the zero-G and one-G vertical (Fz) forces is to use a quasi-static analysis. The bungee cord forces were obtained by taking the average force value over the given "parabolas." The previously discussed average footfall method was used for the forceplate values. The orientation angles in the z direction were approximated from known anchor positions and photographic records. In the one-G environment, the Fz force analysis for walking, jogging, and running is as follows:

Fz =i = 14(Fbi)z + Fpz - {mg}

Fbi = Fbi (- cos(theta1z)k)

Walk (2.0 mph):Fz = -18.5 + 217.0 - 181.5

Fz = 17.0 lbs

Jog (3.5 mph)Fz = -6.3 + 330.3 - 181.5

Fz = 142.5 lbs

Run (5.0 mph)Fz = -7.2 + 333.7 - 181.5

Fz = 145 lbs

In the zero-G environment, the Fz force analysis for walking, jogging, and running is as follows:

Fz =i = 14(Fbi)z + Fpz - {mg}

Fbi = Fbi (- cos(theta1z)k)

Walk (2.0 mph):Fz = - 107.8 + 172.9

Fz = 65.1 lbs

Jog (3.5 mph)Fz = - 110.7 + 214.0

Fz = 103.3 lbs

Run (5.0 mph)Fz = - 112.2 + 268.0

Fz = 155.8 lbs

The above values correspond to the force residuals and represent the amount by which the force sums differ from zero (i.e., exactly satisfy static equilibrium). If the same percent difference formula is used to calculate the percent differences between the one-G and zero-G environments as was used for the z-forces, the following values are obtained for the difference in z-force residuals:

Walking Percent Difference: 282.9%

Jogging Percent Difference: 27.5%

Running Percent Difference: 7.4%

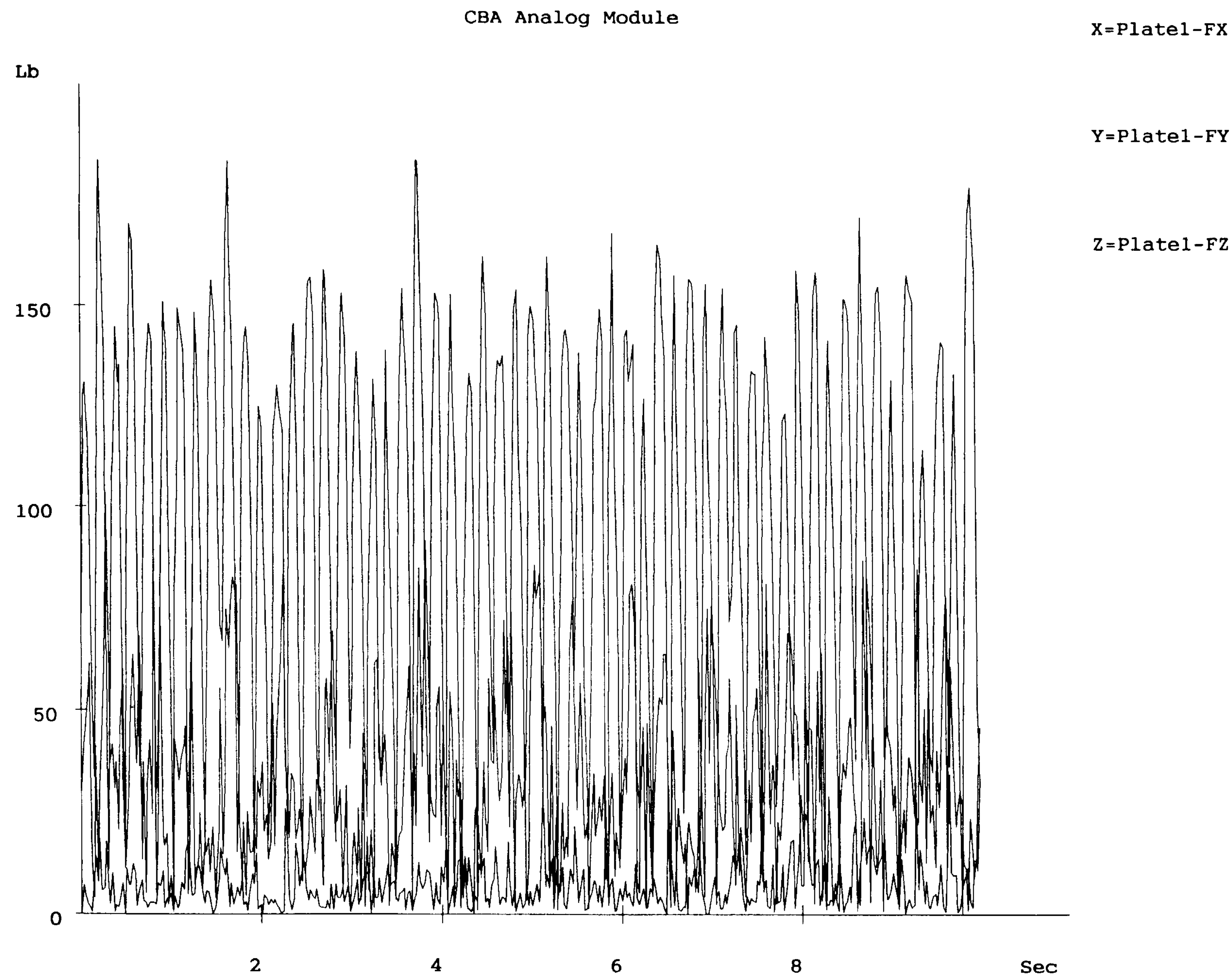
The KC-135 zero-G flight demonstrated that a one-G load can be imposed utilizing the current harness/bungee system. The subject's body weight was replicated through bungee instrumentation and then verified via forceplate feedback. A +1.0 lb difference was obtained in the zero-G versus one-G data which represents less than a 1% difference for the two environments.

The flight on the KC-135 clearly demonstrated that impact loads can be successfully measured in a zero-G environment using the designed treadmill apparatus; however, the percent differences for the dynamic situation of locomotion was considerably higher than the static case.

When the one-G walking data was compared to the zero-G walking data, it was found that the average difference between peak z-forces was 11.8% and was between calculated z-force residuals 282.9%. The assumptions made in the peak force analysis include a constant BPz value and error in averaging all footfalls for a given velocity in the zero-G environment. The zero-G environment errors will be discussed in subsequent paragraphs. The residual force analysis assumptions include the same error in averaging all footfalls for a given velocity in the zero-G environment, as well as additional error in geometrical estimates and averaging the bungee cord values. If these errors were eliminated, the force residuals would represent only inertial effects.

The quasi-static force residual analysis for this study has the potential for greater error due to geometrical estimations. If the errors can be dealt with, it may offer a more realistic scenario in representing Fz and their dynamic differences in a one-G versus zero-G environment. One of the biggest assumptions made was that the attachment points for the bungees remained at a relatively constant z value. This in fact is not true, especially in the zero-G environment. To use the current shuttle passive treadmill, the astronaut must exert a force on the treadmill handle or adjust the bungees to permit a significant rearward force to move the treadmill belt. In either case, the astronaut must adjust his posture by leaning over, thereby forcing the rear bungees to exert a greater force. The line of action for the imposed bungee load is now changed. At present, bungee forces in space flight must be set according to the exerciser's perception. Currently, there is no method for quantifying bungee load.

The average z-force difference for the jogging velocity was 30.8%. The jogging percent difference in z-force residual was 27.5%. For the running velocity, the percent differences were 14.3% and 7.4% for the average peak analysis and residual force analysis, respectively. Once again, the quasi-static method of analysis may be more telling than the average peak analysis. The fact that the two methods are closer in value at higher velocities may indicate a posture change for higher velocities or may possibly be attributable to the internal workings of the treadmill itself. The same error of assumptions that applied for the walking velocity applies for the jogging and running velocities as well.


CBA Analog Module
X=Plate1-FX
Y=Plate1-FY
Z=Plate1-FZ
Lb
150
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2
4
6
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GRAPH 1

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13. ABSTRACT *(Maximum 200 words)*
One of the deleterious adaptations to microgravity of space flight is the loss of bone mineral content. This loss appears to be at least partially attributable to the minimal skeletal axial loading concomitant with microgravity. The purpose of this study was to develop and fabricate the instruments and hardware necessary to quantify the vertical impact forces (Fz) imparted to users of the space shuttle passive treadmill during human locomotion in a three-dimensional zero-gravity environment. The shuttle treadmill was instrumented using a Kistler forceplate to measure vertical impact forces. To verify that the instruments and hardware were functional, they were tested both in the one-G environment and aboard the KC-135 reduced gravity aircraft. The magnitude of the impact loads generated in one-G on the shuttle treadmill for walking at 0. m/sec and running at 1.6 and 2.2 m/sec were 1.1, 1.7, and 1.7 G, respectively, compared with loads of 0.95, 1.2, and 1.5 G in the zero-G environment.

14. SUBJECT TERMS
minimal skeletal axial loading, vertical impact forces, three-dimensional zero-G environment, bone mineral loss

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