Overview: Human Research Program Exercise Countermeasures Project

Presented by:
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Joern Rittweger visit to GRC, October 27, 2011

Overview

- Exercise Countermeasures Project Key Activities Summary at GRC
- Enhanced Zero-gravity Locomotion Simulator
- NSBRI-funded studies in GRC Exercise Countermeasures Project
- Harness Station Development Test Objective (SDTO)
- Advanced Exercise Concepts

Exercise Countermeasures Project

Project Objective

Develop and provide exercise countermeasure prescriptions and systems for space exploration that are effective, optimized, validated and meet medical, vehicle, and habitat requirements.

Project Goals

Develop prescriptions for exercise countermeasures that efficiently reduce the negative effects of zero and partial gravity and meet the medical needs of astronauts.

Establish the requirements for exercise equipment that will provide the prescribed exercise countermeasures within the constraints imposed by the space exploration vehicle and the astronauts' habitat on the Moon or Mars.

GRC Exercise Countermeasures Project

- Flight Harness Station Development Test Objective (SDTO) – Center for Space Medicine (CSM) harness flight development / TVIS harness on-orbit comfort evaluation
- Advanced Exercise Concepts - Identify, design, build prototypes, and evaluate Exploration exercise device concepts for Exploration. Delivered cycle ergometer that met requirements for the Space Exploration Vehicle (SEV) for 3 yearly evaluations at Desert RATS, ExL.
- Ground Based Research and Sustaining Engineering for investigations performed on the enhanced Zero-g Locomotion Simulator (eZLS) and standalone Zero-g Locomotion Simulator (sZLS) at the University of Texas Medical Branch (UTMB) – lunar-g and martian-g capable
- National Space Biomedical Research Institute (NSBRI) Research – Musculoskeletal Alterations
  - "*Monitoring Bone Health by Daily Load Stimulus Measurement During Lunar Missions*" University of Washington, PI, Cavanagh
  - "*Foot Reaction Forces During Simulated Treadmill and Advanced Concept Exercise Countermeasures*" – effect of interface compliance on ground reaction force – status complete

Harness SDTO

Lunar Electric Rover Ergometer

Enhanced Zero-g Locomotion Simulator

Standalone Zero-g Locomotion Simulator

Zero-gravity Locomotion Simulators and the Exercise Countermeasures Laboratory

Lab Manager: Kelly M. Gilkey, GRC

Project Manager: Gail P. Perusek, GRC

Collaborators: Christopher M. Sheehan (Zin), John K. DeWitt (JSC), Carlos M. Grodsinsky (Zin), Peter R. Cavanagh (U. of Washington), Brian L. Davis (Austen BioInnovation Institute, Akron, Ohio)

Suspension Approaches to Zero-G Simulation

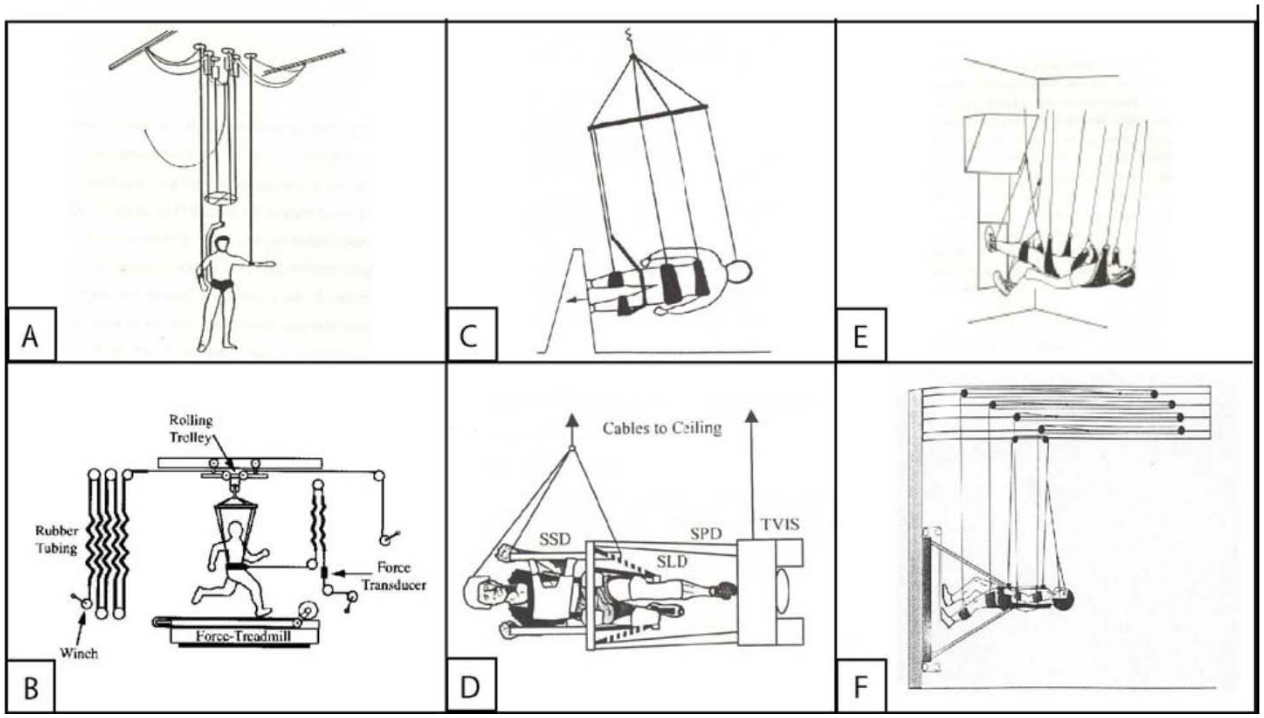


Figure 1. Various suspension techniques used (upright, side and supine). (A) Prototype of the upright technique used by Spady (1969). (B) Upright technique used by Chang et al. (2000) with applied horizontal force applied to the anterior of the subject; note the lack of lower-extremity support for both upright suspension techniques. (C) Side-suspension technique used by Hewes (1969); note the curved bar used to suspend the lower leg. (D) Side-suspension technique used by Peterman et al. (2000); note that no suspension was used for leg closest to the ground. (E) Cable suspension in a supine position (Grigor'yev et al.,1987); note the bifurcation in the cables supporting each leg. (F) First iteration of the ZLS (Davis et al., 1996); note that all limbs are independently supported.

Suspension Approaches to Zero-G Simulation

- **Suspension methods**
  - **F – Supine suspension** – "Zero Gravity Locomotion Simulator" (ZLS) first implemented in 1990's, treadmill rigidly mounted to wall, subjects suspended by harness with latex cords (Davis, et. al., 1996)
  - Subject suspended horizontally or nearly horizontal while facing upwards
    - Each limb segment supported independently
    - Servo-motor with force feedback used for Subject Load Device (Genc, 2003)
  - **Benefits**
    - Constant force subject load device
    - Supine suspension eliminates problems with unsupported lower limbs
    - Horizontal subject position maintained – bedrest analog
  - **Limitations**
    - Upper body supported in cradle – upper body kinematics constrained

Zero-G Locomotion Simulators

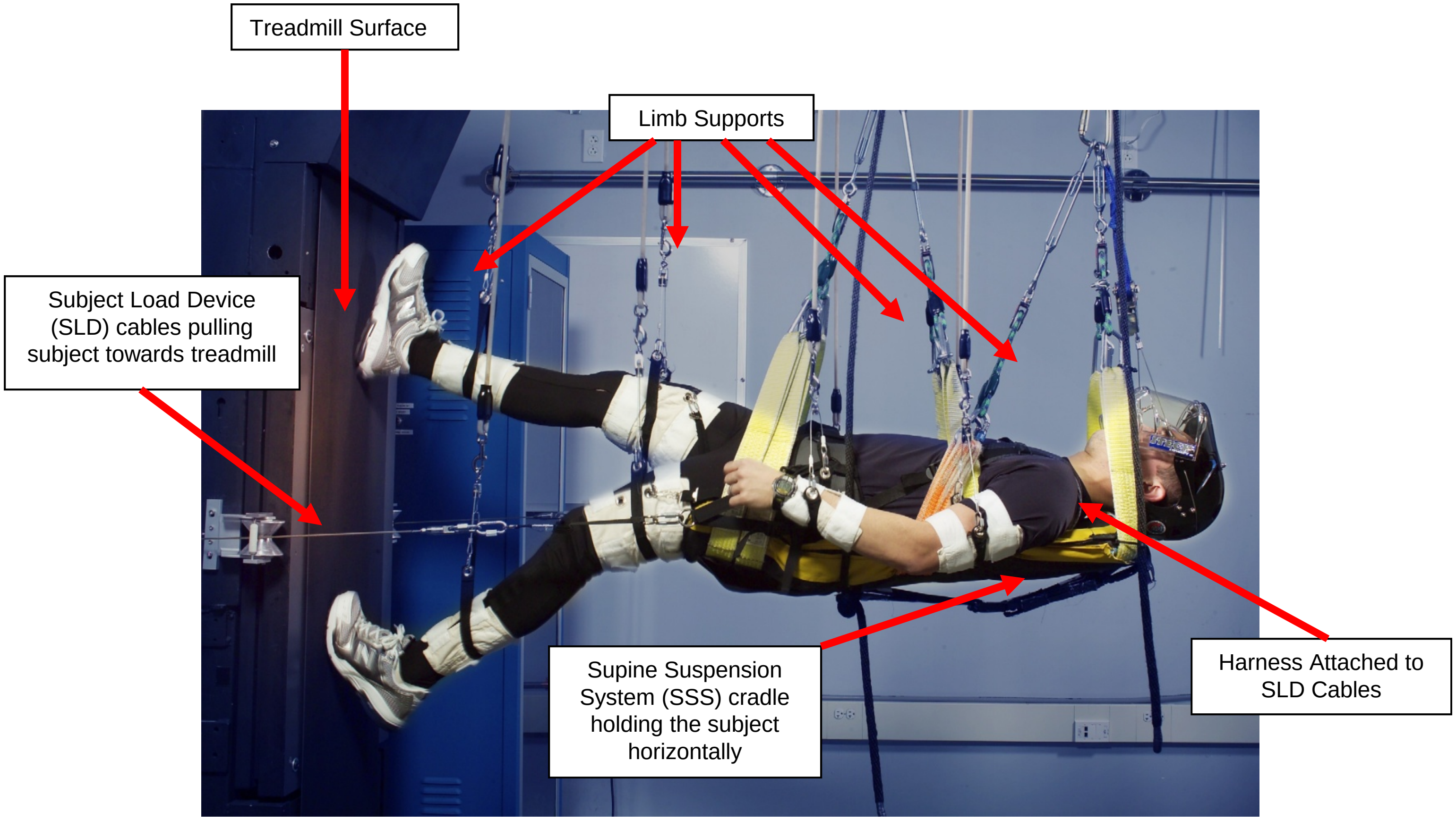
ZLS at Center for Locomotion Studies, Penn State University, State College, Pennsylvania

ZLS at the Cleveland Clinic, Cleveland, Ohio

eZLS at NASA Glenn, Cleveland, Ohio

sZLS for UTMB, Galveston, Texas

Zero-gravity Locomotion Simulator



Effect of Interface Compliance

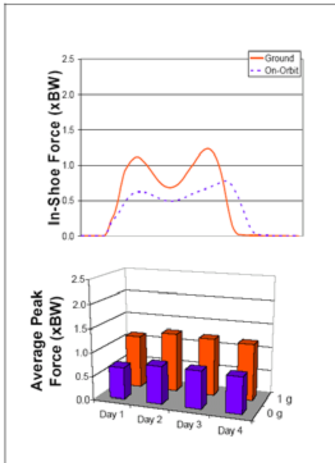


Figure 12: Average peak foot reaction forces from 25 cycles of the same subject during 4 days of free walking on Earth (red bars) and walking on the TVIS on the ISS (blue bars). Typical individual force-time curves from a single foot contact in each condition are shown above the bar graphs.

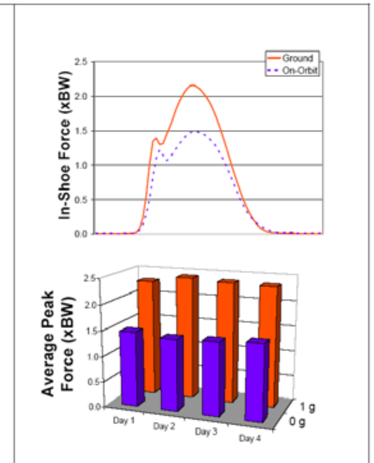


Figure 13: Average peak foot reaction forces from 25 cycles of the same subject during 4 days of free running on Earth (red bars) and running on the TVIS on the ISS (blue bars). Typical individual force-time curves from a single foot contact in each condition are shown above the bar graphs.

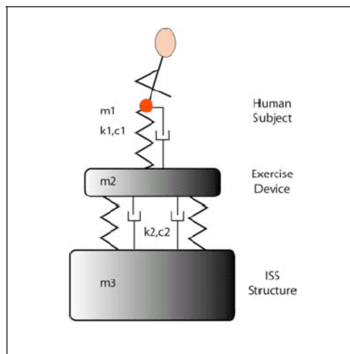


Figure 8: Simplified mass-spring-damper model of human subject, exercise device, and ISS interface.

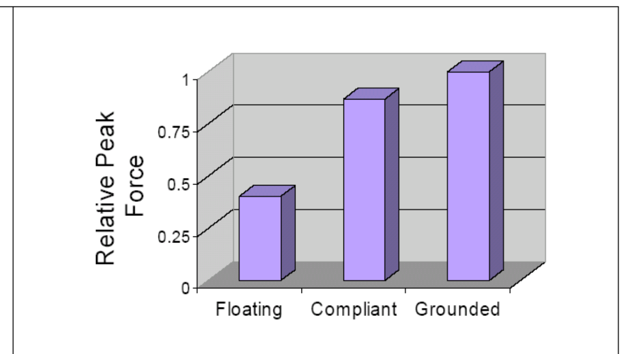
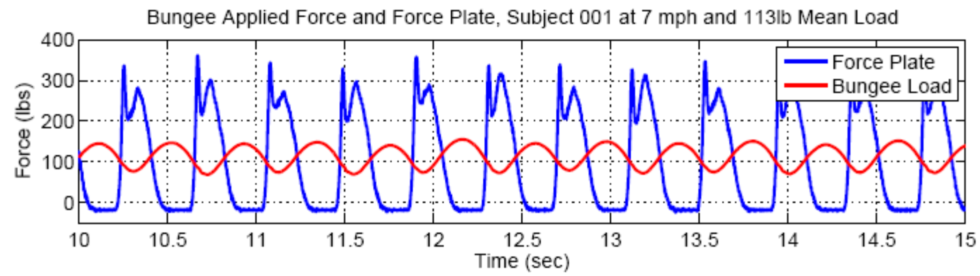
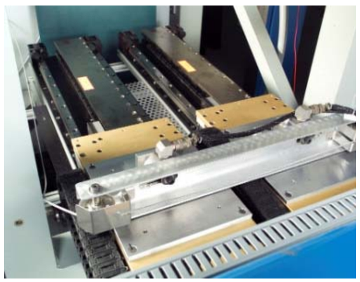


Figure 9: Predicted relative peak force at 3 Hz from the simulation of the three interface conditions.

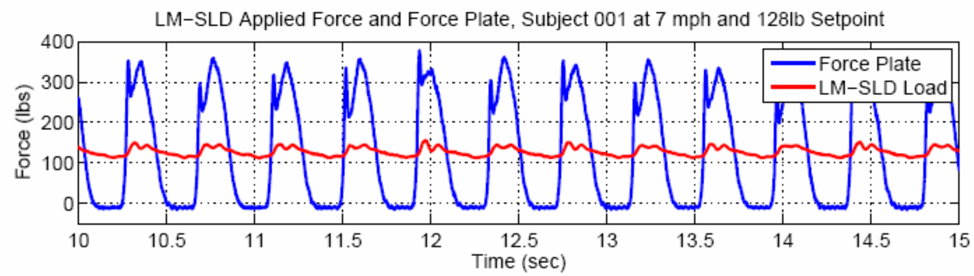
Subject Load Devices (Gravity - Replacement)

Series Bungee System (SBS) bungees

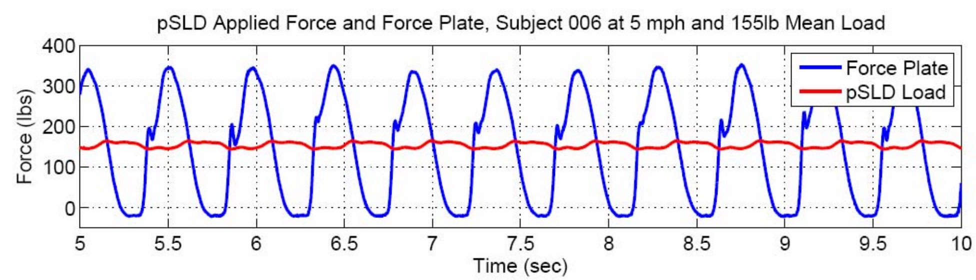




Linear Motor SLD (LM-SLD)



Pneumatic (P-SLD)



In Summary

The Zero-gravity Locomotion Simulators (ZLS, eZLS, sZLS) provide ground-based simulation of in-flight (0-g) and surface (fractional-g) exercise.

Differences and similarities to actual microgravity locomotion have been quantified.

The ZLS (Cleveland Clinic) and sZLS (NASA JSC) are co-located with bed-rest research facilities for evaluating efficacy of exercise prescriptions in simulated Zero-g.

The eZLS (NASA GRC) provides additional capability for simulating fractional gravity locomotion (tilt), and floats the treadmill for high-fidelity simulation of in-flight vibration isolation systems / compliant exercise devices.

Capability exists for training crewmembers on a compliant running surface using the eZLS system.

NSBRI-funded studies in GRC Exercise Countermeasures Project

Foot Reaction Forces During Simulated ISS Exercise Countermeasures

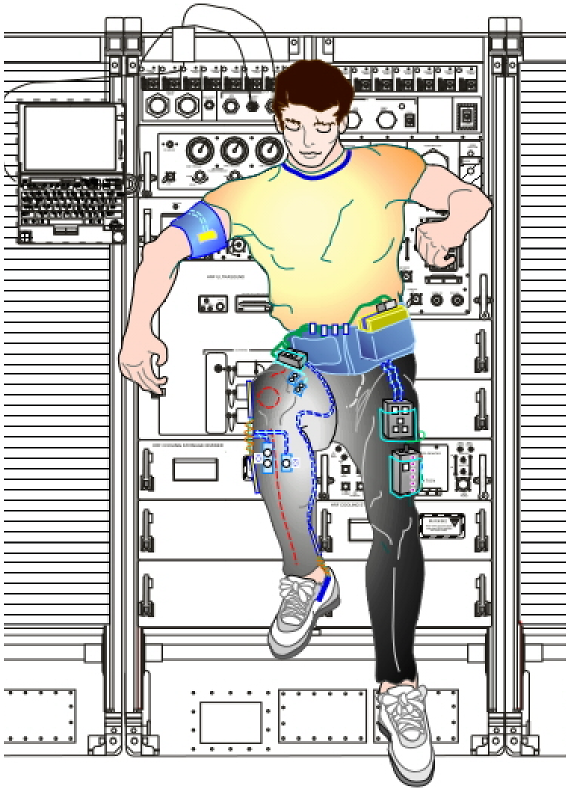
Monitoring Bone Health by Daily Load Stimulus Measurement During Lunar Missions

NSBRI – funded study (‘04 – ’08) Musculoskeletal Alterations

PI: Peter R. Cavanagh, U. of W

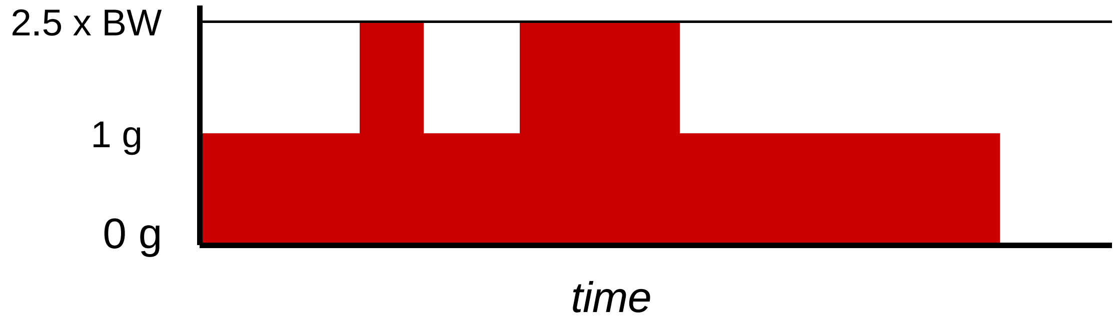
Co-I: Gail P. Perusek, GRC ; Carlos M. Grodsinsky, Zin

Foot Reaction Forces During Spaceflight (Foot) – PI: P.R. Cavanagh, Ph.D., D.Sc.

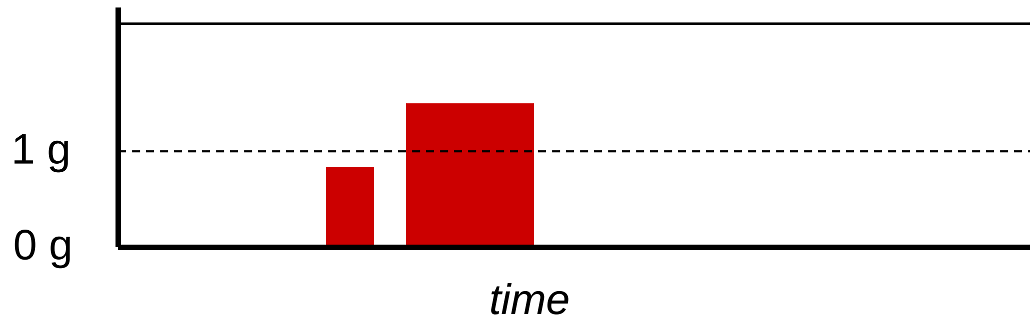


Relative Notional DLS Doses in 1-g, 0-g, Lunar-g

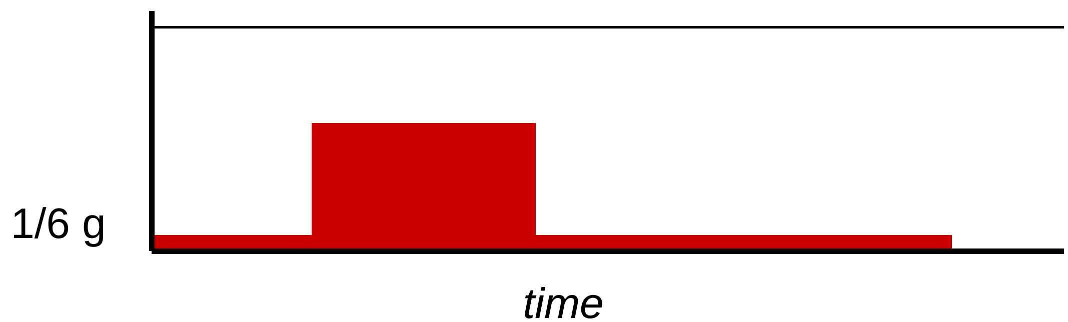
Earth



On-orbit



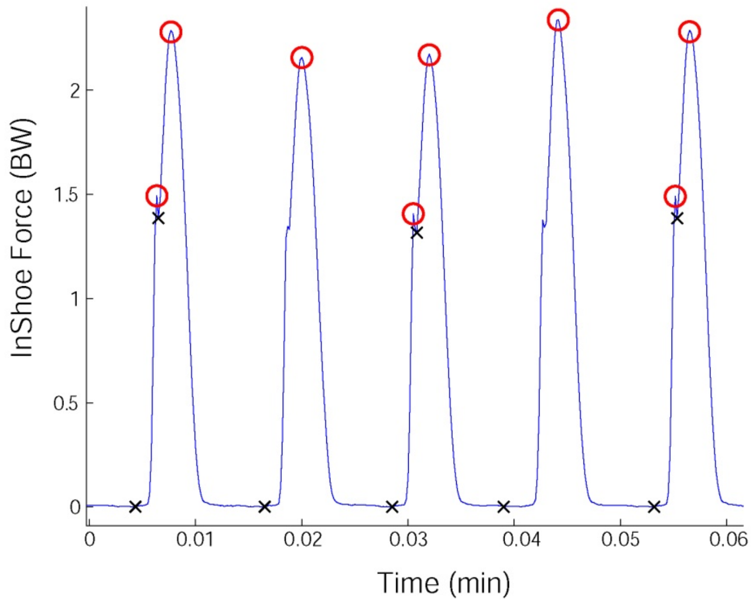
Lunar



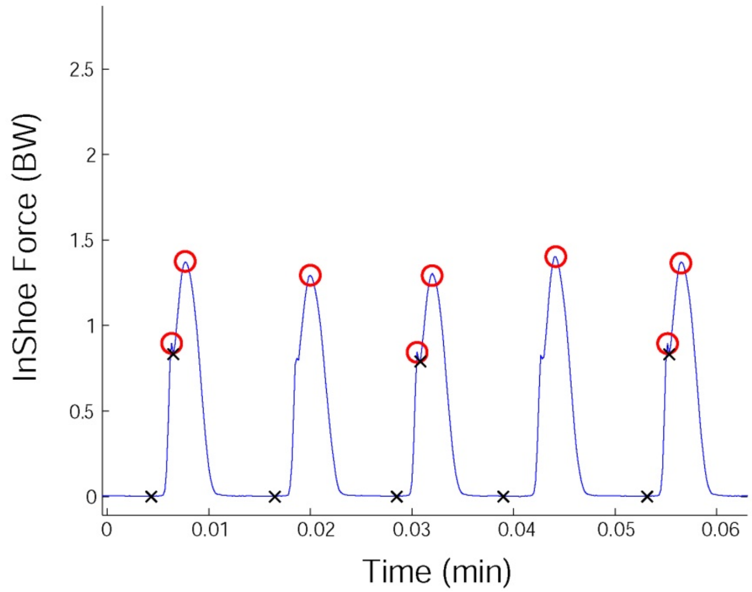
Exercise Prescriptions for Bone Mass Maintenance

$$DLS = \left[\sum_{j=1}^{k} n_j \left(G z_j \right)^m \right]_{perday}^{1/2m}$$

1 BW and 30 min.



0.6 BW and 123 min.



Time to reach equivalent DLS at 100% BW for 30 minutes exercise session → over 2 hours at 60% BW

Foot Reaction Forces – HRP IWG 2008

THE EFFECT OF TREADMILL COMPLIANCE ON FOOT REACTION FORCES DURING SIMULATED ISS EXERCISE COUNTERMEASURES

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[1]The Cleveland Clinic Center for Space Medicine, [2]Departments of Biomedical Engineering and [3]Orthopaedic Surgery and the [4]Orthopaedic Research Center,
[5]Department of Biomedical Engineering, Case Western Reserve University, [6]NASA Glenn Research Center, [7]ZIN Technologies; cavanap@ccf.org

Introduction

Exercise on the International Space Station (ISS), performed to counteract bone and muscle loss experienced in space, currently includes the use of a Treadmill with Vibration Isolation and Stabilization (TVIS). The TVIS runner dons a harness connected to the TVIS by a subject load device (SLD), which pulls the runner towards the TVIS so that loads can be imparted upon the runner. As a result of the vibration isolation of TVIS, a compliant interface is created, which may exert an important influence on the forces imparted to the subject. Preliminary modeling of these compliant interfaces supports the hypothesis that the interface affects the forcing function [1] in a complex manner. Further, foot reaction forces experienced during TVIS exercise are lower than desired (~60% of 1*g* loads [2]) as the result of SLD settings and possibly the compliant nature of TVIS. These low forces may contribute to the lack of success that exercise countermeasures have had to date in preventing bone and muscle loss on ISS.

Purpose

The purpose of the current study was to better understand the effects of compliant interfaces on exercise efficacy by using a variably compliant treadmill interface mounted on the enhanced Zero Gravity Locomotion Simulator (eZLS).

Methods

All testing was conducted at the Exercise Countermeasures Laboratory at NASA Glenn Research Center (GRC) on the eZLS, configured with frictionless air bearings and isolators to provide 1 Degree of Freedom (DOF) movement in the "heave" axis (Figure 1). Five subjects were tested with external loads of 75% and 100% of body weight using a bungee system SLD. Subjects were asked to walk (3 mph) and run (6 mph) for periods of 3 minutes using the Cleveland Clinic harness. Four compliant conditions were tested including grounded, least compliant, mid-compliant, and most compliant conditions. Parameters measured include ground reaction forces, treadmill motion, and SLD load.

Conclusion

The data is currently being reduced and analyzed. Results will be available and presented at the February 2008 Human Research Programs' Investigators' Meeting.

The experiment should provide insight into if and how compliance of the treadmill surface affects loading, ground reaction forces, gait parameters, and SLD load.

Acknowledgment

This work is supported by the National Space Biomedical Research Institute through NASA NCC 9-58.

References

[1] Just, M.L., Grodsinsky, C., Perusek, G., Davis, B. L., Cavanagh, P. R. Modeling And Simulation Of Reaction Forces In A Reduced Gravity Exercise System, XXth Congress of the International Society of Biomechanics, July 31 - August 5, 2005, Cleveland, OH.

[2] Cavanagh PR and Rice AJ, Eds. *Bone Loss During Spaceflight*. Cleveland Clinic Press. 2007.

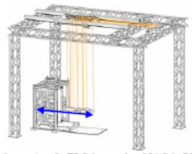


Figure 1: Schematic of eZLS located at NASA GRC showing 'heave' direction of treadmill 1 DOF compliance.

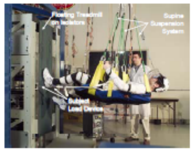
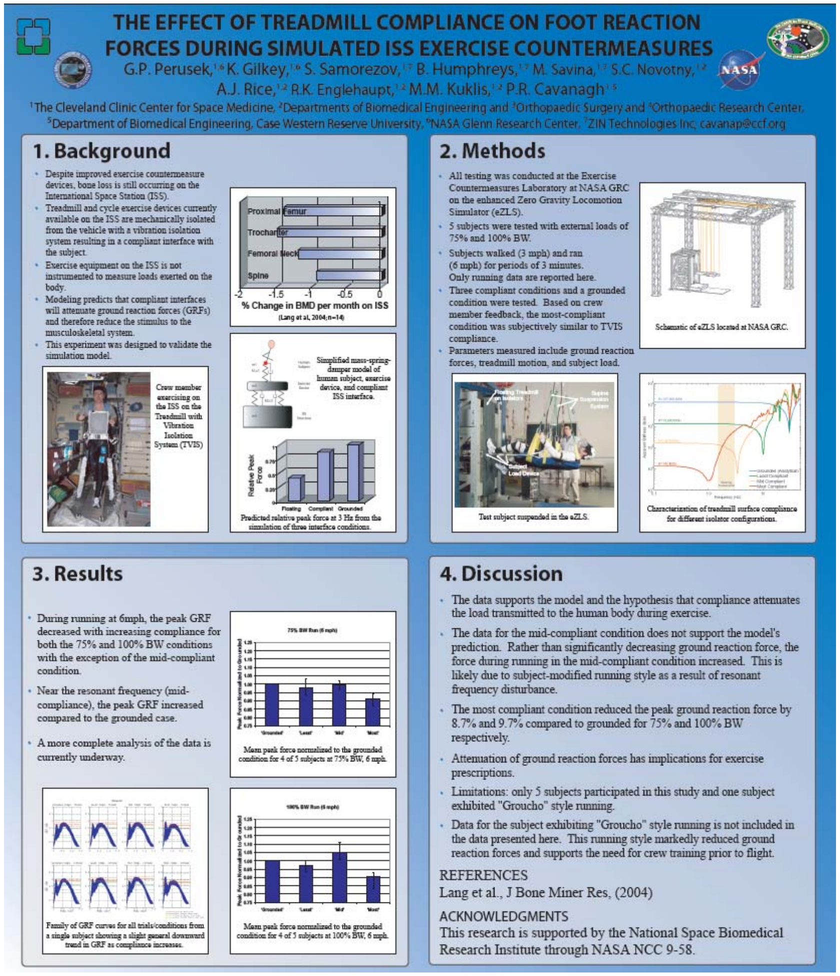


Figure 2: Test Subject Suspended in the eZLS.



Daily Load Stimulus Abstracts – ASB 2008

ALOGRITHM FOR IDENTIFICATION OF RUNNING, WALKING, AND STANDING ACTIVITY IN FOOT FORCE DATA

Brad T. Humphreys[1], Kerim O. Genc [2,3], Gail P. Perusek[4] and Peter R. Cavanagh [2,3]

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INTRODUCTION

In-shoe force data collected with a portable, device can provide valuable insight into a subject's free daily activity both in and outside of the laboratory (Hurkmans et al, 2006). However, as the length of data collection increases, the feasibility of manually classifying ground reaction forces (GRFs) into different activities decreases.

A magnitude based activity identification algorithm would be poisoned by the pseudo-random activity of subjects. For example, transferring of weight between feet during rocking would incorrectly indicate walking.

A spectral based method can be inherently problematic due to the relatively small differences or overlap in fundamental frequencies of walking and running. (Figure 1, Table 1).

The following must be considered in the development of a spectral algorithm that utilizes both frequency and magnitude criterions: 1) Running can have harmonics with significant magnitude content outside of the running and walking band (Figure 1). 2) A large transient movement, like a sudden jumping motion, can have broad frequency content that "spreads" frequency content into the running/walking band. 3) The base frequency peak of running and walking can vary with locomotion speed.

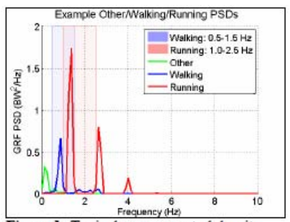

Figure 1: Typical power spectral density (PSD) of standing walking and running.

Therefore an adaptive comb filter algorithm that utilizes both frequency and magnitude criterion for the identification of activity type from total foot force data has been developed. This algorithm can be utilized in either real-time applications or post processing.

METHODS

The GRF data used for the development of the algorithm (128 Hz.) was obtained from a previous experiment (Cavanagh *et* al. 2004) in which subjects wore Pedar force measuring insoles (NOVEL Gmbh. Munich, Germany) for entire typical work days. Data were collected using a wearable, portable computer, normalized to body weight (BW) and downloaded for data analysis completed

THE ENHANCED DAILY LOAD STIMULUS (eDLS): ACCOUNTING FOR SATURATION, RECOVERY AND STANDING

Kerim O. Genc [1,2], Brad T. Humphreys[3], Gail P. Perusek [4] and Peter R. Cavanagh [1,2]

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INTRODUCTION

The Daily Load Stimulus (DLS), first proposed by Carter *et al.* (1987), is a method of quantifying daily stress histories of bone in terms of daily cyclic stress magnitudes and the number of daily loading cycles.

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

Gz = Peak magnitude of vertical component of ground reaction force (GRF)
j = Number of loading conditions
m = Weighing factor {eg. 4}
k = Number of different loading conditions

Recent studies, however, indicate that the osteogenic potential of bone can also be influenced by temporal factors such as saturation (Turner and Robling, 2004), recovery (Robling *et al.*, 2001, Gross and Srinivasan, 2006), and standing (Fritton *et al.*, 2000). Based on animal data from Umemura et al. (1997), Turner and Robling (2004) demonstrated that bone tissue sensitivity to cyclical mechanical loading can be described by 1/(N+1) where N is the number of cyclic loads after saturation. Robling et al. (2001) were able to show that increasing the time of recovery between bouts of cyclical mechanical loading can enhance bone formation. The recovery of osteogenic potential can then be described by: Recovery (%) = $100(1-e^{-t/\tau})$, where t is time in hours between bouts and τ is a time constant (2hrs). Standing can also play a role in the maintenance of bone due to the micro strains imparted through postural stabilization (Fritton et al, 2000).

Currently, the DLS model does not account for saturation, recovery or standing. Therefore, the purpose of this study is to propose an updated method of determining the DLS that accounts for variables such as saturation and recovery of osteogenic potential with cyclical loading and standing.

METHODS

Ground reaction force (GRF) data was obtained from a previous experiment (Cavanagh *et* al. 2004) in which subjects wore Pedar force measuring insoles (NOVEL Gmbh. Munich, Germany) for entire typical work days. Data were collected using a wearable, portable computer and downloaded for data analysis completed using custom Matlab software (Mathworks Inc. Natick MA).

A peak detection algorithm was used to detect all fluctuations in the GRF data above 5% of body weight (BW). The GRF data was then categorized into sitting, standing, walking, running or other. This was done by an algorithm that took advantage of the repetitive and predictable nature of walking

Foot Forces on ISS publication, JOB 2010

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Foot forces during typical days on the international space station

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ABSTRACT

Decreased bone mineral density (BMD) in astronauts returning from long-duration spaceflight missions has been well documented, but the altered mechanical loading environment experienced by the musculoskeletal system, which may contribute to these changes, has not been well characterized. The current study describes the loading environment of the lower extremity (LE) during typical days on the International Space Station (ISS) compared to similar data for the same individuals living on Earth. Data from in-shoe force measurements are also used as input to the enhanced daily load stimulus (EDLS) model to determine the mechanical "dose" experienced by the musculoskeletal system and to associate this dose with changes in BMD.

Four male astronauts on approximately 6-month missions to the ISS participated in this study. In-shoe forces were recorded using capacitance-based insoles during entire typical working days both on Earth and on-orbit. BMD estimates from the hip and spine regions were obtained from dual energy X-ray absorptiometry (DXA) pre- and post-flight.

Measurable loading was recorded for only 30% of the time assigned for exercise. In-shoe forces during treadmill walking and running on the ISS were reduced by 25% and 46%, respectively, compared to similar activities on Earth. Mean on-orbit LE loads varied from 0.20 to 1.3 body weight (BW) during resistance exercise and were ~0.10 BW during bicycle ergometry. Application of the EDLS model showed a mean decrease of 25% in the daily load experienced by the LE. BMD decreased by 0.71% and 0.83% per month during their missions in the femoral neck and lumbar spine, respectively.

Our findings support the conclusion that the measured ISS exercise durations and/or loading were insufficient to provide the loading stimulus required to prevent bone loss. Future trials with EDLS values closer to 100% of Earth values will offer a true test of exercise as a countermeasure to on-orbit bone loss.

1. Introduction

Bone mineral density (BMD) in the lower extremities (LE) and spines of astronauts on long-duration space missions show a decrease of ~1–2% per month despite the now widespread use of exercise as a countermeasure (LeBlanc et al., 2000; Lang et al., 2004). Such changes are highly relevant to astronaut health and fitness-for-duty since the consequent reduction in strength-to-fracture of the proximal femur, for example, has been estimated to be up to 5.0% per month (Keyak et al., 2009). In contrast, bones in the upper extremities do not experience significant loss in BMD (LeBlanc et al., 1996). This site-specific bone adaptation is likely caused by the change in the mechanical loading environment of the astronaut in microgravity (Lang et al., 2006; LeBlanc, 1998).

Several bone remodeling theories (e.g. the mechanostat) have proposed that bone homeostasis is guided and maintained by a range of routine daily mechanical loads, such that skeletal structure is optimized for the ambient operating conditions (Hernandez et al., 2000; Frost, 1987; Maldonado et al., 2008; Turner, 1998). Carter and colleagues proposed that a routine of daily mechanical loading could be modeled with an empirical relationship called the daily load stimulus (DLS), which results from a weighted summation of the multiple individual loading events (Carter et al., 1987). Bowley and Whalen devised a bone density index based on the DLS but accounting for differences in subject body weight (Bowley and Whalen, 2001; Worthen et al., 2005). We have recently extended the DLS and refer to it as the enhanced DLS (EDLS), to account for recent observations on the importance of factors such as saturation, recovery, and standing and their effects on the osteogenic response of bone to daily physical activity (Genc et al., 2009).

Spaceflight offers a unique environment to examine the relationship between loading and bone homeostasis since high

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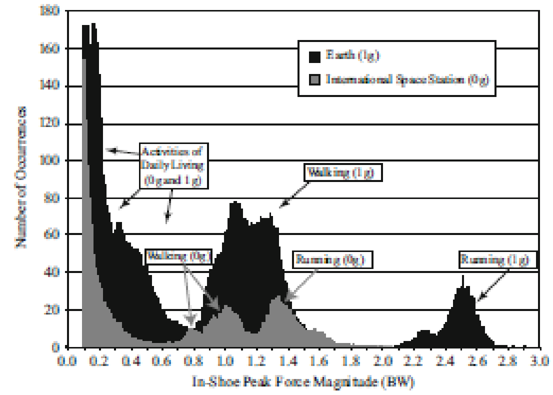


Fig. 2. A histogram of mean in-shoe force peak magnitudes vs. their frequency of occurrence for all astronauts. Peaks from about 0.85–1.5 BW and 2.1–2.8 BW are likely generated from walking and running on Earth (1g), respectively, while peaks from about 0.7–1.5 BW and 1.15–1.78 BW are likely generated from walking and running on board ISS (0g), respectively. Peaks below 0.85 BW on Earth and 0.7 BW on the ISS are likely from activities of daily living, cycle ergometer and resistance type exercises. Note: in-shoe peak force magnitudes below 10% BW were not included for clarity.

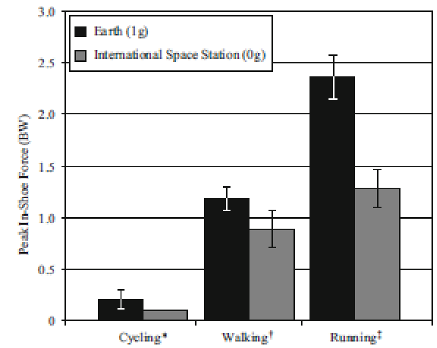
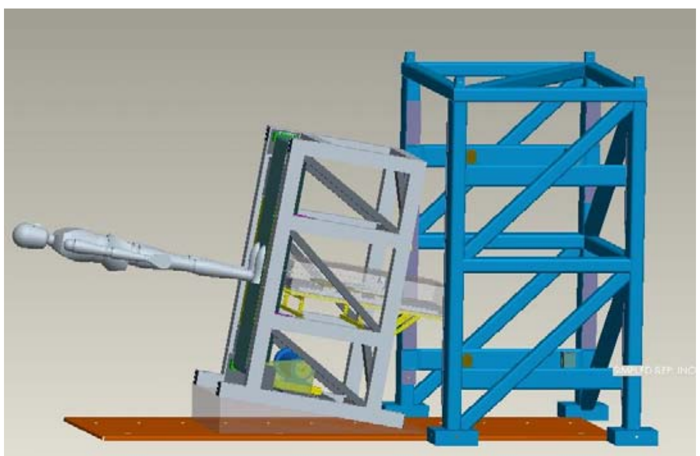


Fig. 5. Average peak in-shoe forces (in BW) during all bouts of exercise on Earth and ISS. *On Earth: $n=3$ (6 sessions), In-flight: $n=1$ (1 session). †On Earth: $n=4$ (16 sessions), In-flight: $n=2$ (8 sessions). ‡On Earth: $n=2$ (5 sessions), In-flight: $n=4$ (15 sessions).

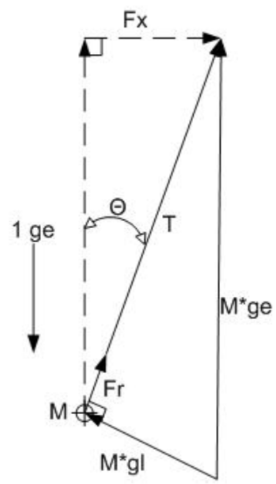
Lunar gravity (1/6th-g) simulation

Apollo Era -- NASA Langley Reduced Gravity Simulator -- 1968

Apollo 17 astronaut on the moon



eZLS Lunar Gravity Simulation at NASA GRC -- 2007



Where:

T = Total Tension in Supports
Fr = Frictional Force
$\Theta = 9.5°$
M = mass of subject
ge = gravitational constant on earth
gl = lunar gravitational constant
= (1.62 / 9.806)*ge
$Fr = \mu * M * gl$
$\mu = 0.20$ for static situations

Summation of Forces in X-Direction:
$(T+Fr)\sin\Theta - M*gl\cos\Theta = 0$
$T*\sin\Theta = M*gl\cos\Theta - Fr*\sin\Theta$
$T = (M*gl\cos\Theta - Fr*\sin\Theta) / \sin\Theta$
$T = (M*gl\cos\Theta - \mu*M*gl\sin\Theta) / \sin\Theta$
$T = M*gl(\cos\Theta - \mu\sin\Theta) / \sin\Theta$
$T = M*ge*(1.62 / 9.806)*(\cos\Theta - \mu\sin\Theta) / \sin\Theta$
$T = 0.9542\ M*ge$ (or 0.9542 Body Weight)

C-2010-3734

National Aeronautics and Space Administration
Glenn Research Center at Lewis Field

NSBRI Monitoring Bone Health Publication

SHORT COMMUNICATION

Miniaturized Sensors to Monitor Simulated Lunar Locomotion

ANDREA M. HANSON, KELLY M. GILKEY, GAIL P. PERUSEK, DAVID A. THORNDIKE, GILEAD KUTNICK, CARLOS M. GRODSINSKY, ANDREA J. RICE, AND PETER R. CAVANAGH

HANSON AM, GILKEY KM, PERUSEK GP, THORNDIKE DA, KUTNICK G, GRODSINSKY CM, RICE AJ, CAVANAGH PR. *Miniaturized sensors to monitor simulated lunar locomotion.* **Aviat Space Environ Med 2011; 82:1–5.**

Introduction: Human activity monitoring is a useful tool in medical monitoring, military applications, athletic coaching, and home healthcare. We propose the use of an accelerometer-based system to track crewmember activity during space missions in reduced gravity environments. It is unclear how the partial gravity environment of the Moon or Mars will affect human locomotion. Here we test a novel analogue of lunar gravity in combination with a custom wireless activity tracking system. ***Methods:*** A noninvasive wireless accelerometer-based sensor system, the activity tracking device (ATD), was developed. The system has two sensor units; one footwear-mounted and the other waist-mounted near the midlower back. Subjects ($N = 16$) were recruited to test the system in the enhanced Zero Gravity Locomotion Simulator (eZLS) at NASA Glenn Research Center. Data were used to develop an artificial neural network for activity recognition. ***Results:*** The eZLS demonstrated the ability to replicate reduced gravity environments. There was a 98% agreement between the ATD and force plate-derived stride times during running ($9.7\ km \cdot h^{-1}$) at both 1g and 1/6 g. A neural network was designed and successfully trained to identify lunar walking, running, hopping, and loping from ATD measurements with 100% accuracy. ***Discussion:*** The eZLS is a suitable tool for examining locomotor activity at simulated lunar gravity. The accelerometer-based ATD system is capable of monitoring human activity and may be suitable for use during remote, long-duration space missions. A neural network has been developed to use data from the ATD to aid in remote activity monitoring.

Keywords: activity recognition, eZLS, gait, reduced gravity, wireless sensor, neural network.

HUMAN ACTIVITY monitoring is a useful tool in many fields, including medical monitoring, military applications, athletic coaching, and home healthcare (12). Here we are interested in tracking the activity of astronauts while on remote missions to the Moon or Mars. Tracking the daily activity of crewmembers can provide valuable information to ground-based mission controllers who are monitoring physical health, the possibility of injury, or are deciding on individual caloric intake needs. Monitoring crewmember activity across the lunar surface could also provide information on the unique challenges of traversing over the local regolith in this new environment. Gait parameters have not been characterized in reduced gravity environments. Understanding how reduced gravity affects locomotor activity can aid in suit design and help in risk mitigation strategies.

Accelerometry has evolved as a useful means of monitoring human activity (8) and, more recently, as an important component of activity recognition tools (9). Advances in miniaturized electronics, embedded systems, and wireless communication protocols have made development of noninvasive body-worn instrumentation affordable and desirable for human activity monitoring (12). Human locomotion often results in repetitive and recognizable patterns, and a number of authors have been successful in applying the theories of machine learning and artificial neural networks together with data from body-mounted sensors to recognize human activities (1,11,13). In this study, an artificial neural network was developed to recognize and distinguish distinct forms of lunar locomotion from feature characteristics of the accelerometer signals in post-processing analysis. Such recognition would enable activity identification and monitoring during remote missions.

Simulated lunar gravity and locomotion have been studied with a variety of off-loading devices, including water immersion, over-head suspension, off-loading pulley systems, and parabolic flight (2). The enhanced Zero Gravity Locomotion Simulator (eZLS) facility located at NASA Glenn Research Center simulates reduced gravity environments and locomotor activity on an instrumented treadmill (3,10). A gravity replacement load (e.g., 1/6 g or 1 g) can be applied to a subject using subject loading devices (SLDs) (5).

The goals of this study were threefold. First, we aimed to design an accelerometer-based system to wirelessly and remotely monitor daily activity while using an artificial neural network to characterize the activity. Second, we aimed to characterize gait parameters in simulated lunar gravity. Third, we aimed to validate the eZLS as a suitable simulation of lunar gravity. Successful

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This manuscript was received for review in May 2010. It was accepted for publication in November 2010.

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Aviation Space and Environmental Medicine, February 2011

Similarities between Simulated and Actual 0-g

Enhanced Zero-g Locomotion Simulator (SM)

C-9 Microgravity Laboratory (AM)

Kinematic and EMG Comparisons of Gait in Normal, Simulated, and Actual 0-g

KINEMATIC AND EMG COMPARISON OF GAIT IN NORMAL G AND MICROGRAVITY

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INTRODUCTION

Astronauts regularly perform treadmill locomotion as part of their exercise prescription while they are on board the International Space Station. Although locomotive exercise has been shown to be beneficial for bone, muscle, and cardiovascular health, astronauts return to Earth after long-duration missions with net losses in all three areas [1]. These losses might be partially explained by fundamental differences in locomotive performance between normal gravity (NG) and microgravity (MG).

During locomotive exercise in MG, the subject must wear a waist and shoulder harness that is attached to elastomer bungees. The bungees are attached to the treadmill, and provide forces that are intended to replace gravity. However, unlike gravity, which provides a constant force on all body parts, the bungees provide a spring force only to the harness. Therefore, exercise in MG has two fundamental differences from exercise in NG: 1) forces returning the subject to the treadmill are not constant, and 2) forces are applied to the axial skeleton only at the waist and shoulders. The effectiveness of the exercise may also be affected by the magnitude of the gravity replacement load. Historically, astronauts have difficulty performing treadmill exercise with loads that approach body weight (BW) because of discomfort and inherent stiffness in the bungee system.

The unique requirements for locomotion in MG could cause differences in performance between gravitational locations. These differences may help to explain why long-term effects of treadmill exercise training in MG may differ from those found in NG. The purpose of this investigation was to compare locomotion in NG and MG to determine if differences in kinematic or muscular activation pattern occur between gravitational environments.

METHODS

Five subjects (2M, 3F) completed treadmill walking at 1.34 $m \cdot s^{-1}$ and running at 3.13 $m \cdot s^{-1}$ in NG and MG. NG trials were collected on a laboratory treadmill at NASA Glenn Research Center. MG trials were collected during parabolic flight on a C-9 aircraft at NASA Johnson Space Center. The external load (EL) was provided by bungees during MG trials. Trials were completed under low EL ($56.2 \pm 6.3\%$ BW) and high EL ($87.3 \pm 6.6\%$ BW) conditions.

Kinematic data were collected with a video motion capture system (SMART Elite, BTS Bioengineering SpA, Milan, Italy) at 60 Hz. The 3-D positions of markers on the lower extremity and trunk were recorded, rotated into a treadmill reference frame, and projected onto the sagittal plane. All subsequent kinematic calculations were completed in 2-D.

Telemetered electromyography (EMG) (Myomonitor III Wireless EMG System, Delsys Inc., Boston, MA) was used to obtain data on activation of the tibialis anterior, gastrocnemius, rectus femoris, semimembranosus, and gluteus maximus. Before any motion trials were conducted, subjects performed maximal voluntary isometric contractions of each muscle to standardize electrode placement. All motion capture and EMG data were synchronized via a global analog pulse that was recorded simultaneously by each hardware device.

Hip, knee, and ankle joint range of motion (ROM) and flexion and extension extremes were computed using the angles between adjacent segments, with markers defining their long axes. EMG data were rectified and filtered and then examined to quantify the time of initial activation and the total activation duration of each stride using the methods of Browning et al. [2]. Multiple strides were analyzed

Submitted to: Aviation Space and Environmental Medicine

A Comparison of Locomotion in Normal Gravity, Simulated Microgravity and Actual Microgravity

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American Society of Biomechanics 2009

Aviation Space and Environmental Medicine, Aug. 2010

Differences and Similarities to Actual 0-g

- Locomotion in 3 gravitational environments compared –
  - **N** = Normal Gravity (upright treadmill)
  - **SM** = Simulated Microgravity (eZLS)
  - **AM** = Actual Microgravity (NASA DC-9 aircraft)
- 7 subjects
- Elastomer bungee subject load system
- 2 loading conditions (55%, 90% body weight)
- 2 speeds (3 mph walk, 7 mph run)
- Joint Kinematic, Muscle Activity (EMG), Ground Reaction Force and Temporal Kinematic data collected
- Subjects age 21-49 yrs., pre-screened (modified Air Force Class III physical, stress tests), JSC Institutional Review Board approval

Differences and Similarities to Actual 0-g

- More similarities than differences -- most notable differences between locations were in the Hip flexion and ROM -- greater in AM than SM and N for running ($p < 0.05$)
  - Extended exercise on the SM may not affect the hip musculature similar to long-term exercise in microgravity.
  - SM suspension cradle possible restriction of motion / forward lean

  - SM = Simulated Microgravity
  - AM = Actual Microgravity

ISS Second Generation Treadmill (T2) Vibration Isolation System (VIS) Test

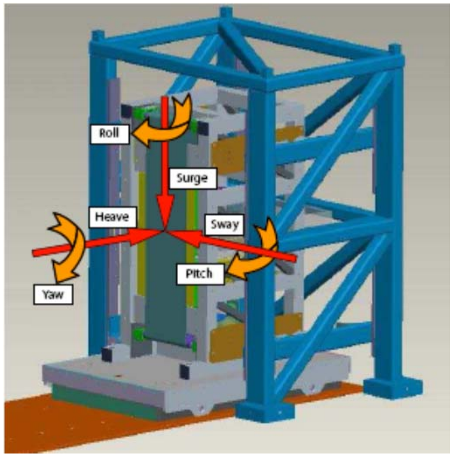
Purpose

- Man-in-the-loop testing at GRC Exercise Countermeasures Lab (ECL) to produce data set to validated T2VIS verification model specific to sway space performance (representative stiffness, mass and inertia) and utilizing Boeing PaRIS isolators. Validate transfer functions and attenuation performance.

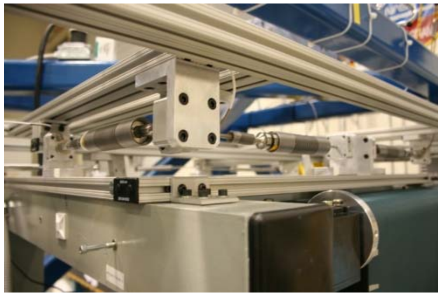
Status - Complete

- Expand eZLS treadmill degrees of freedom (1 DOF to 3 DOF) to accept PaRIS isolators completed in Nov. ’07. Mass / C.G. of treadmill matched to T2 characteristics for comparable dynamic response.
- Human subject testing (n=4) completed Nov. ’07 - Jan. ’08 with 3 DOF and PaRIS isolators in place. Treadmill speeds 1.5 mph (slow walk) to 12 mph (run).
- Kickload tests completed
- Data delivered to Boeing for isolator design input
- Expensive active vibration isolation (ARIS, gyroscope) proven unnecessary

Subject runs on 3 DOF PaRIS-isolated treadmill at GRC



T2 coordinate system / conventions



Close-up view of PaRIS isolators used for T2VIS simulation test

Harness Comfort Study Summary

Background

- Discomfort from U.S. TVIS Harness is common complaint from crewmembers exercising on the ISS TVIS treadmill.

Purpose

- Develop standard test protocol and conduct pilot test on enhanced Zero-g Locomotion Simulator to compare comfort and loading with TVIS Harness and Cleveland Clinic (CC) Prototype harness (n=6).

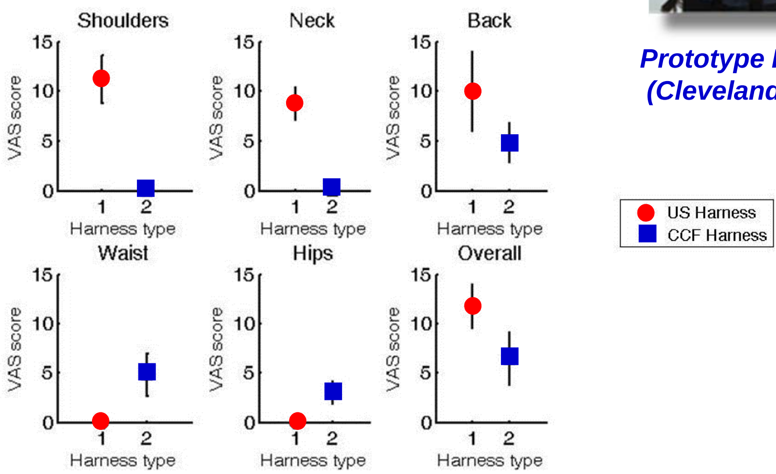
Outcomes

- CC Prototype found to be **more comfortable at shoulders and overall** than the TVIS Harness under similar loading conditions – statistically significant differences.
- The TVIS Harness appears to concentrate loading at the shoulders, **CC Prototype hip belt appears more effective at sharing load**.
- **Final report** submitted to LSDA June 2007.
- Move forward with flight hardware development as a Station Development Test Objective (SDTO)

Exercise Countermeasures Laboratory at GRC

U.S. Harness

Prototype Harness (Cleveland Clinic)



Comfort Data (Visual Analog Scale, VAS) results after 20-min jog

In Summary

The Zero-gravity Locomotion Simulators (ZLS, eZLS, sZLS) provide ground-based simulation of in-flight (0-g) and surface (fractional-g) exercise – unique man-in-the-loop capabilities for exercise system design and verification.

Differences and similarities to actual microgravity locomotion have been quantified.

The sZLS (NASA JSC) is co-located with bed-rest research facility for evaluating efficacy of exercise prescriptions in simulated Zero-g.

The eZLS (NASA GRC) provides additional capability for simulating whole-body fractional gravity locomotion (lunar and martian-g), and floats the treadmill for high-fidelity simulation of in-flight vibration isolation systems / compliant exercise devices.

Capability exists for training crewmembers on a compliant running surface using the eZLS system.

Crew Equipment (e.g., Glenn Harness) improvements may benefit long term musculoskeletal health for crewmembers

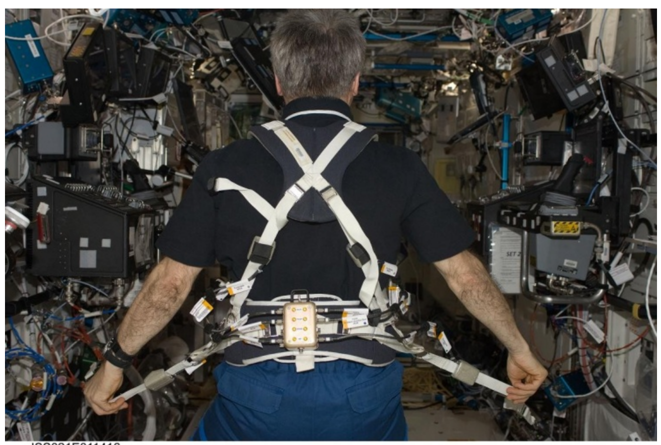
Harness Station Development Test Objective (SDTO)

PI: Gail P. Perusek, GRC
Co-Investigators: Jeffrey Ryder, JSC; Tammy Owings, Cleveland Clinic

SDTO 17013-U: Harness

Purpose

- Current TVIS Treadmill Harness causes crew discomfort including chafing, broken skin and scarring
- An alternate harness design ("Glenn Harness") was evaluated for improved comfort compared to the current Treadmill Harness (up to ~90% bodyweight).
    - Greater comfort may allow increased loading during treadmill running and may improve the health benefit of exercise (e.g., bone mass)
- Load data were captured on both Glenn and Treadmill Harness to provide hip:shoulder loading ratio and total load into harness



ISS021E011416

Features of the Glenn Harness

- “S”-shaped padded shoulder straps which avoid sensitive regions of the neck and shoulder while minimizing chest compression, better load distribution
- Biocidal fabric on inside surfaces eliminates odor buildup
- Waist belt with cupped and canted regions to apply load to the iliac crests and lumbar shelf. Split padding feature, stiff outer shell, removable lumbar padding
- Pre-curved and padded waist belt for customized fit (S,M,L male/female) – no complicated adjustment for size differences
- Load attached to multiple points and transferred over the semi-rigid shell of the waist belt for better load distribution

Protocol Overview

- Crewmembers ran up to 90% bodyweight loading and compared each harness type ‘side-by-side’
- Protocol was completed during nominal exercise time
  - First month on-orbit use normal Treadmill Harness, then 4 data collection sessions with Glenn (or Treadmill), 4 data collection sessions with Treadmill (or Glenn) – remainder of mission wear harness of choice
  - Load data captured on both Glenn and Treadmill Harness to provide hip:shoulder loading ratio and total load into harness
  - Crewmembers provided qualitative comfort / fit / function feedback via a Questionnaire after selected sessions for both harness types (Borg Scale, and Likert Scale)

SDTO 17013-U: Harness

SDTO Results

- SDTO ran from September 2009 through end of November 2010, across ISS Increments 21-25, N=7 crew enrolled (5 males, 2 females)
- Four (4) of five (5) male crewmembers preferred Glenn Harness based on comfort surveys and crew debriefs. One crewmember wore Glenn Harness exclusively outside of the SDTO protocol (prior to and after protocol completion) during Increment.
- One female crewmember opted out of protocol (would have been 7th subject, second female subject) – shoulder strap discomfort.
- Current ISS CDR is wearing spare Glenn Harness at personal request (not a consented test subject).
- Females encountered issues and a forward plan is in place with HRP to re-design/evaluate the female harness shoulder strap assembly.
- Based on positive crew feedback, Astronaut Office has requested consideration of the Glenn Harness as a crew preference item.

Conclusions and Recommendations

- Conclusion:
  - Glenn Harness preferred by 4 of 5 male crewmembers, potentially allowing greater loading with improved comfort. Female crewmembers did not prefer Glenn Harness.
  - Crew preference was most clearly indicated through comments rather than absolute comfort differences reflected in data.
  - Astronaut Office has indicated past and future crews would like harness option.
- Recommendations:
  - Redesign/ground test female shoulder strap assembly (HRP action). Present findings to VCB when complete.
  - Recommend operational implementation of the Glenn Harness for males as a crew preference item.

Advanced Exercise Concepts

Project Manager: Gail P. Perusek, GRC

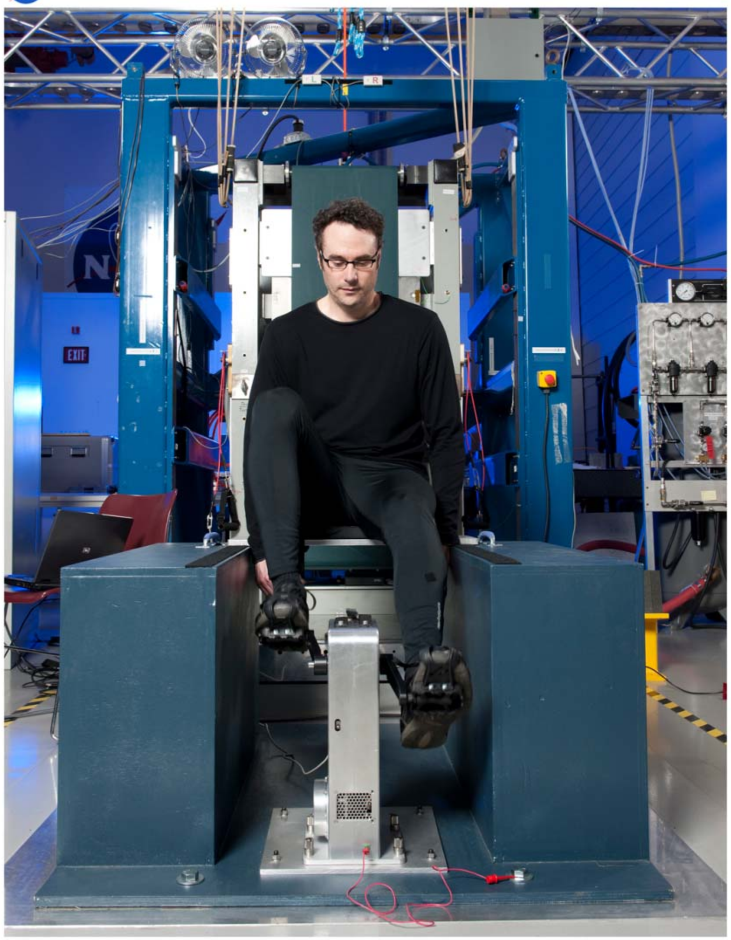
Task Lead: Christopher M. Sheehan (Zin)
Contributors: Nathan Funk (Zin), Justin Funk (Zin), John K. DeWitt (JSC)

Lunar Electric Rover (LER) Ergometer
Human Subject Test Demonstration

NASA Glenn, Exercise Countermeasures Lab

Delivered to JSC / Desert RATS for 2010 trials

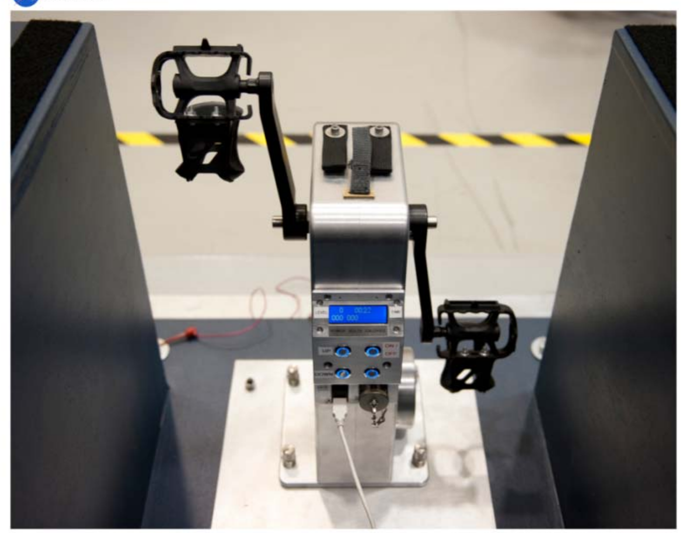
C-2010-2011



National Aeronautics and Space Administration
Glenn Research Center at Lewis Field

Lunar Electric Rover (LER) at NASA JSC

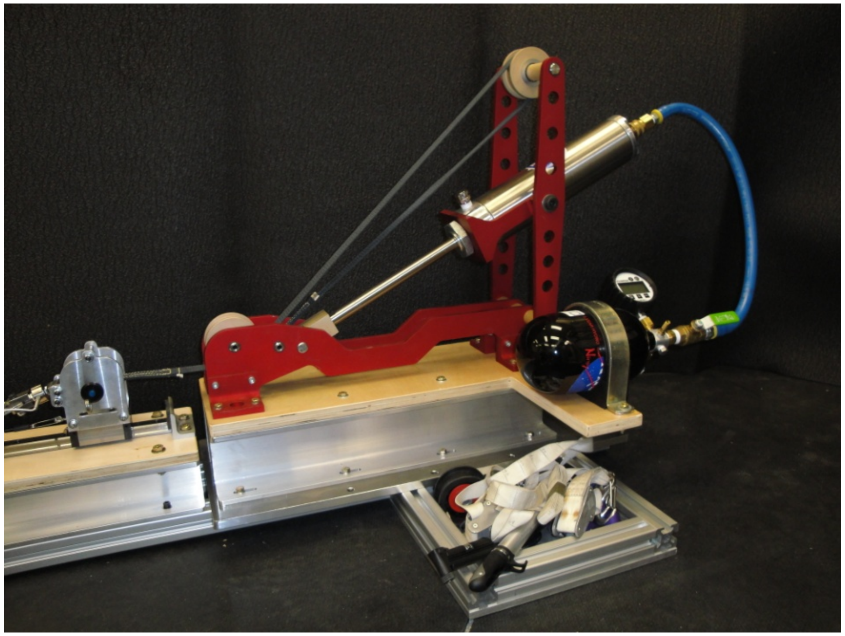
C-2010-2023



National Aeronautics and Space Administration
Glenn Research Center at Lewis Field

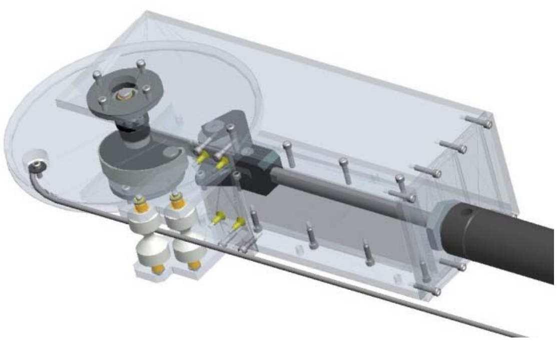
Ergometer generates power during use for recharging batteries, provides aerobic and resistive modes, data logging capability – displays Watts, Voltage, Calories, Elapsed Time

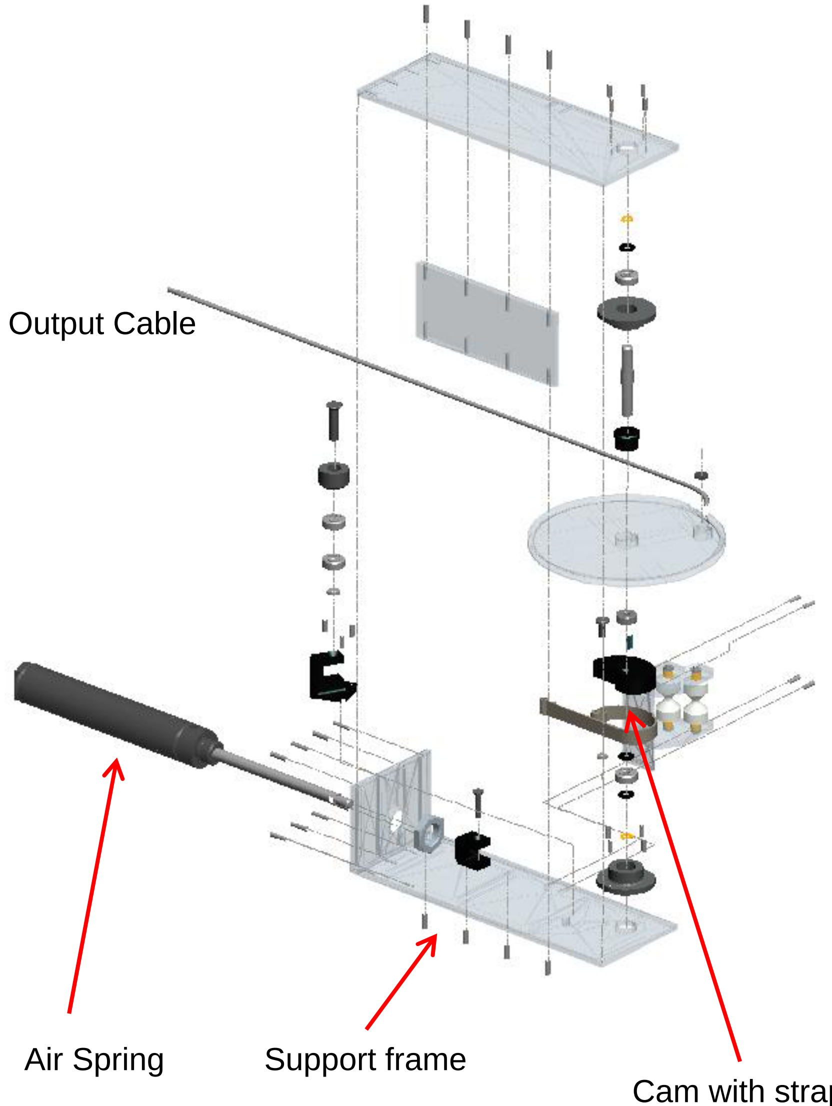
Lunar Electric Rover (LER) Gas Spring Device
Evaluated against Wyle Inertial Wheel at JSC EXL
(March 15, 2010 Final Report, J. DeWitt)
Delivered to JSC / Desert RATS for 2010 trials



Cam Air Spring Device

- Cam Air Spring Device is designed as a bench top unit to test system for ability to provide near perfect-linear loading
- The cam profile is designed using Excel, which adjusts the cam radius length in relation to the cam angle to produce a constant torque output from the varying piston force
- Bench top unit has been designed to accept different cam profiles, as well as different air springs/pistons for future test iterations
- Initial bench-top testing reveals near uniform (+/- ~2%) eccentricc and concentric strokes with regards to force linearity

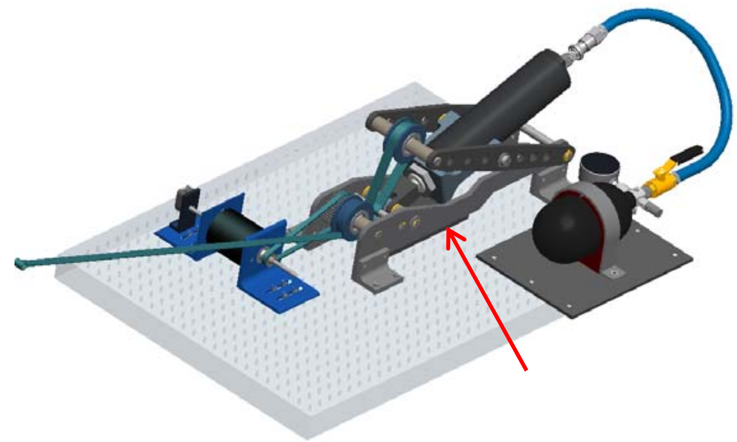




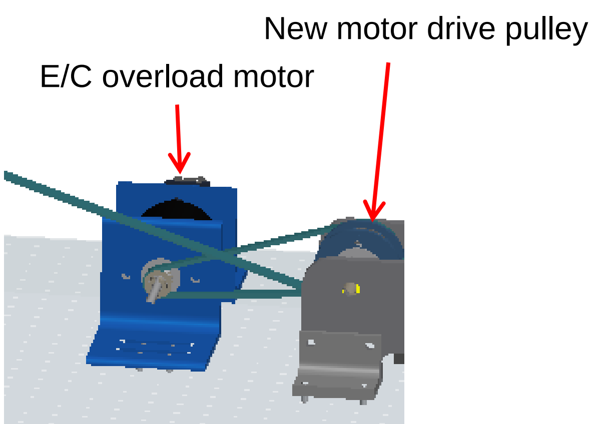
E/C Overload Assist Device

- There has always been a desire for devices that have the ability to provide the user an Eccentric to Concentric overload

- However, because friction always works against the user, for passive devices (unpowered), this is nearly impossible without sacrificing force linearity. An example of this is the Wyle Inertial Spring Device. E/C overloads are possible, but force exerted on the user varies greatly in relation to the speed in which the user pulls on the device and the place within the stroke



- E/C Overload Assist Device combines the benefits of a passive system, which can provide near linear loads at a range of values, with the ability to add an E/C overload aspect to the exercise



- A motor/gearing system will be able to be engaged/disengaged from the passive system. When exercising, the motor will be controlled to apply small loads on the eccentric stroke. Instead of providing the entire load, this system will only be used to supplement ~10-20% on the eccentric stroke. This will also greatly reduce power requirements

- Testing of this concept is currently underway with promising results

Compact Subject Load Device (C-SLD)

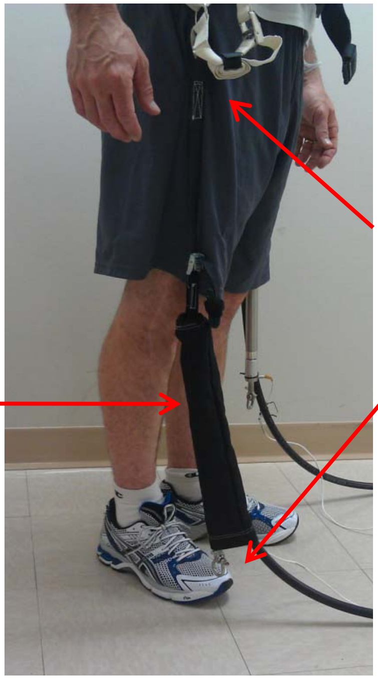
- The C-SLD system was designed to provide a subject load solution for treadmill applications

- The C-SLD makes use of in-line air cylinders which clip onto the eZLS in a similar fashion to existing bungee straps

- C-SLD is an entirely COTS based solution, which offers distinct advantages in cost, device life (cylinders are factory rated to 22 million cycles), and size over previous pneumatic based solutions

- C-SLD also offers advantages in force linearity over existing bungee straps and other solutions. Initial testing shows the force linearity to be as good as +/- 4%, and with an average of ~+/-7%

- C-SLD is designed with in-line force transducers and control software that monitor force and pressure vs. time and allow the test operator to change the input load (even on the fly)



Air cylinders shown in protective sock

Attachment points

C-SLD control box