Abstract for ESA Symposium Technology for artificial gravity and microgravity simulation

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ESTEC, Noordwijk, The Netherlands

Zero-Gravity Locomotion Simulators -- New Ground-Based Analogs for Microgravity Exercise Simulation Developed for Space Exploration

Maintaining health and fitness in crewmembers during space missions is essential for preserving performance for mission-critical tasks. NASA's Exercise Countermeasures Project (ECP) provides space exploration exercise hardware and monitoring requirements that lead to devices that are reliable, meet medical, vehicle, and habitat constraints, and use minimal vehicle and crew resources. ECP will also develop and validate, efficient exercise prescriptions that minimize daily time needed for completion of exercise yet maximize performance for mission activities. In meeting these mission goals, NASA Glenn Research Center (Cleveland, OH, USA), in collaboration with the Cleveland Clinic (Cleveland, Ohio, USA), has developed a suite of zero-gravity locomotion simulators and associated technologies to address the need for ground-based test analog capability for simulating in-flight (microgravity) and surface (partial-gravity) exercise to advance the health and safety of astronaut crews and the next generation of space explorers.

Various research areas can be explored. These include improving crew comfort during exercise, and understanding joint kinematics and muscle activation pattern differences relative to external loading mechanisms. In addition, exercise protocol and hardware optimization can be investigated, along with characterizing system dynamic response and the physiological demand associated with advanced exercise device concepts and performance of critical mission tasks for Exploration class missions.

Three zero-gravity locomotion simulators are currently in use and the research focus for each will be presented. All of the devices are based on a supine subject suspension system, which simulates a reduced gravity environment by completely or partially offloading the weight of the exercising test subject's body. A platform for mounting treadmill is positioned perpendicularly to the test subject. The Cleveland Clinic Zero-g Locomotion Simulator (ZLS) utilizes a pneumatic subject load device to apply a near constant gravity-replacement load to the test subject during exercise, and is currently used in conjunction with the General Clinical Research Center for evaluating exercise protocols using a bedrest analog. The enhanced ZLS (eZLS) at NASA Glenn Research Center features an offloaded treadmill that floats on a thin film of air and interfaces to a force reaction frame via variably-compliant isolators, or vibration isolation system. The isolators can be configured to simulate compliant interfaces to the vehicle, which affects mechanical loading to crewmembers during exercise, and has been used to validate system dynamic models for new countermeasures equipment designs, such as the second International Space Station treadmill slated for use in 2010. In the eZLS, the test subject and exercise device can be pitched at the appropriate angle for partial gravity simulations, such as lunar gravity (1/6th earth gravity). On both the eZLS and the NASA-Johnson Space Center standalone ZLS installed at the University of Texas Medical Branch in Galveston, Texas, USA, the subject's body weight relative to the treadmill is controlled via a linear motor subject load device (LM-SLD). The LM-SLD employs a force-feedback closed-loop control system to provide a relatively constant force to the test subject during locomotion, and is set and verified for subject safety prior to each session.

Locomotion data were collected during parabolic flight and on the eZLS. The purpose was to determine the similarities and differences between locomotion in actual and simulated microgravity. Subjects attained greater amounts of hip flexion during walking and running during parabolic flight. During running, subjects had greater hip range of motion. Trunk motion was significantly less on the eZLS than during parabolic flight. Peak impact forces, loading rate, and impulse were greater on the eZLS than during parabolic while walking with a low external load (EL) and running with a high EL. Activation timing differences existed between locations in all muscles except for the rectus femoris. The tibialis anterior and gluteus maximus were active for longer durations on the eZLS than in parabolic flight during walking. Ground reaction forces were greater with the LM-SLD than with bungees during eZLS locomotion. While the eZLS serves as a ground-based analog, researchers should be aware that subtle, but measurable, differences in kinematics and leg musculature activities exist between the environments.

Aside from space applications, zero-gravity locomotion simulators may help medical researchers in the future with development of rehabilitative or therapeutic protocols for injured or ill patients. Zero-gravity locomotion simulators may be used as a ground-based test bed to support future missions for space exploration, and eventually may be used to simulate planetary locomotion in partial gravity environments, including the Moon and Mars.

Figure: Zero-gravity Locomotion Simulator at the Cleveland Clinic, Cleveland, Ohio, USA

Zero-Gravity Locomotion Simulators: New Ground-Based Analogs for Microgravity Exercise Simulation

Human Research Program
Exercise Countermeasures Project
ISS and Human Research Project Office

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Space Flight Deconditioning

- **Bone:** Skeletal unloading in microgravity, fluid shifts, loss of bone mass
- **Muscle:** Atrophy, strength & endurance loss, cramps & soreness
- **Cardiovascular:** Endurance reductions (higher heart rate for given workload), lower oxygen carrying capacity, orthostatic intolerance in g-transitions
- **Sensorimotor / Neurovestibular:** Balance and coordination impaired
- **Psychological:** Mental fatigue & stress

⇨ **Exercise** is one of the most promising means to mitigate these losses and provides whole-system benefits to crewmembers

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.

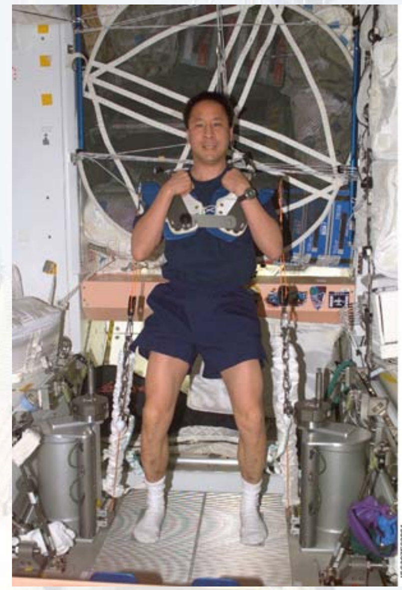
Project Goals

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.

Current ISS Exercise Equipment – U.S.

Cycle Ergometer (CEVIS)



Interim Resistive Exercise Device (iRED)

Treadmill with Vibration Isolation and Stabilization (TVIS)

Suspension Approaches to Zero-G Simulation

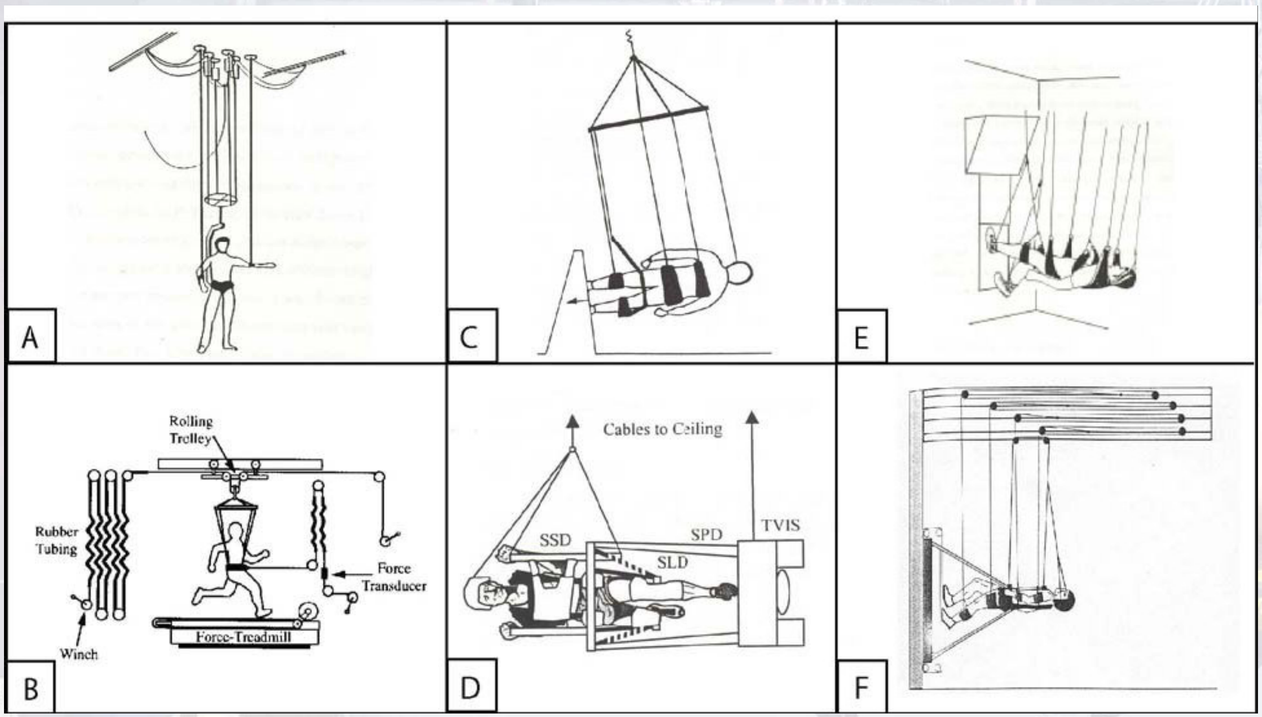
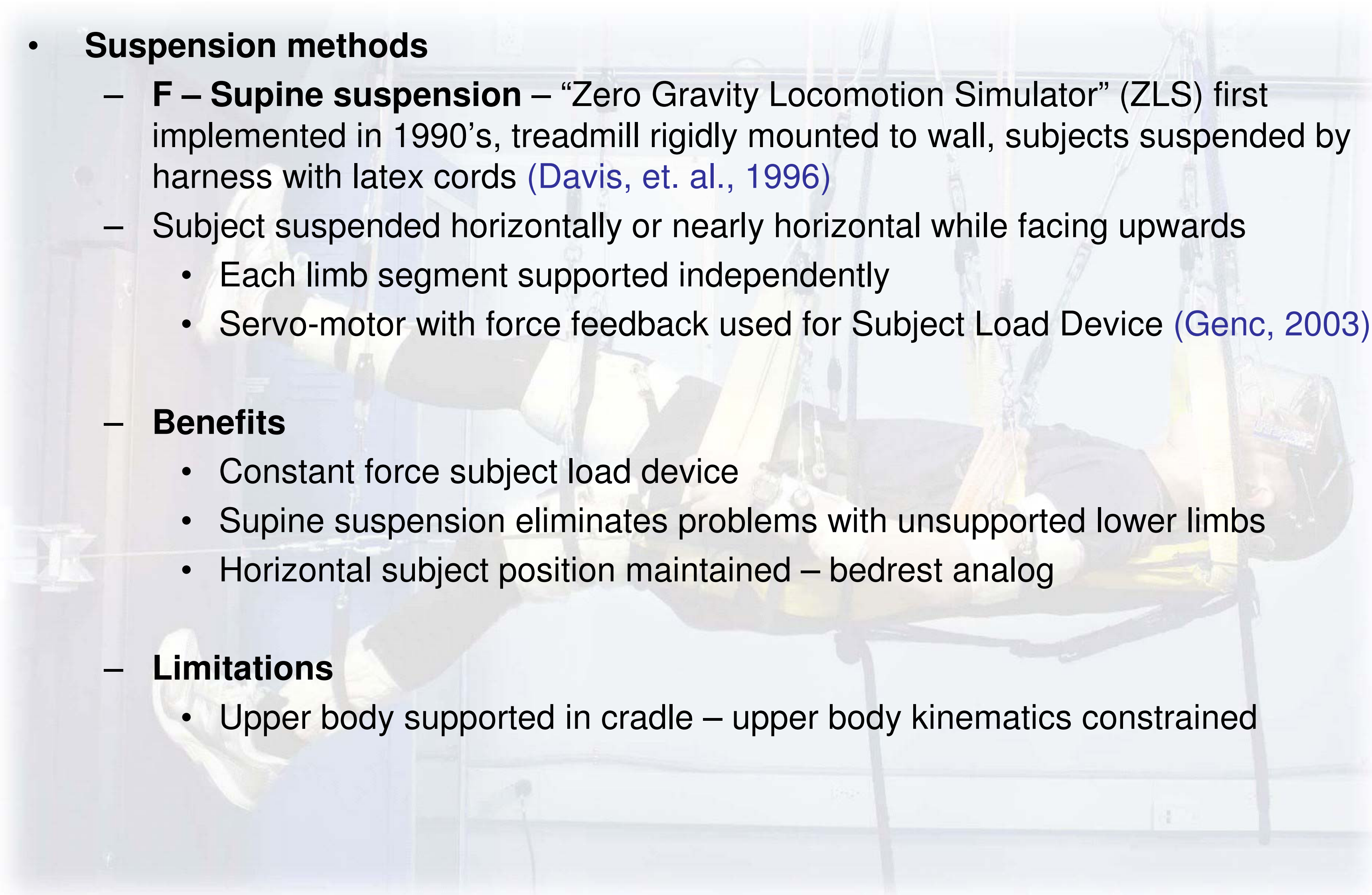


Figure 1. Various suspension techniques used (upright, side and supine). (A) Prototype of the upright technique used by Spady (1969). (B) Upright technique used by Chang et al. (2000) with applied horizontal force applied to the anterior of the subject; note the lack of lower-extremity support for both 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

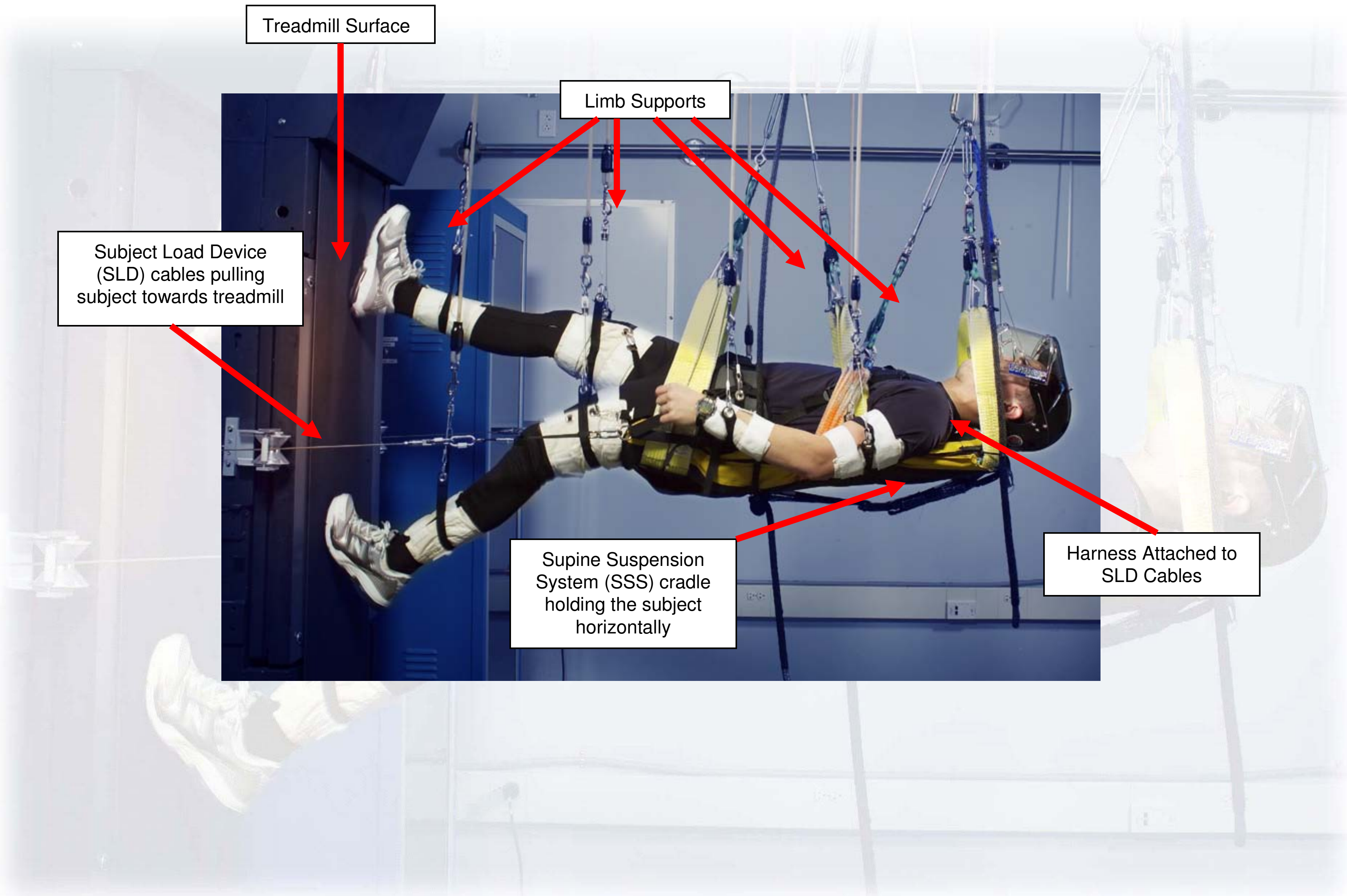
eZLS at NASA Glenn, Cleveland, Ohio

sZLS for UTMB, Galveston, Texas

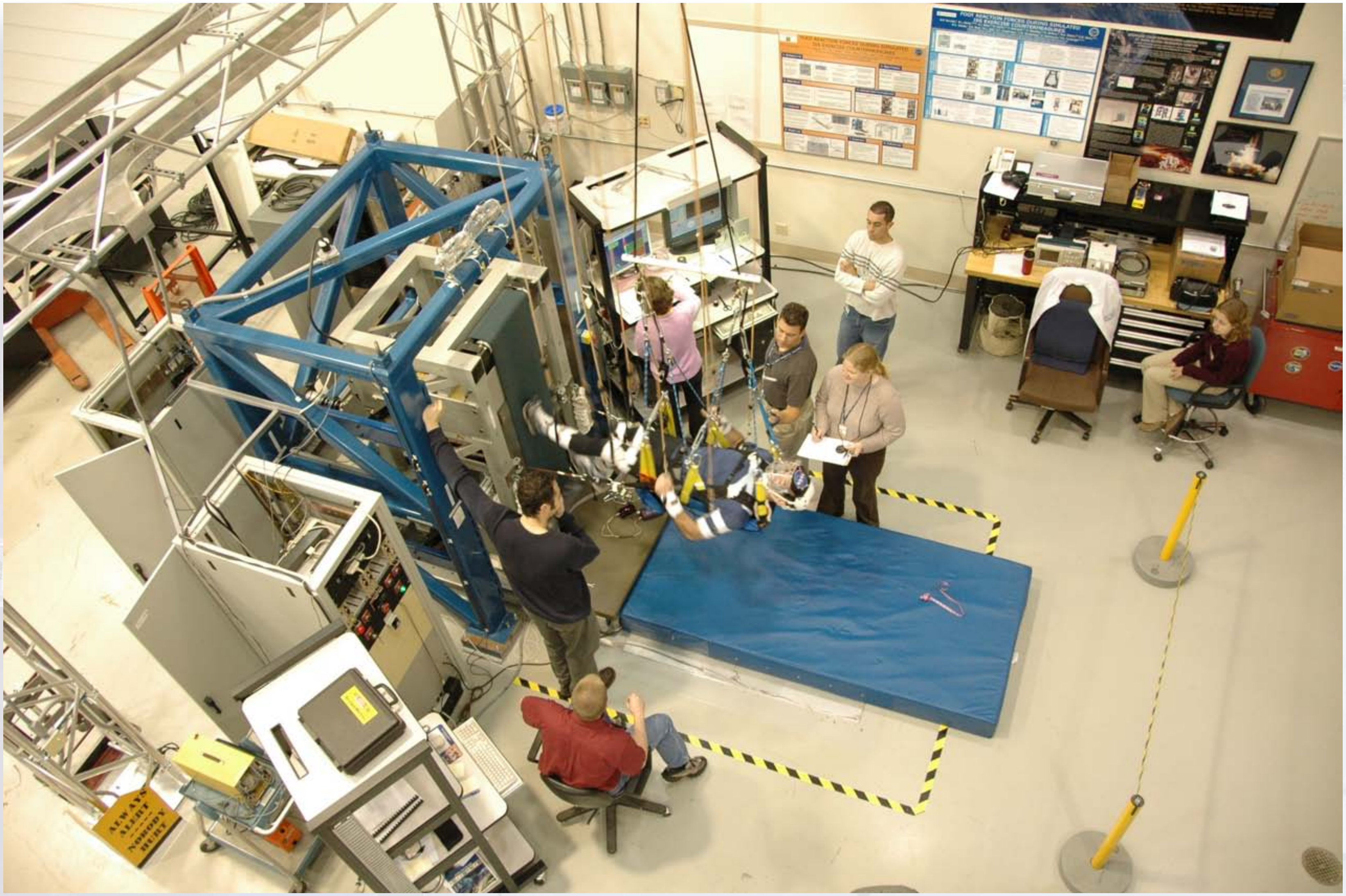
Supine Suspension Approach to Zero-G Simulation

Supine Suspension Approach to Zero-G Simulation

Zero-gravity Locomotion Simulator



Exercise Countermeasures Laboratory at NASA GRC



Differences and Similarities to Actual 0-g

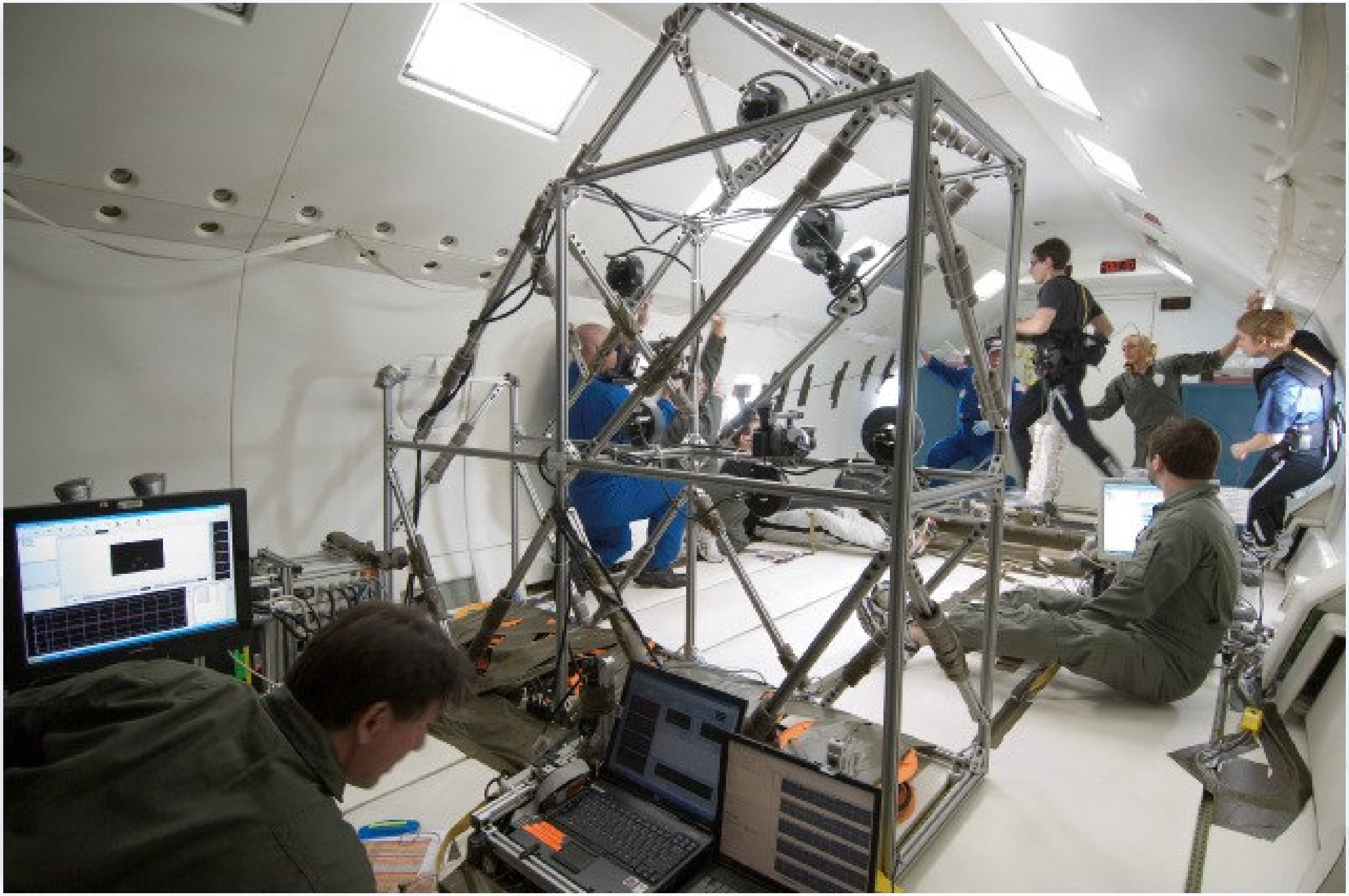
Enhanced Zero-g Locomotion Simulator (SM)

C-9 Microgravity Laboratory (AM)

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

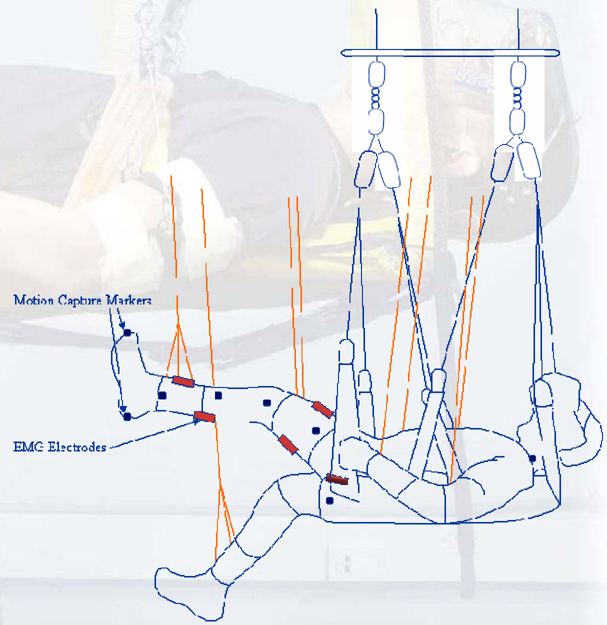
NASA DC-9 Microgravity Laboratory



Differences and Similarities to Actual Microgravity

- Activation timing differences existed between locations in all muscles except the rectus femoris.
- Tibalis anterior and gluteus maximus were active for longer durations in SM than AM during walking.

  – Researchers should be aware that subtle, but measurable differences in kinematics and leg musculature activities exist between the environments



Differences and Similarities to Actual 0-g

- 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
- Greater contact time on the SM than AM
  - Increases in contact time allows the body to experience ground reaction forces for a longer period, which is reflected by a larger impulses in SM
- During longer durations of exercise, subjects may experience a greater total magnitude of GRF on the SM than in AM
  - When prescribing exercise on the SM, a shorter period of exercise may be equivalent to a longer period in AM when increased total GRF is the primary aim.

Effect of Interface Compliance

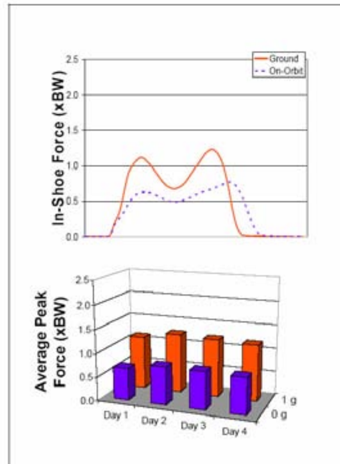


Figure 12: Average peak foot reaction forces from 25 cycles of the same subject during 4 days of free walking on Earth (red bars) and walking on the TVIS on the ISS (blue bars). Typical individual force-time curves from a single foot contact in each condition are shown above the bar graphs.

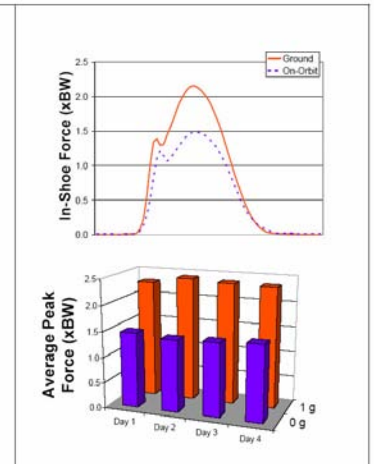


Figure 13: Average peak foot reaction forces from 25 cycles of the same subject during 4 days of free running on Earth (red bars) and running on the TVIS on the ISS (blue bars). Typical individual force-time curves from a single foot contact in each condition are shown above the bar graphs.

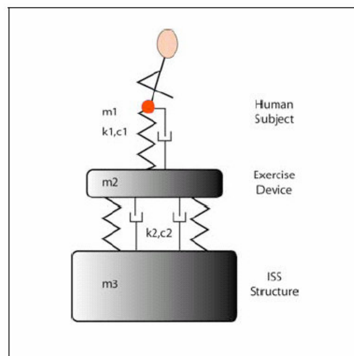


Figure 8: Simplified mass-spring-damper model of human subject, exercise device, and ISS interface.

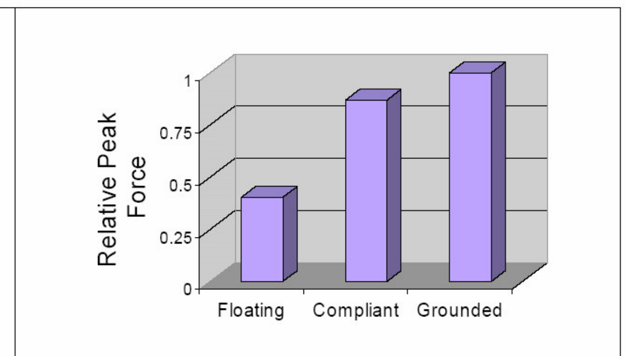
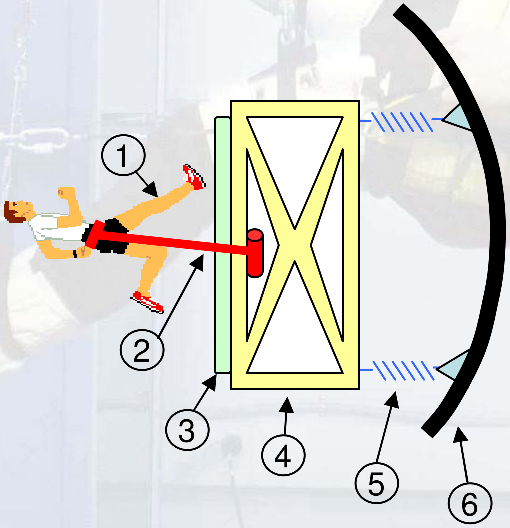


Figure 9: Predicted relative peak force at 3 Hz from the simulation of the three interface conditions.

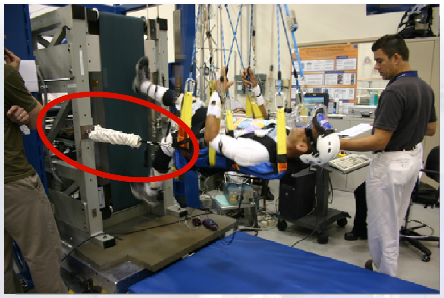
System Dynamic Modeling

The interplay between these variables will directly affect reaction force loads on subject's musculoskeletal system:

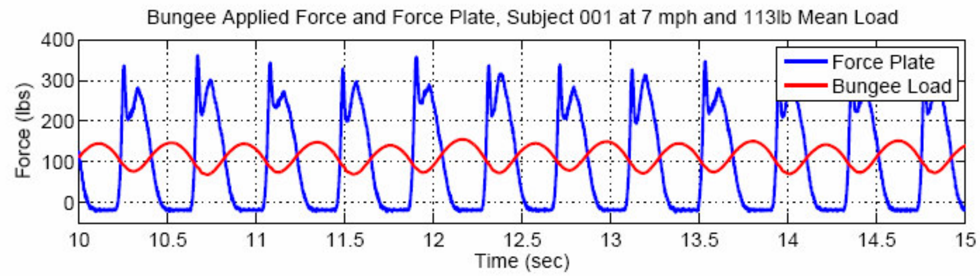
1. Biomechanics;
2. Subject Load Device (SLD);
3. Treadmill Dynamics;
4. Rack Dynamics;
5. Isolation Elements;
6. Vehicle Structural Dynamics.



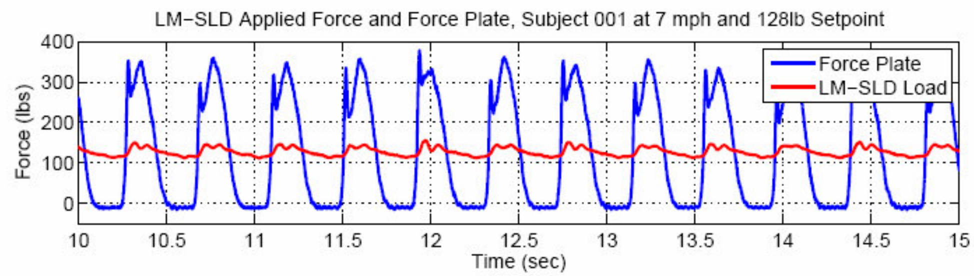
Subject Load Devices (Gravity - Replacement)

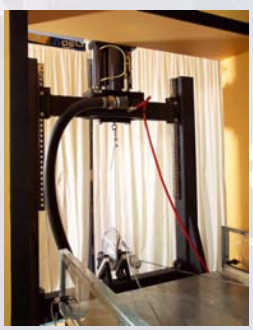


Series Bungee System (SBS) bungees

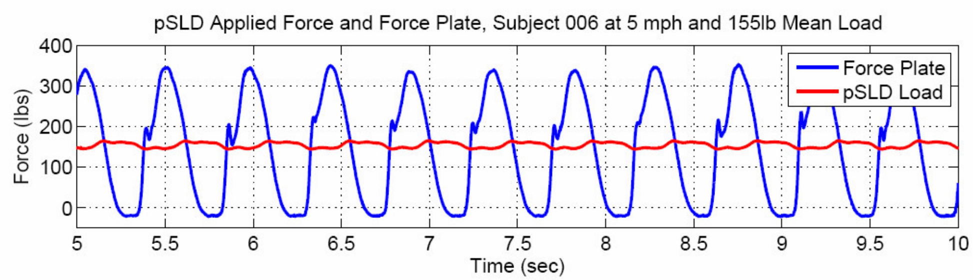


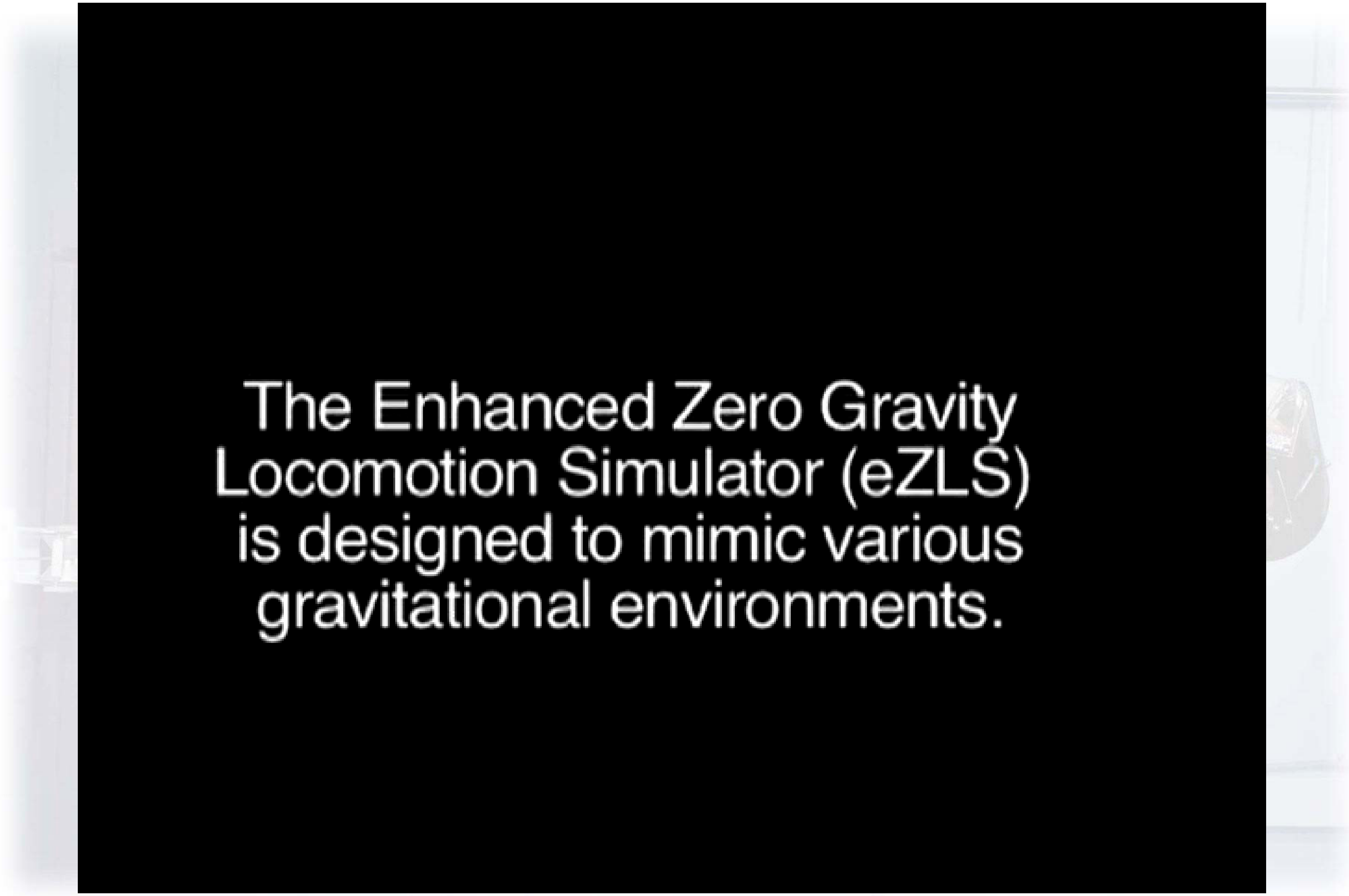
Linear Motor SLD (LM-SLD)





Pneumatic (P-SLD)

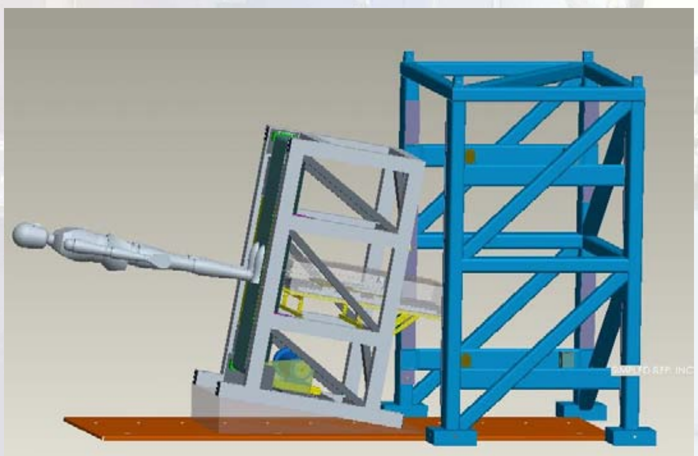



The Enhanced Zero Gravity
Locomotion Simulator (eZLS)
is designed to mimic various
gravitational environments.

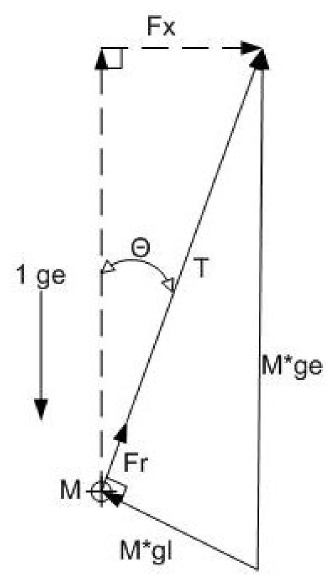
Lunar gravity ($1/6^{th}$-g) simulation

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)

Lunar gravity ($1/6^{th}$-g) simulation

- Play movies
  - ZLS
  - On-orbit TVIS
  - Compliant treadmill
  - Lunar-g simulation with SLDs
  - Lunar-g 10 deg. Tilt
  - Lunar-g Carry Load

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.