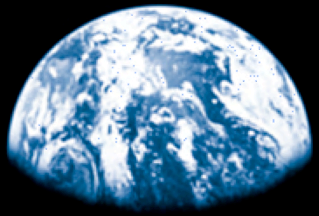
An Astronaut 'Bio-Suit' System for Exploration Missions



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NIAC Annual Meeting, Broomfield, Colorado

10 October 2005

Image, © Michael Light, Full Moon

Industry Partners

Trotti & Associates, Inc. (TAI)

TAI is a design consulting firm helping private and public organizations visualize and develop solutions for new products, and technologies in the areas of Architecture, Industrial Design, and Aerospace Systems.

Award-winning designs for: Space Station, South Pole Station, Underwater Habitats, Ecotourism. (Phase I and II)

Midé Technology Corporation is a R&D company that develops, produces, and markets High Performance Piezo Actuators, Software, and Smart (Active) Materials Systems; primarily for the aerospace, automotive and manufacturing industries.

Advisory Board

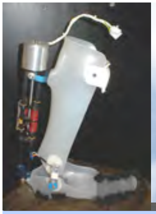
Dr. Chris McKay, expert in astrobiology, NASA ARC.
Dr. John Grunsfeld, NASA astronaut.
Dr. Cady Coleman, NASA astronaut.
Dr. Buzz Aldrin, Apollo 11 astronaut.

Bio-Suit Design Concepts

- **Human Performance: Background**
    - Augmented Human Locomotion
    - Partial Gravity
    - Human EVA History
    - Spacesuit Mobility Database: Joint Torque-Angles (Schmidt, Frazer)
    - Mathematical Models of Astronauts and Spacesuits (Schaffner, Rahn)

- **Revolutionary Spacesuit Design: Bio-Suit System**
    - Mechanical Counter Pressure Skin Suit

- **Results**
    - **Human Modeling**
    - **Prototypes**
    - **Visualizations**
    - **Mock-Up**
    - **Educational Outreach**

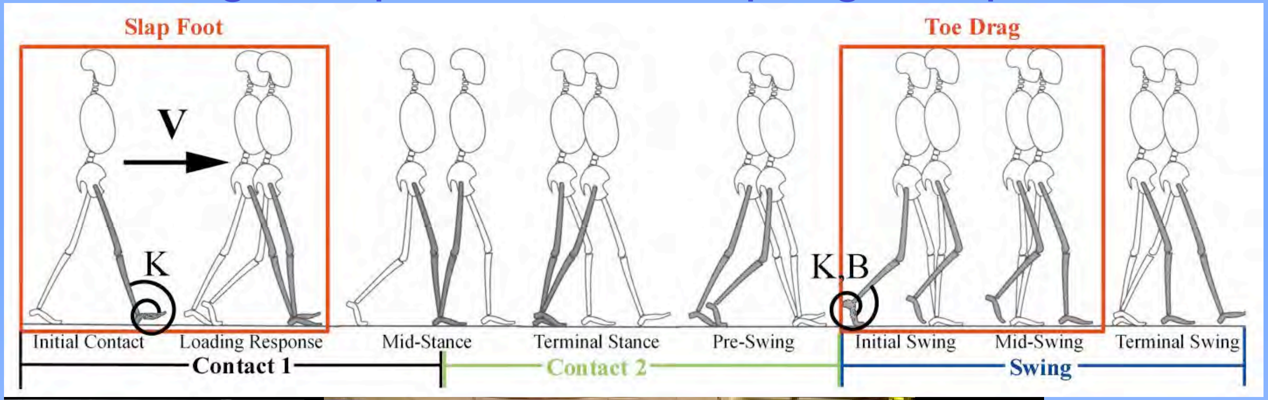


Augmented Human Performance

Problem: Drop foot, pathology (stroke, CP, MS)

Variable-impedance control active ankle device

- Contact 1: Adaptive biomimetic torsional spring - min. slap
- Contact 2: Minimized impedance
- Swing: Adaptive torsional spring-damper to lift foot



Next: Exoskeleton

-Harness, hip bearing, fiberglass members, ankle

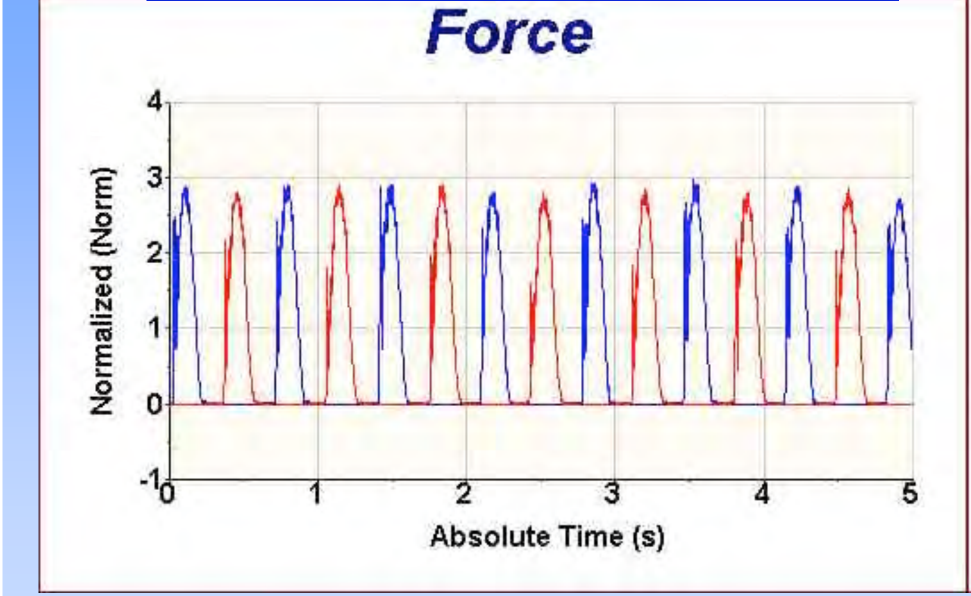
-Fiberglass spring mechanism provides energy

Blaya, J.A., Newman, D.J., Herr, H.M., “Comparison of a variable impedance control to a free and rigid ankle foot orthoses (AFO) in assisting drop foo *Proceedings of the International Society of Biomechanics (ISB) XIXth Congress*, Dunedin, New Zealand, July 10, 2003.

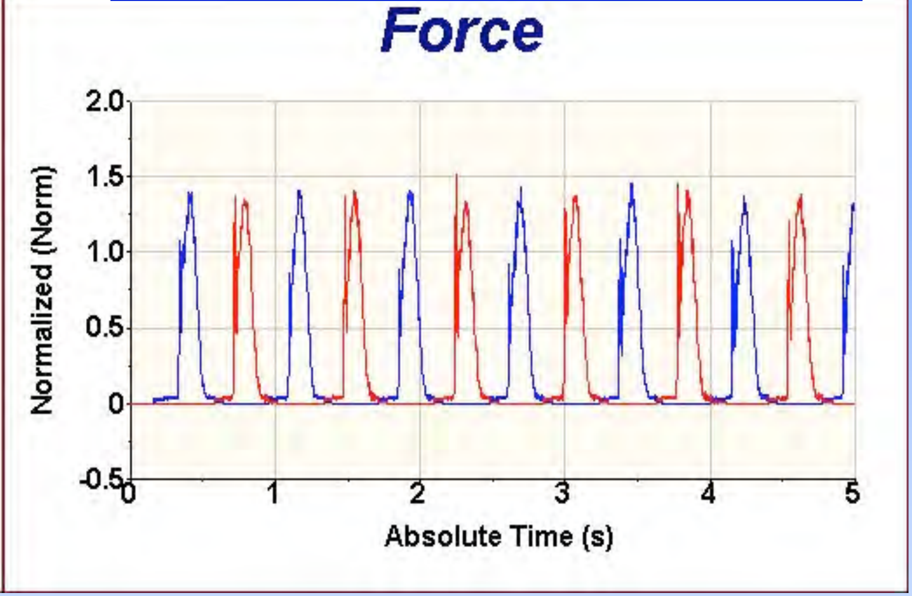
Results: Partial Gravity Locomotion

MIT
MoonWalker
1-G Simulation

MIT
MoonWalker
Martian Simulation



Force

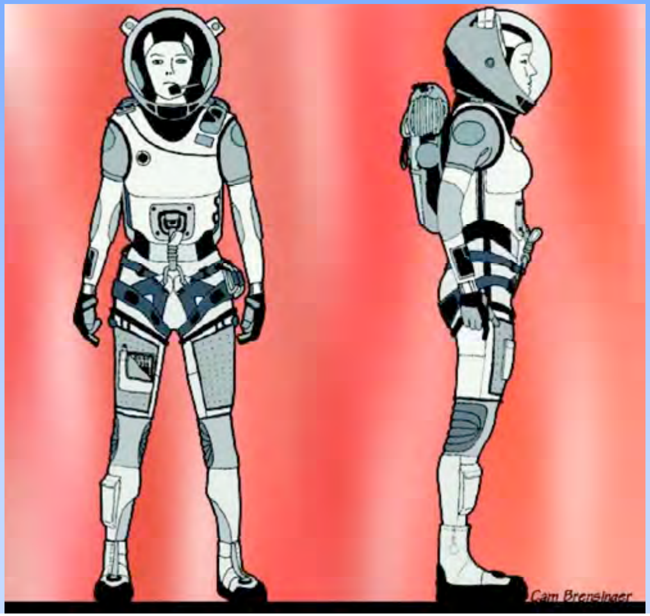


Force

Space Suit Design: Motivation

- Extravehicular Mobility Unit (EMU)
  - **Designed for weightlessness**
  - **Pressurized suit (29 kPa, 4.3 psi)**
  - **Life support system (O_2, CO_2, etc.)**
  - **2 pieces: pants, arms & upper torso**
  - **Donning and doffing are highly involved**
  - **Adequate mobility for ISS**
  - **NOT a locomotion/exploration suit**

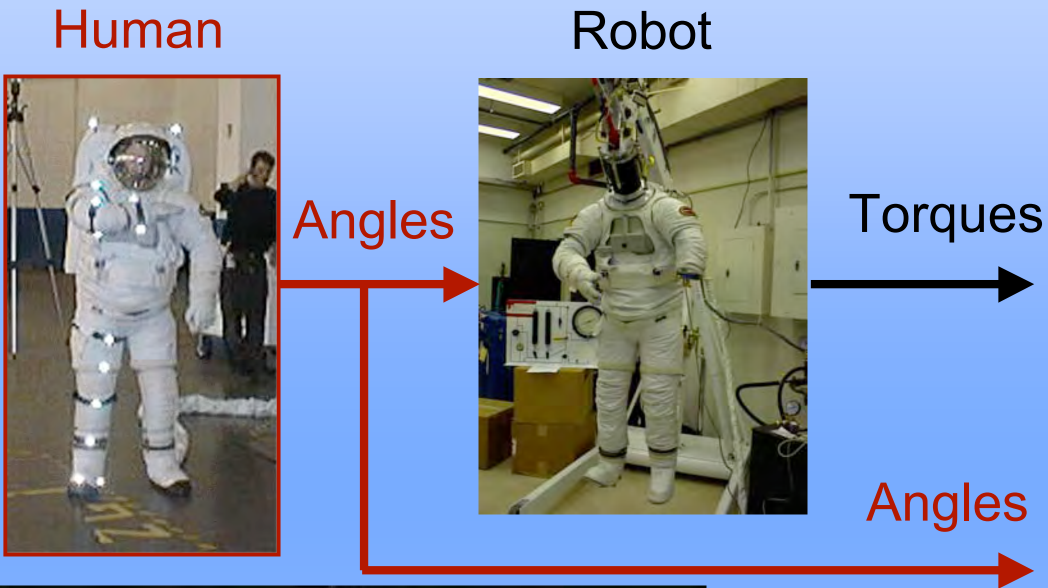
- Mechanical Counter Pressure (MCP)
  - **Skin suit compared to a pressure vessel**
  - **Greater flexibility, dexterity**
  - **Lightweight**
  - **Easy donning and doffing**



Cam Brensinger

Human/Robot Database

- Human, robot, human suited, & robot suited
- 11 simple motions isolating individual degrees of freedom
- 9 complex motions:
  - Overhead reach
  - Cross-body reach
  - Low reach
  - Locomotion
  - Step up 15 cm (6 in)



Human

Robot

Angles

Torques

Angles

M. Tallchief

Robotic Space Suit Tester (RSST)

The Art of Engineering!

Duchamp

Mark Sowa/NASA

Synthesis of Energetics

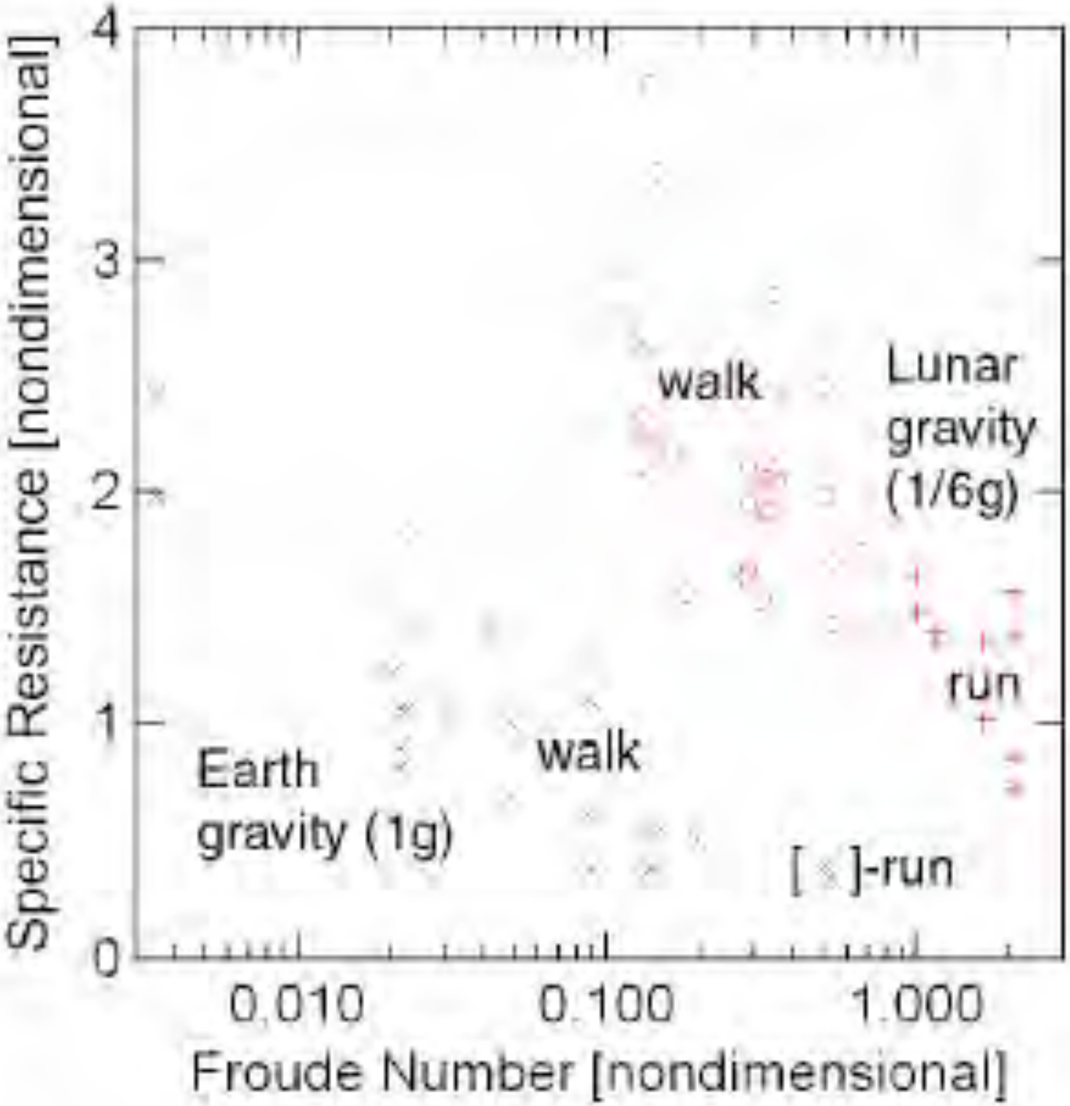
Hypothesis:

Fast running (Fr>1) has lower specific resistance than walking or slow running (Fr<1).

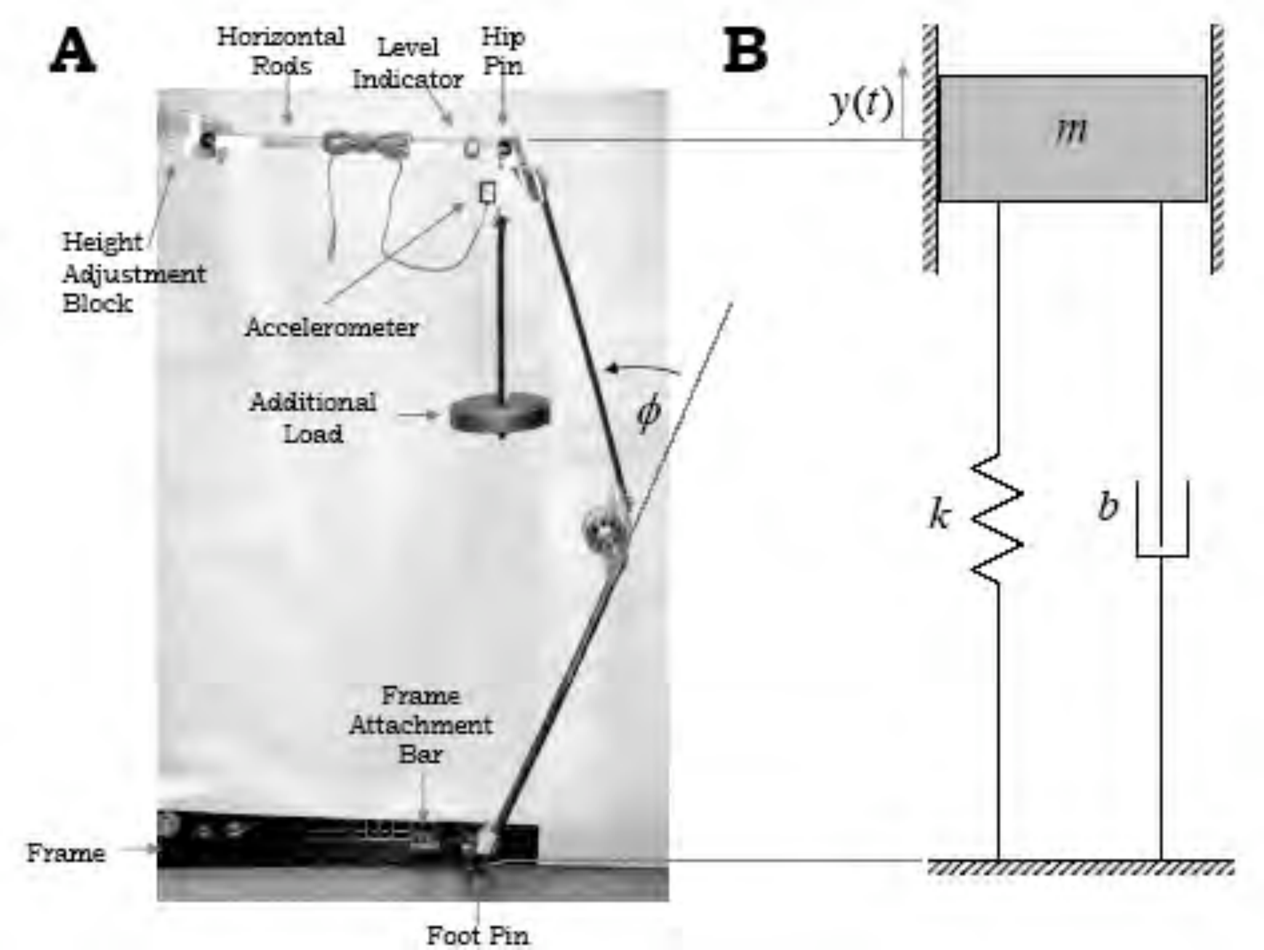
Performed a two-sample T-test.

Significance:

Means are different ($p<0.0005$).

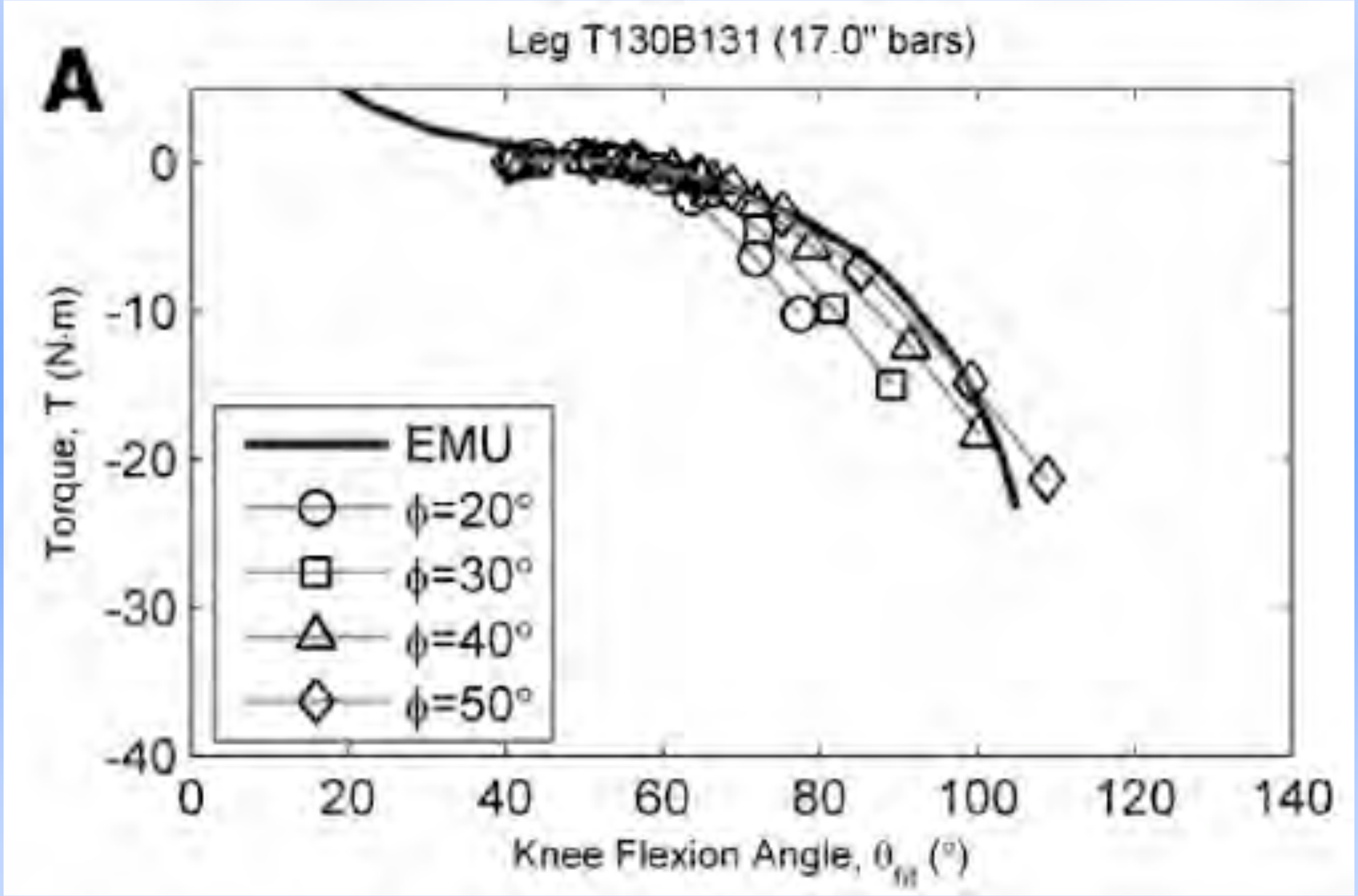


Designing an Exoskeleton

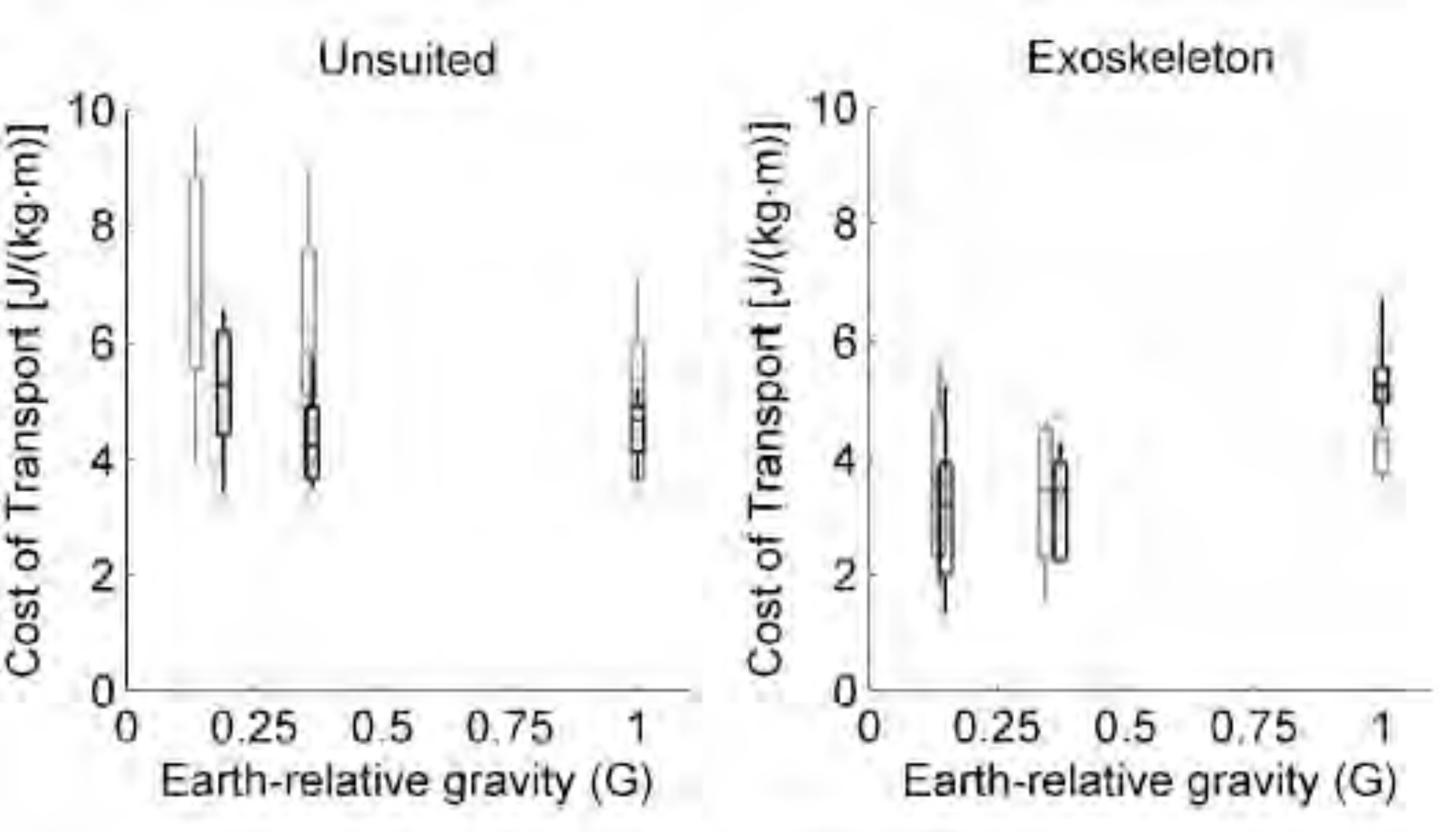



[redacted]

Joint Torque: EMU & Exoskeleton



Exolocomotion: Cost of Transport [J/(kg·m)]



Walk (Gray), Run/walk (Dotted), Run (Black)

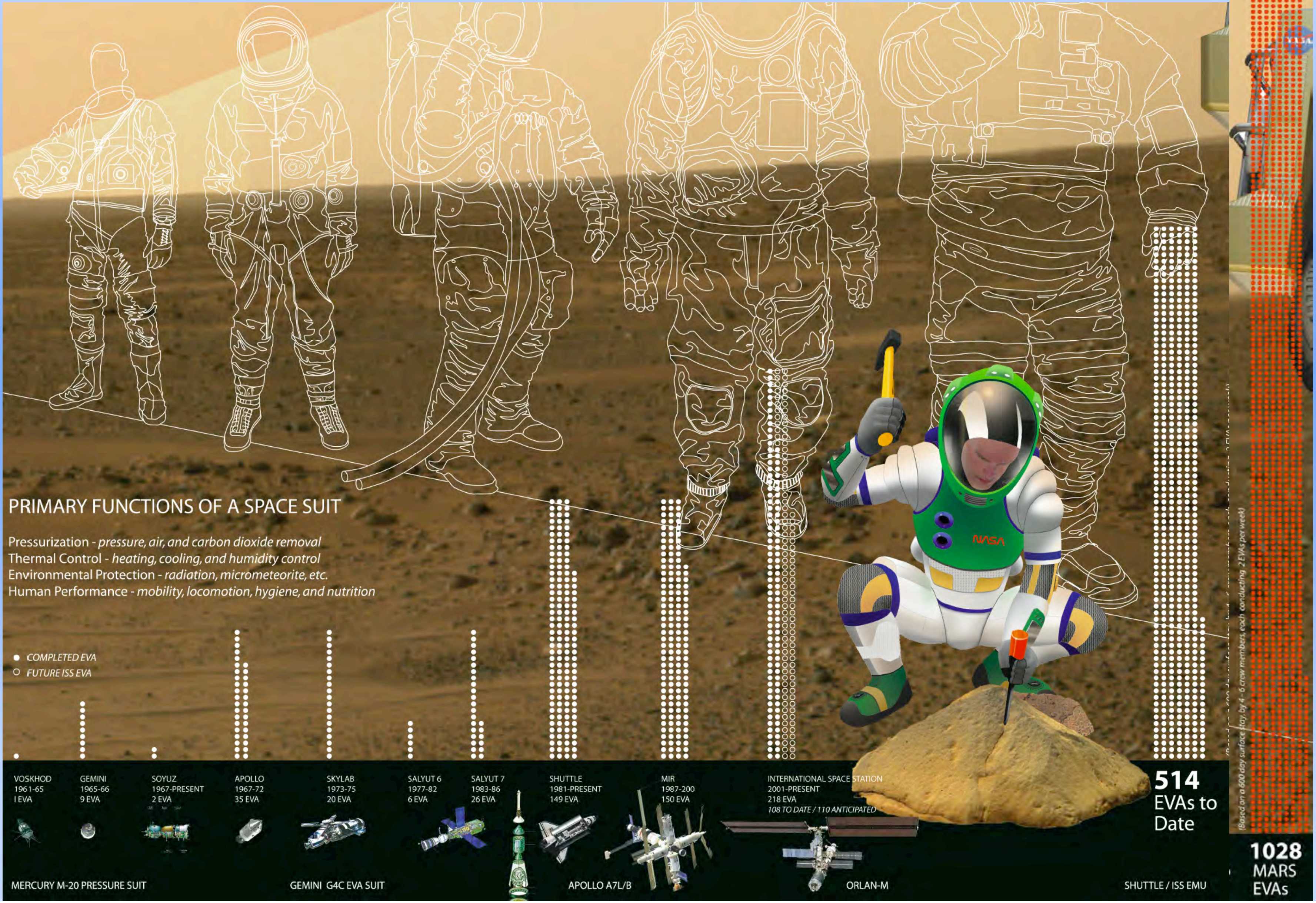
Exoskeleton & Space Suit Comparison

- Similarities
  - Similar knee joint angles
  - High-recovery: springs in parallel w/ legs
  - Cost of Transport in Reduced G running ≤ than unsuited
- Differences
  - Poor ankle & hip mobility in spacesuit
  - Excellent mobility in Exoskeleton (3 dof)
  - Cost of Transport is Elevated in space suits

- Simulated space suit knee joint via an exoskeleton.
- Explained metabolic cost of suited walking & running.
- Evidence of an optimal space suit torque.
- Evidence that energy recovery plays a key role.

Creative Spacesuit Design

Human EVA History



PRIMARY FUNCTIONS OF A SPACE SUIT

Pressurization - *pressure, air, and carbon dioxide removal*
Thermal Control - *heating, cooling, and humidity control*
Environmental Protection - *radiation, micrometeorite, etc.*
Human Performance - *mobility, locomotion, hygiene, and nutrition*

Revolutionary Design: *Bio-Suit System*

Bio-Suit multiple components:

- Mechanical Counter Pressure (MCP) Bio-Suit layer
- A pressurized helmet
- Gloves and boots
- Possible hard torso or frame
- A life support backpack

Components: interchangeable & easy to maintain and repair

Idea: Custom-fit *skin suit* to an individual human/digital model

$W = Wp + We$

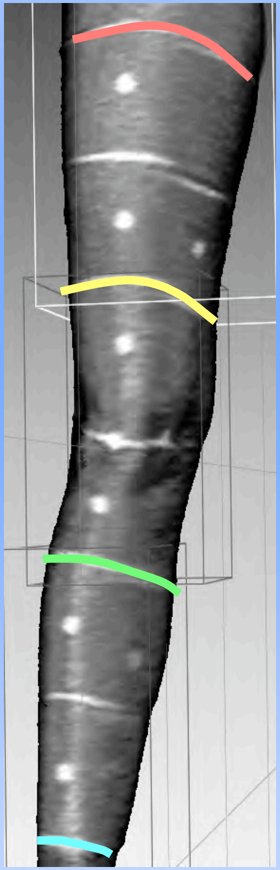
Wp - Minimize through MCP design

We - Bending (design) and Strain Energy (min. or max E)

Results → MCP Requirements

MCP Tension

~2 kN/m



0.8 kN/m

Knee Surface Area

16%

In knee region, when leg flexes from 0 to 90 degrees

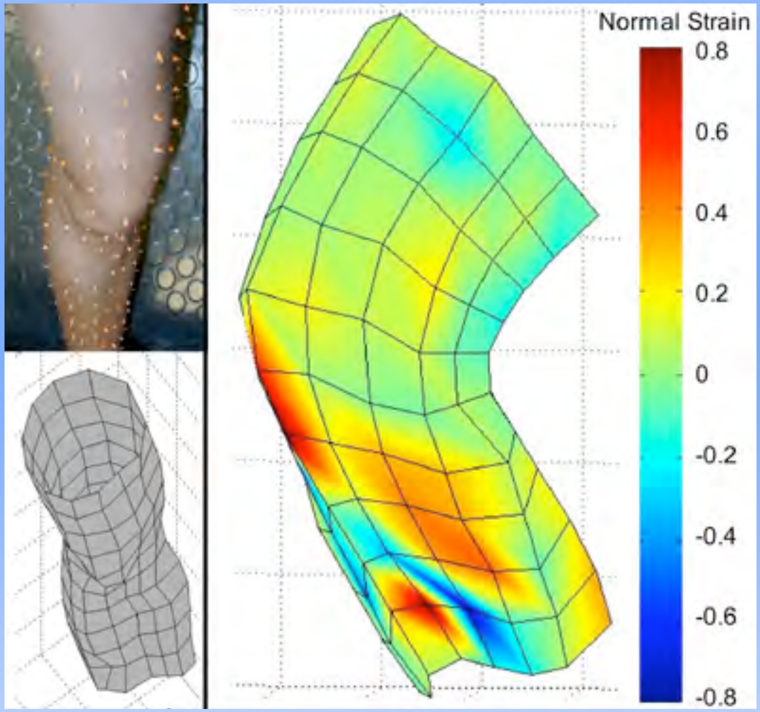
Knee Volume

18%

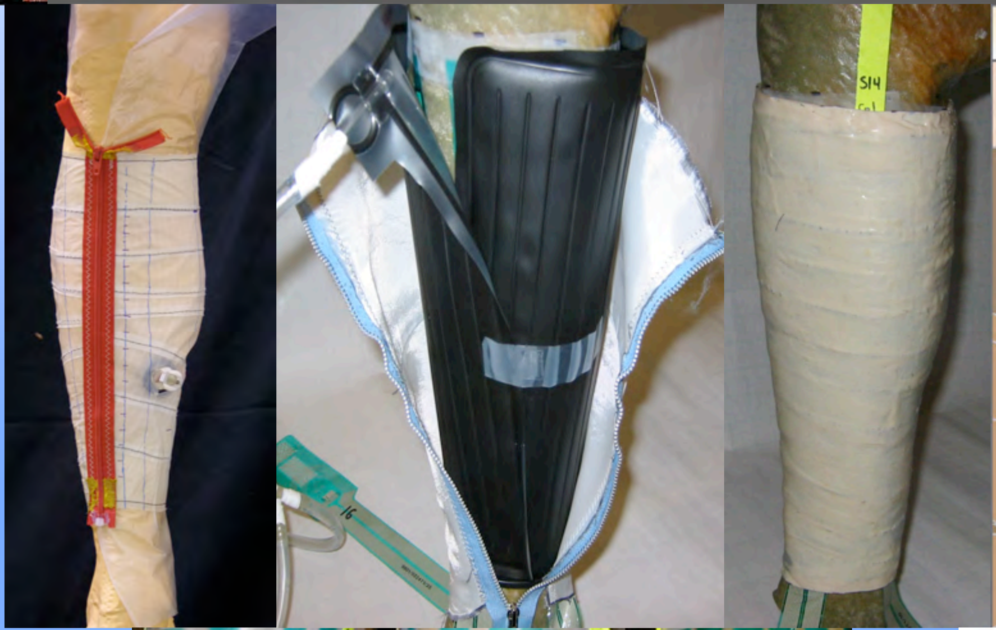
In knee region, when leg flexes from 0 to 90 degrees

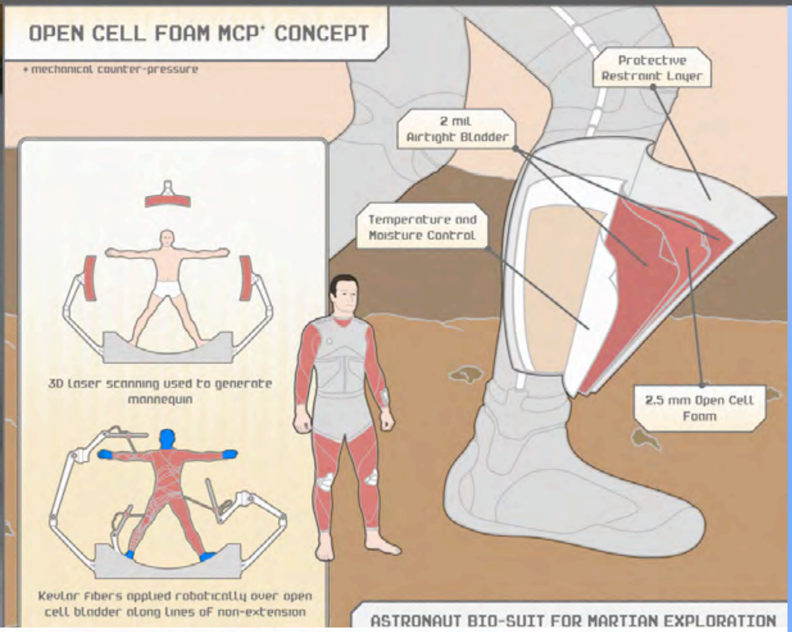
Skin Strain Field Mapping

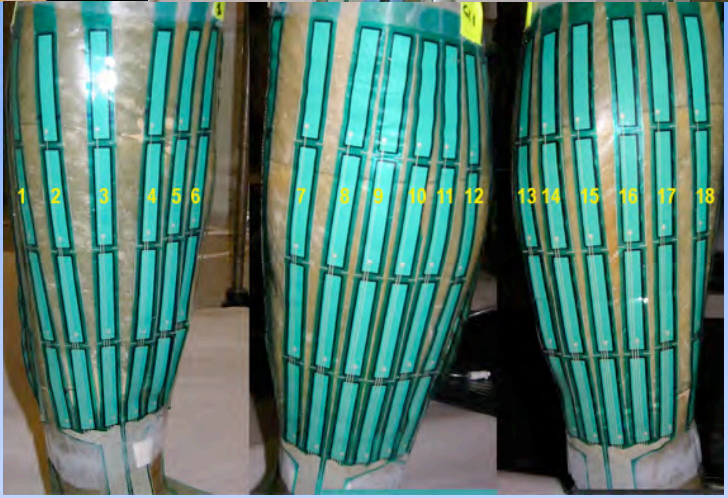
Circumferential Strain



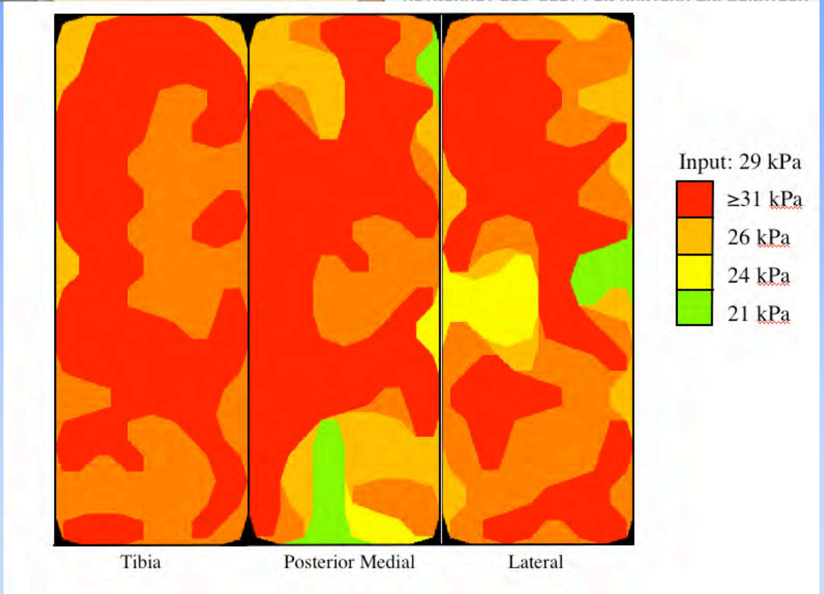
Results: MCP Initial Prototypes





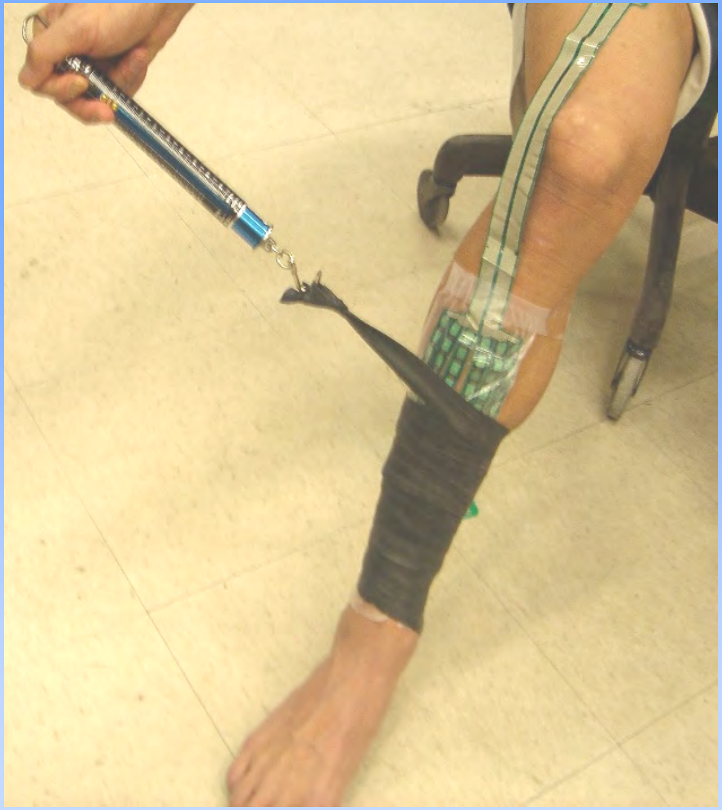


Tibia **Medial-Posterior** **Lateral**



Results: Elastic Bindings

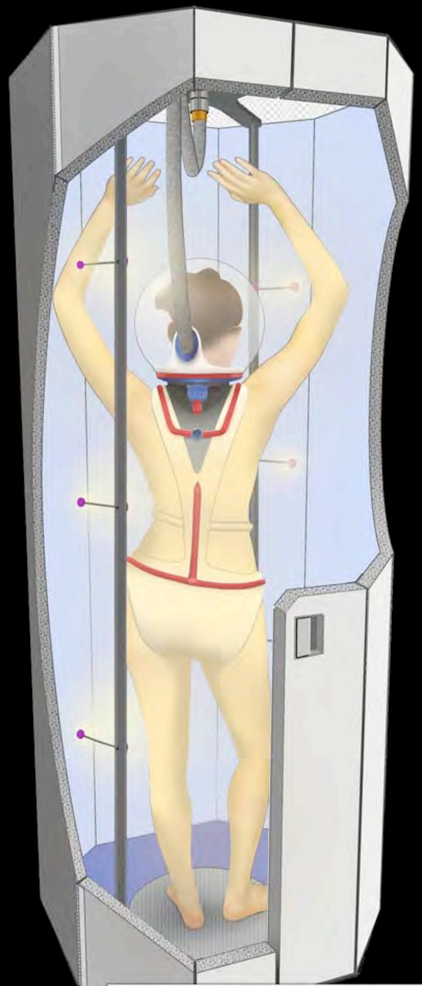
- Maximum mobility
- Active materials (de-couple donning/doffing)
- Shape memory polymers (large max. strain)



Results: Minimum Energy Bio-Suit

- Maximizing mobility
- Minimizing energy

Technology Roadmap: Design



Application of Full-Body Electrospun Bio-Suit
Technology Developed at Natick Soldier Center
Artwork by Cam Brensinger
T02

3D Laser Scanning

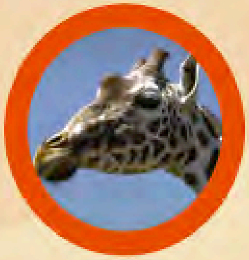
D 1980 – Patented 3D rapid digitizing technology
M 1990 – General purpose 3D scanning systems
P 2005 – Bio-Suit analysis technique for skin strain field mapping

3D and Conductive Textiles

D 1950 – 3D knitting machine for gloves
M 1990 – 3D knit stockings produced, wearable computing proposed
P 2008 – 3D full body garments, conductive polymer wearable clothing

Electrospinlacing

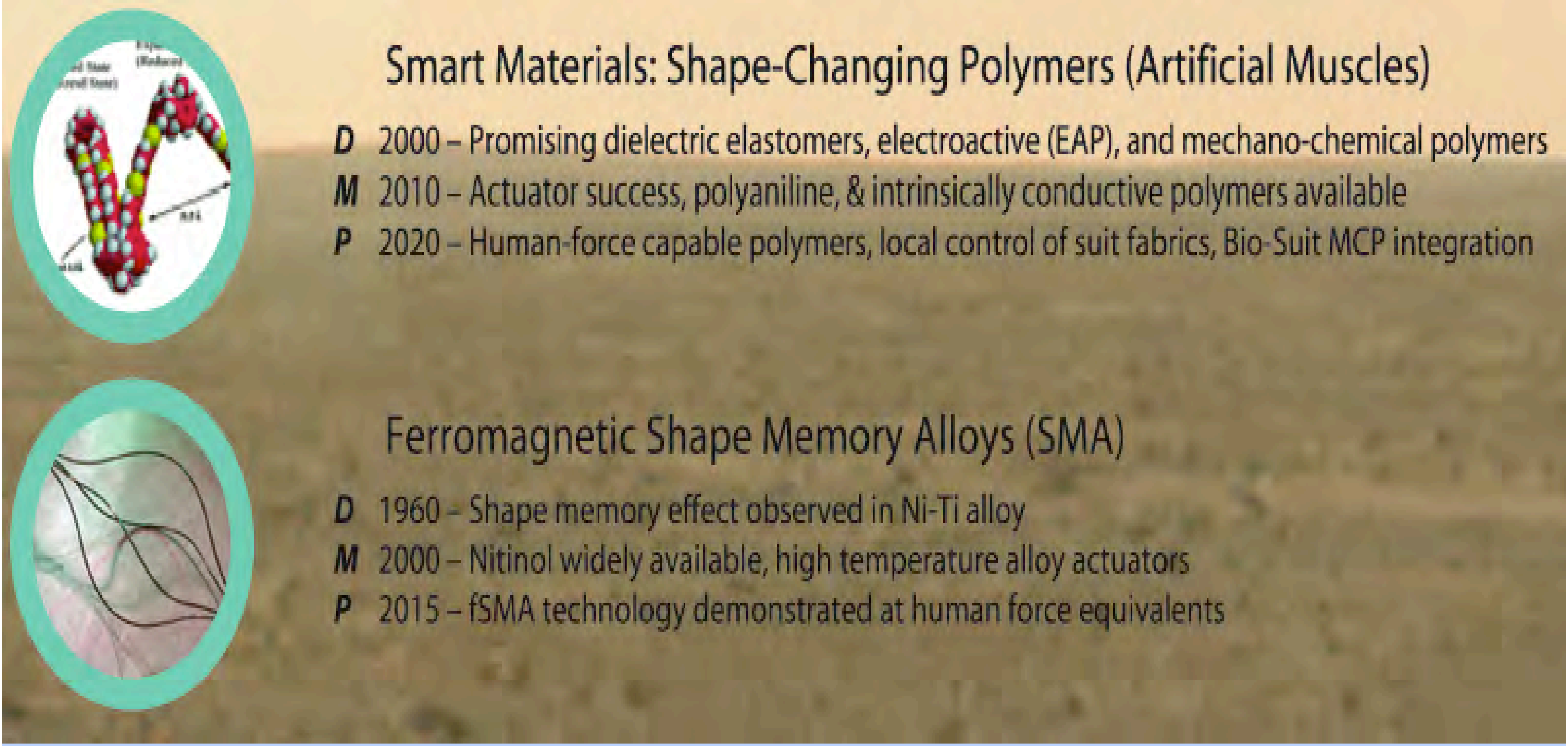
D 1940 – Electrospinlacing proposed and patented
M 2003 – Electrospun nano-fibers realized, anisotropic spray capability proposed
P 2015 – 3D electrospun polymer Bio-Suit garment with specified mechanical properties



Design from Nature

D 4 Billion BC – Evolution on Earth, Nature's mysteries unfold
M 2000 – Biomimetic design enthusiasm, multidisciplinary approaches
P 2020 – Realization of giraffe counterpressure mechanism for g-suits & Bio-Suit

Technology Roadmap: Pressure



Smart Materials: Shape-Changing Polymers (Artificial Muscles)

D 2000 – Promising dielectric elastomers, electroactive (EAP), and mechano-chemical polymers
M 2010 – Actuator success, polyaniline, & intrinsically conductive polymers available
P 2020 – Human-force capable polymers, local control of suit fabrics, Bio-Suit MCP integration

Ferromagnetic Shape Memory Alloys (SMA)

D 1960 – Shape memory effect observed in Ni-Ti alloy
M 2000 – Nitinol widely available, high temperature alloy actuators
P 2015 – fSMA technology demonstrated at human force equivalents

Technology Roadmap: 2010

Smart Gels & Fluid Filled Bladders

D 1970-80 – Radio Frequency (RF) welding for polyurethane bladders, smart gels discovered
M 2005 – Thermal control for divers, MEMS valves and actuators make pressure bladders practical
P 2010 – Electronically activated smart gels and bladders for Bio-Suit body concavities

Biomedical Monitoring

D 1990 – Prototypes for MEMS medical "Lab-on-a-chip"
M 2005 – Perfusion monitors used in BioSuit prototype to assess edema formation
P 2015 – Astronaut specific miniaturized monitoring systems embedded in Bio-Suit

Human Power Harvesting

D 1998 – Shoe designs incorporate piezoelectrics to generate 10 mW average power
M 2001 – EAP energy harvesting boot generates 2 W of power
P 2010 – Energy harvesting becomes more mature, integrated into Bio-Suit for power assist

Bio-Suit Mock Up

Outreach: Knowledge Station

Explore Space!

The Knowledge Station is an educational portal where you can Explore, Interact, and Learn.

Explore the International Space Station (ISS), Mars, and Europa.

Interact through the gestural interface to exercise on the ISS, explore Mars with Max in an advanced spacesuit, or teleoperate M. Tallchief (a robot) on Jupiter's moon of Europa.

Learn about the world of NASA and NSBRI's science and technology breakthroughs.

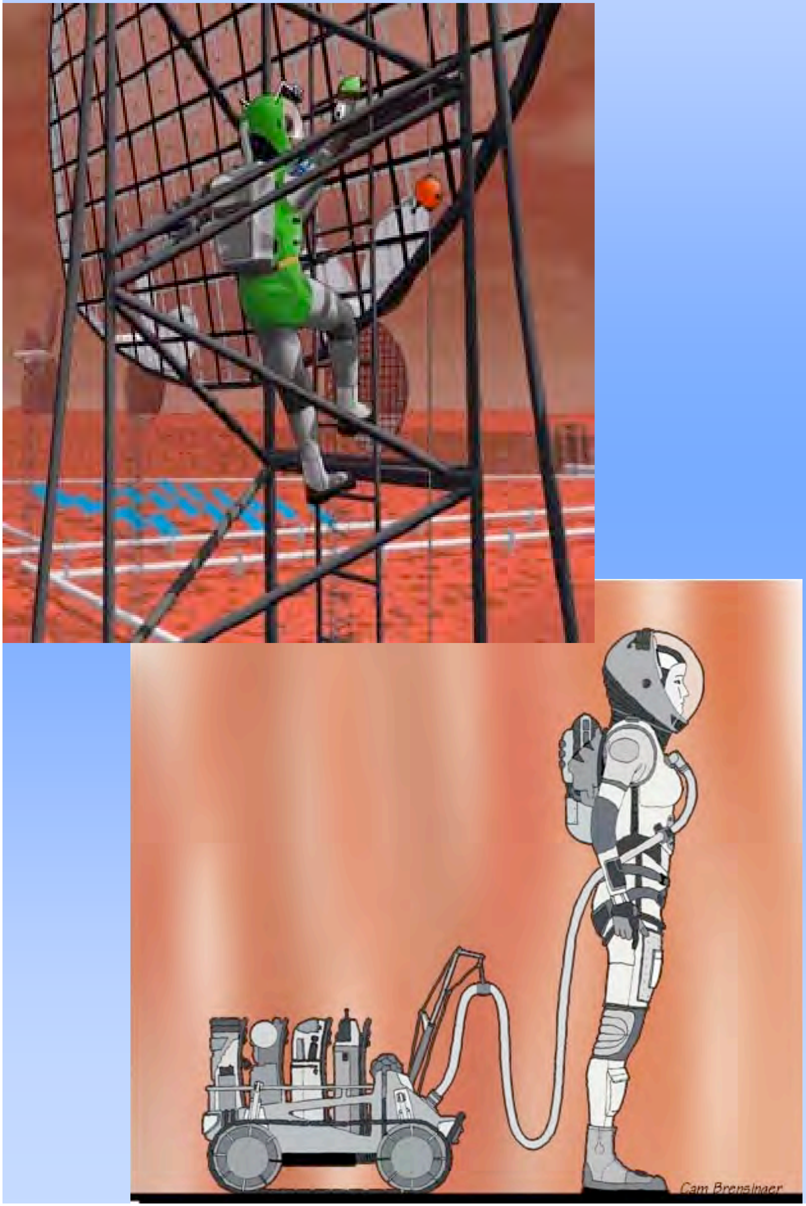
Virtually Travel in the Knowledge Station – an educational environment with freestanding mobility designed for museums and public outreach. Our outreach vehicle is designed for 1-2 users and shares a global vision for peaceful space exploration and hopes to inspire the imaginations of future astronauts.

Outreach and Education

Explore Space: Knowledge Station

- Interactive Multimedia Station
- High-Impact Design
- 1-2 users
- Bio-Suit System Theme: Max the Martian Explorer
  - Life on Mars?
  - Moby Music
- Deployment at MIT, museums & public spaces
- Educational assessment

Advisory Board & Second Year Reviews



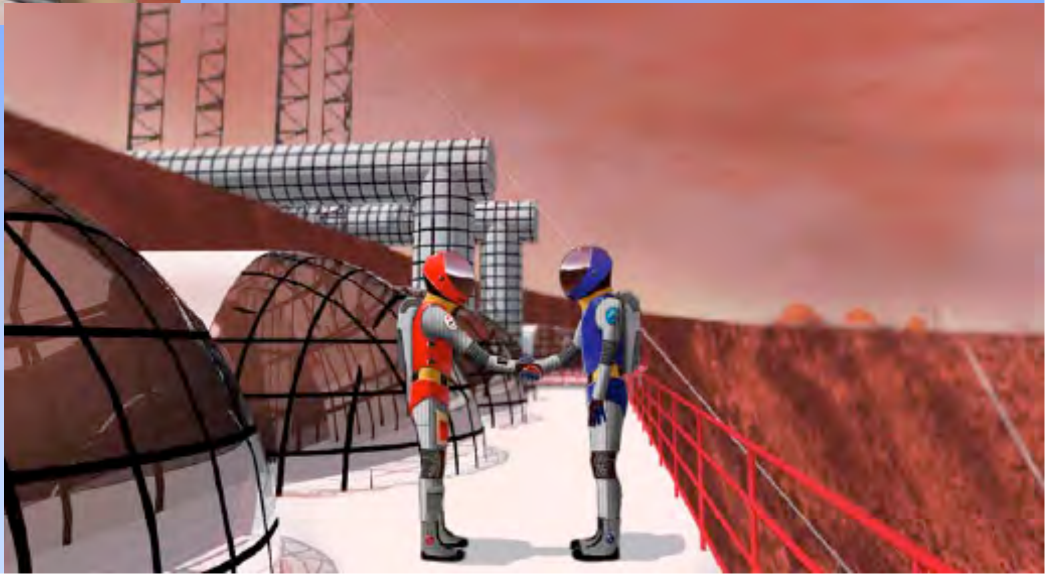
- Bio-Suit MCP feasibility
- Exploration Systems
- Human Modeling
- Human Performance
  - Pathologies, Rehabilitation
  - Traverse & Mission Planning
  - Human Robotic Interaction

- Executive Summary
- Phase II Report
- Prototypes
- Posters/Publications
- Visualizations
- Please See Proceedings at http://mvl.mit.edu/EVA/biosuit.html

Visualizations and Press

ABC
BBC/RDF
Boston Business Forward
Boston Globe
CNN
Discovery Film
Folha de S.Paulo
GEO (German design)
Russian GEO
Leonardo
Harvard-MIT Connector

Men’s Journal (centerfold)
Metropolis
National Geographic Film
NPR
New Scientist
Popular Science (cover)
Space.com
Technology Review
Numerous newspapers and on-line



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2. Carr, C.E., Newman, D.J., and Hodges, K.V., "**Geologic Traverse Planning for Planetary EVA**," 33rd International Conference on Environmental Systems, Vancouver, Canada, 2003.
3. Saleh, J.H., Hastings, D.E., Newman, D.J. “**Flexibility in system design and implication for aerospace systems**,” Acta Astronautica 53 (2003) 927-944.
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6. Saleh, J.H., Hastings, D.E., Newman, D.J. “**Weaving time into system architecture: satellite cost per operational day and optimal design lifetime**,” Acta Astronautica 54 (2004) 413-431.
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8. Carr, C.E, Newman, D.J. **When is running more efficient than walking in a space suit?** #2005-01-2970, AIAA and SAE International Conference on Environmental Systems (ICES 2005), Rome, Italy, July 2005.
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Thank You!

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