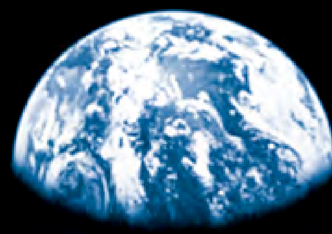
An Astronaut 'Bio-Suit' System for Exploration Missions



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NIAC NASA Institute for Advanced Concepts

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)

MIDE TECHNOLOGY CORPORATION

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.

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Dr. Chris McKay, expert in astrobiology, NASA ARC.
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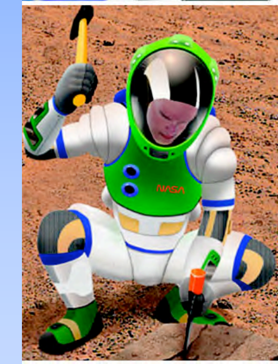
MIT Advanced EVA Research

- **Astronaut EVA Performance**
  - Human/Robotic database
  - Spacesuit Modeling (Hysterisis, Physics-Based, Dynamic Analysis)
  - Energetics and Biomechanics – Design Requirements
  - Mission Planning and Geological Traverse Analysis
- **Space Suit Simulator – Exoskeleton**
- **Advanced Spacesuit Design: Bio-Suit MCP System**
  - Human Modeling & Requirements Definition
  - Bio-Suit MCP Feasibility and Prototypes
- **EVA Systems Flexibility and Uncertainty Analysis**
  - EVA community and EVA system are/should be at the center of the U.S. Vision for Space Exploration

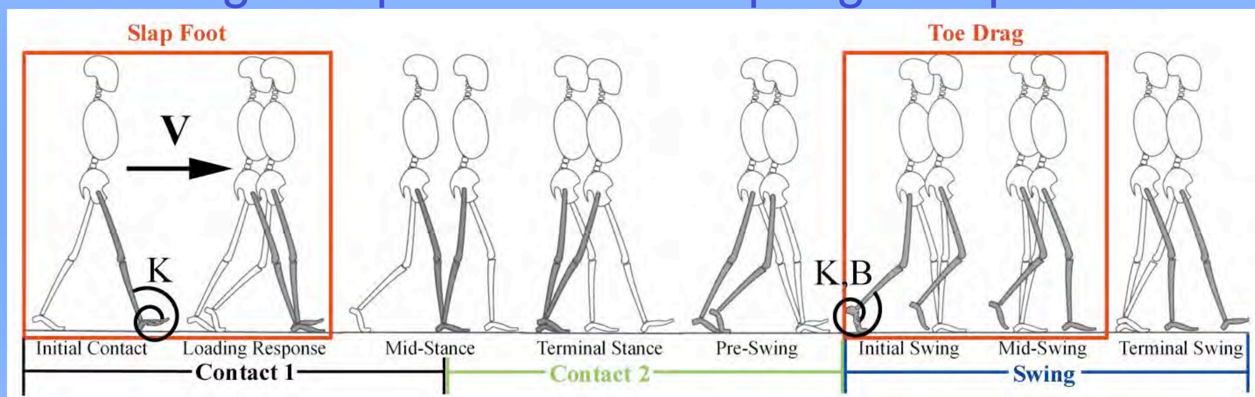


Augmented Human Performance

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



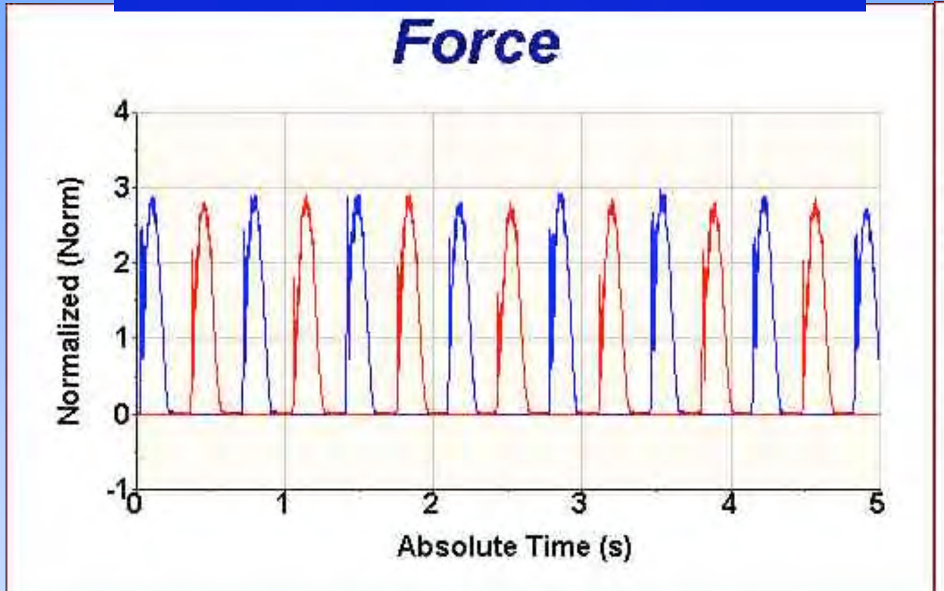
Next: Exoskeleton

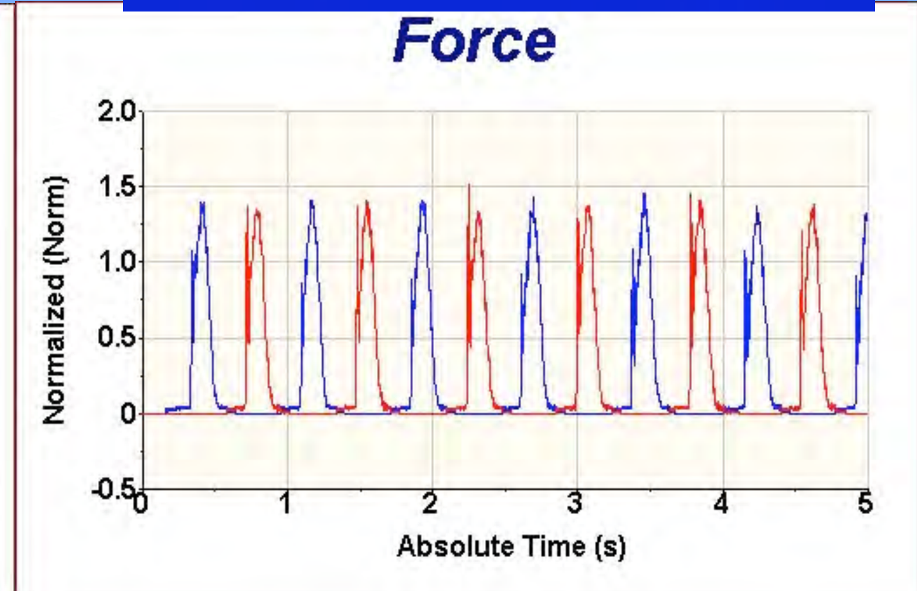
-Harness, hip bearing, fiberglass members, ankle

-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

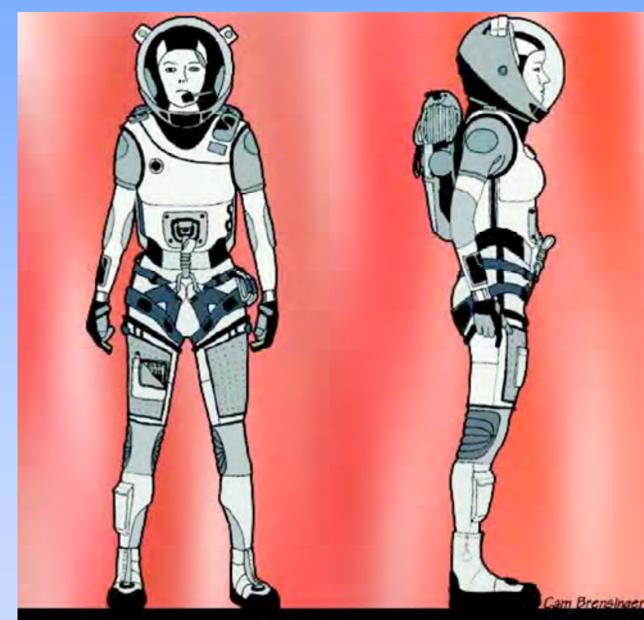




Space Suit Design: Motivation

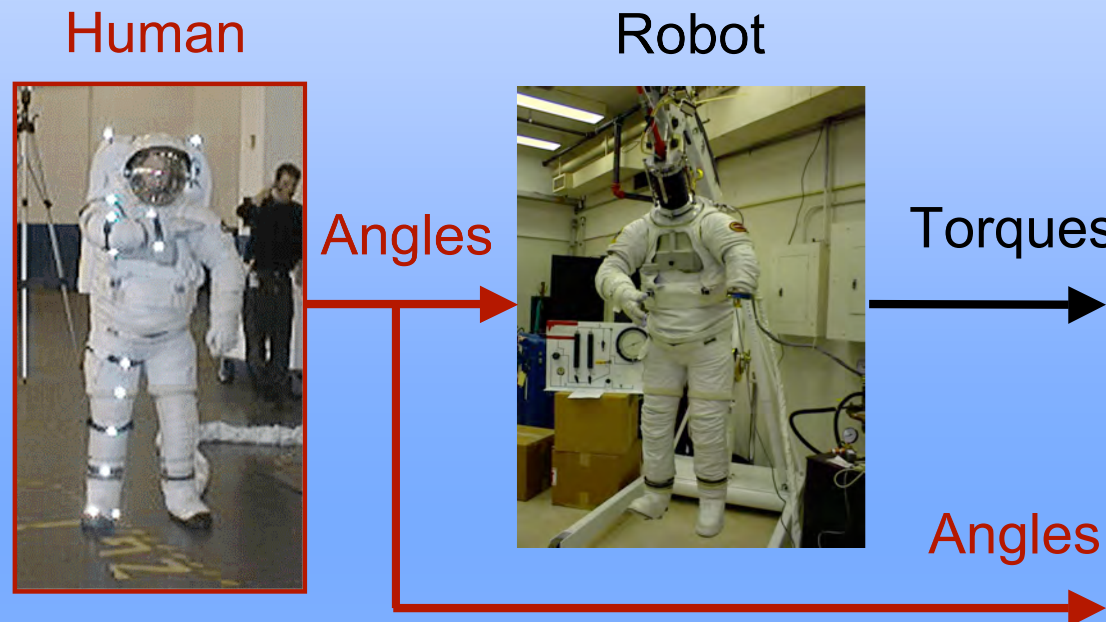
- Extravehicular Mobility Unit (EMU)
  - **Designed for weightlessness**
  - **Pressurized suit (29 kPa, 4.3 psi)**
  - **Life support system (O_2, CO_2, etc.)**
  - **2 pieces: pants, arms & upper torso**
  - **Donning and doffing are highly involved**
  - **Adequate mobility for ISS**
  - **NOT a locomotion/exploration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

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



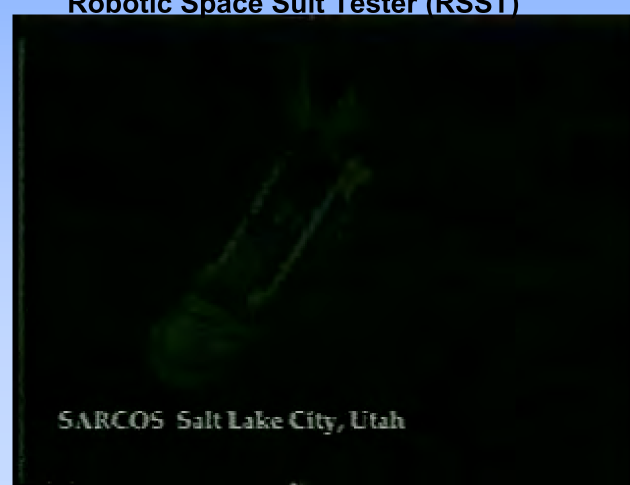
Human/Robot Database

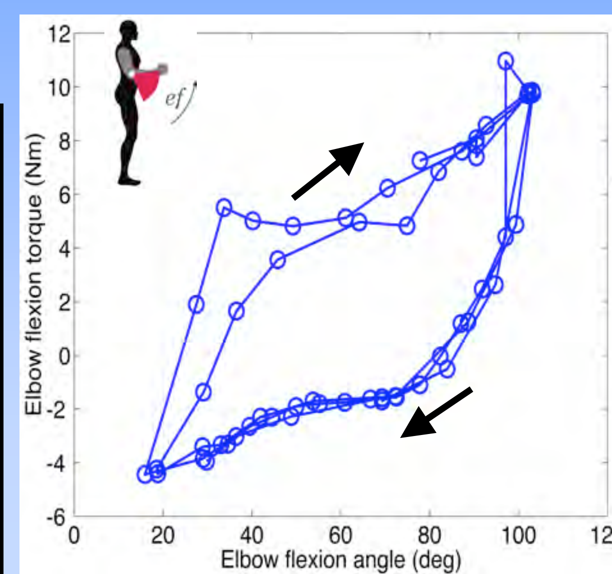
- Human, robot, human suited, & robot suited
- 11 simple motions isolating individual joints
- 9 complex motions:
  - Overhead reach
  - Cross-body reach
  - Low reach
  - Locomotion
  - Step up 15 cm (6 in)



M. Tallchief

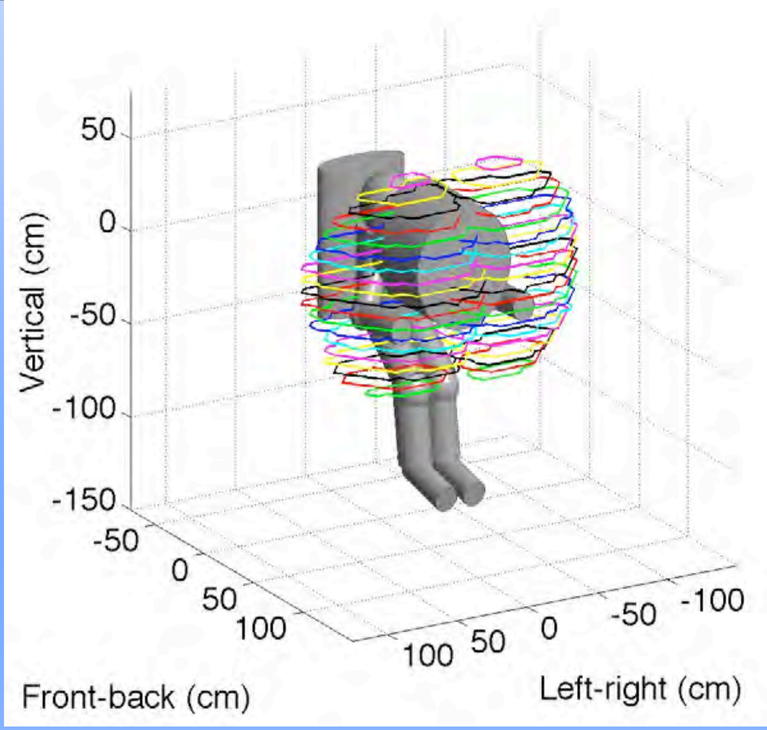
Robotic Space Suit Tester (RSST)

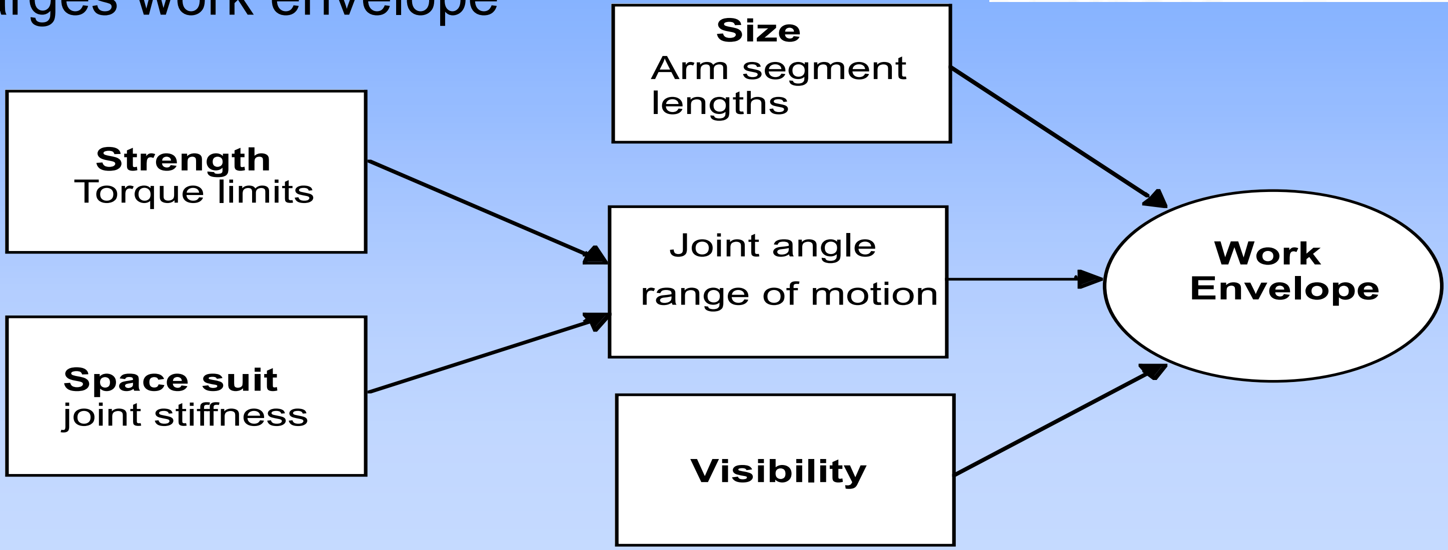




Re-Thinking Work Envelope Analysis

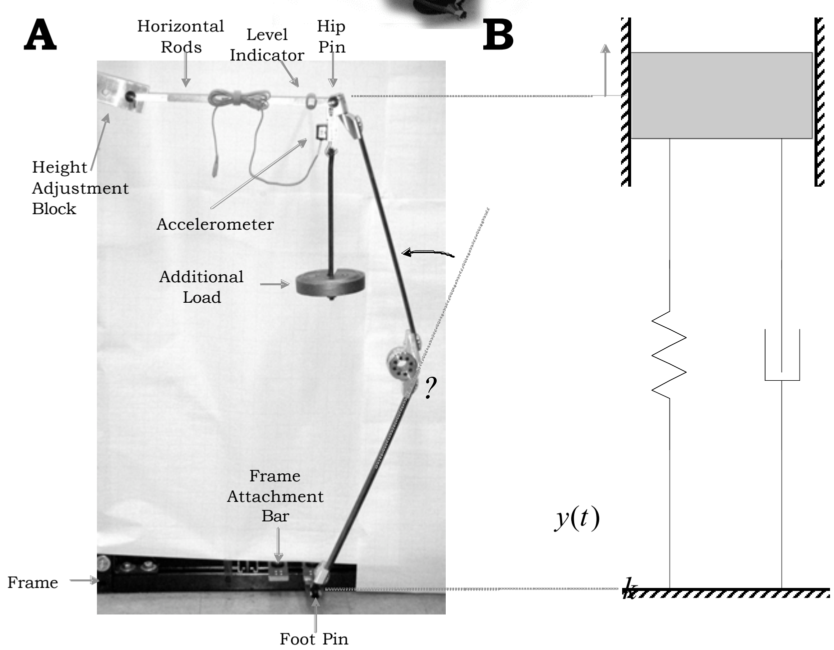
- Can predict large-scale human factors metric from joint torque-angle models
- Work envelope analysis method is easily reconfigurable for different anthropometrics and strengths
- Sensitivity analysis indicates
  - Improving shoulder mobility adds most volume to work envelope
  - Improving upward and downward visibility enlarges work envelope

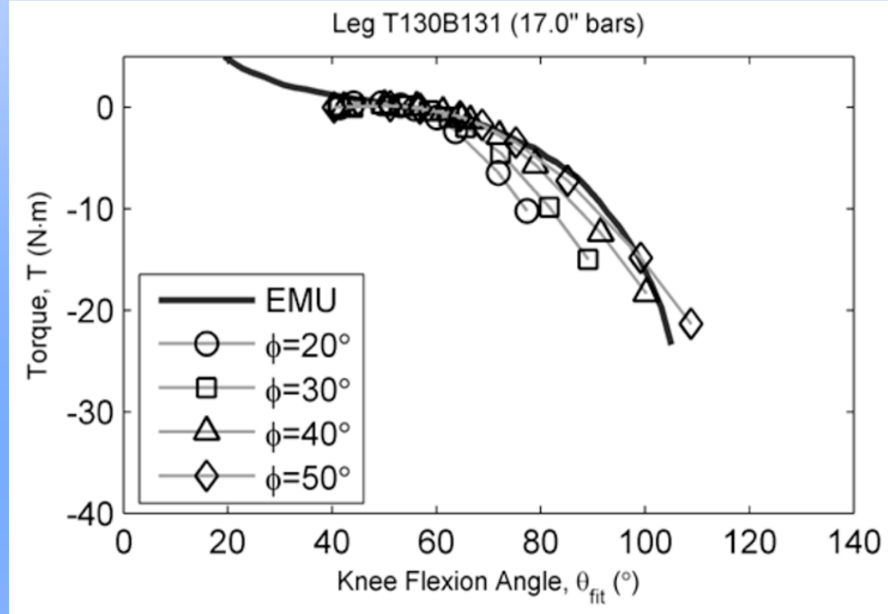


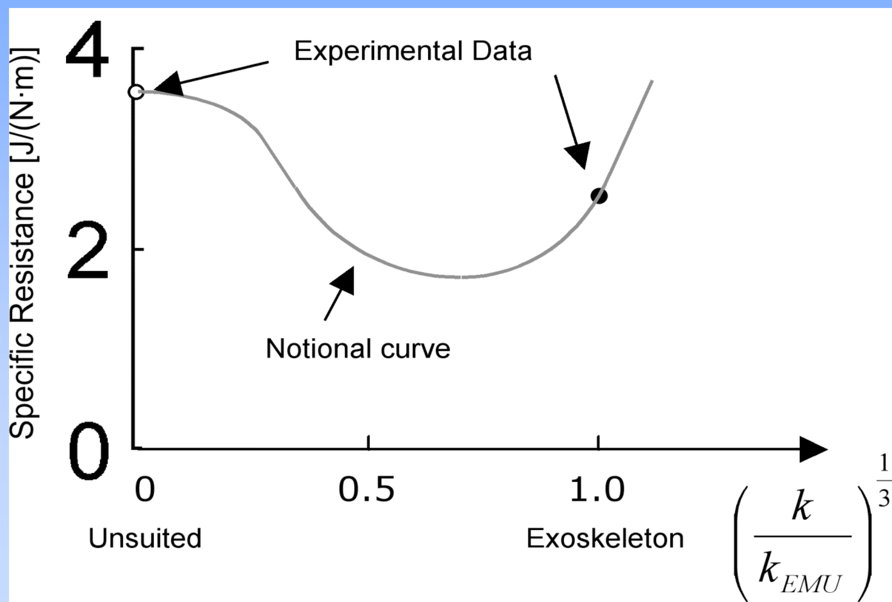


Space Suit Simulator – Exoskeleton

- Exoskeleton joint torques match EMU knee torques
- “Tuned space suit”







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.

Synthesis of Energetics

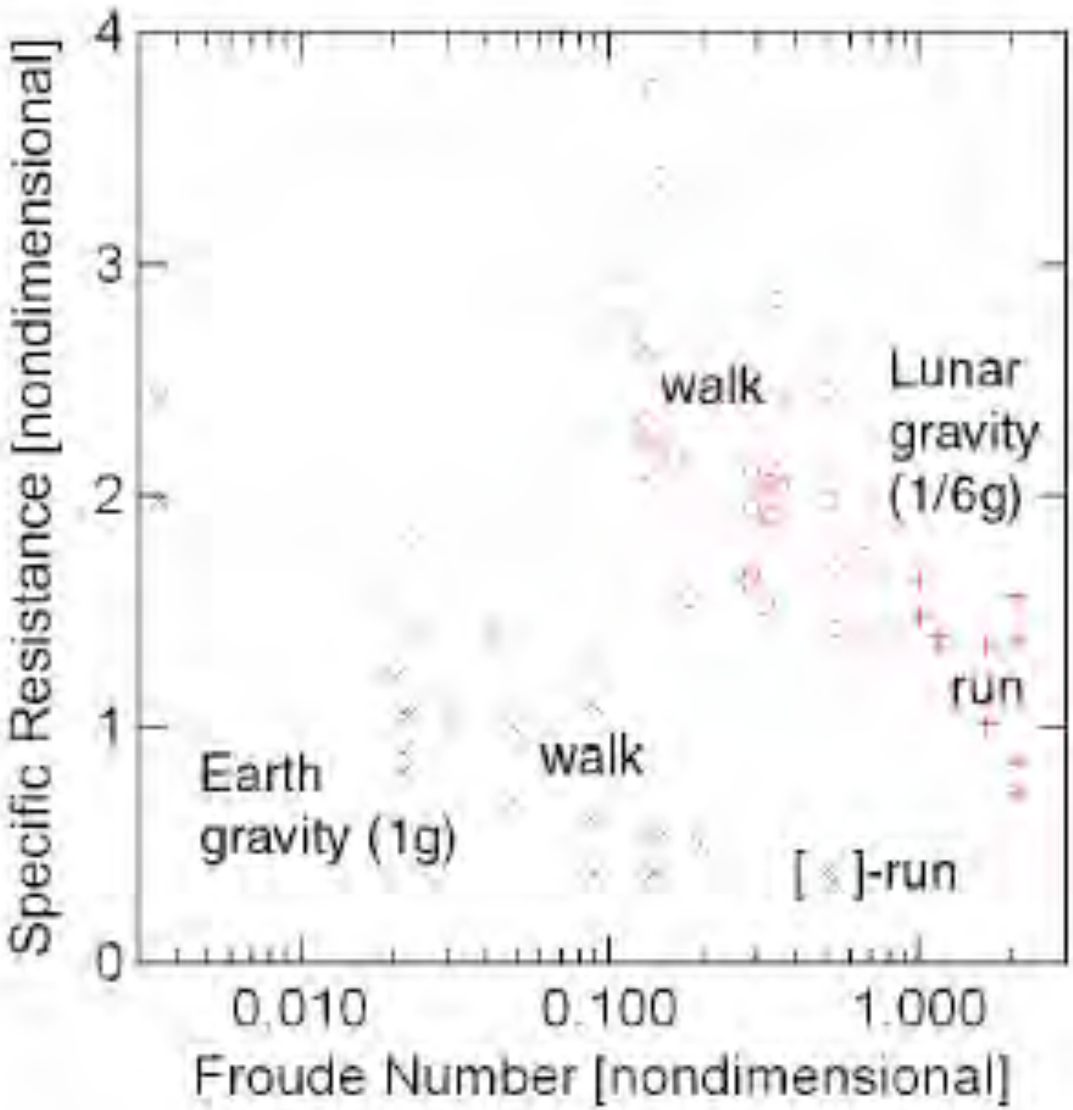
Hypothesis:

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

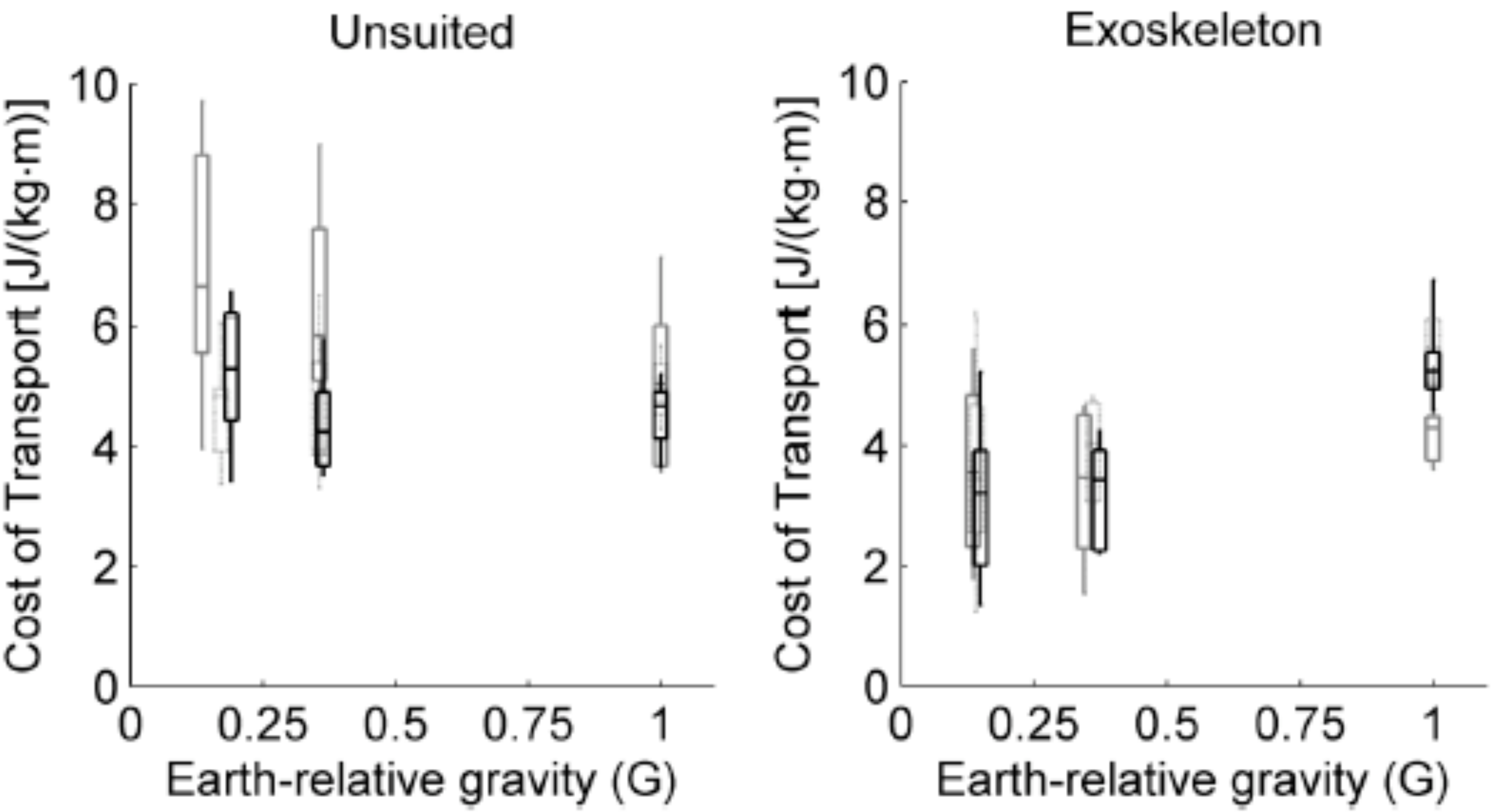
Performed a two-sample T-test.

Significance:

Means are different ($p<0.0005$).

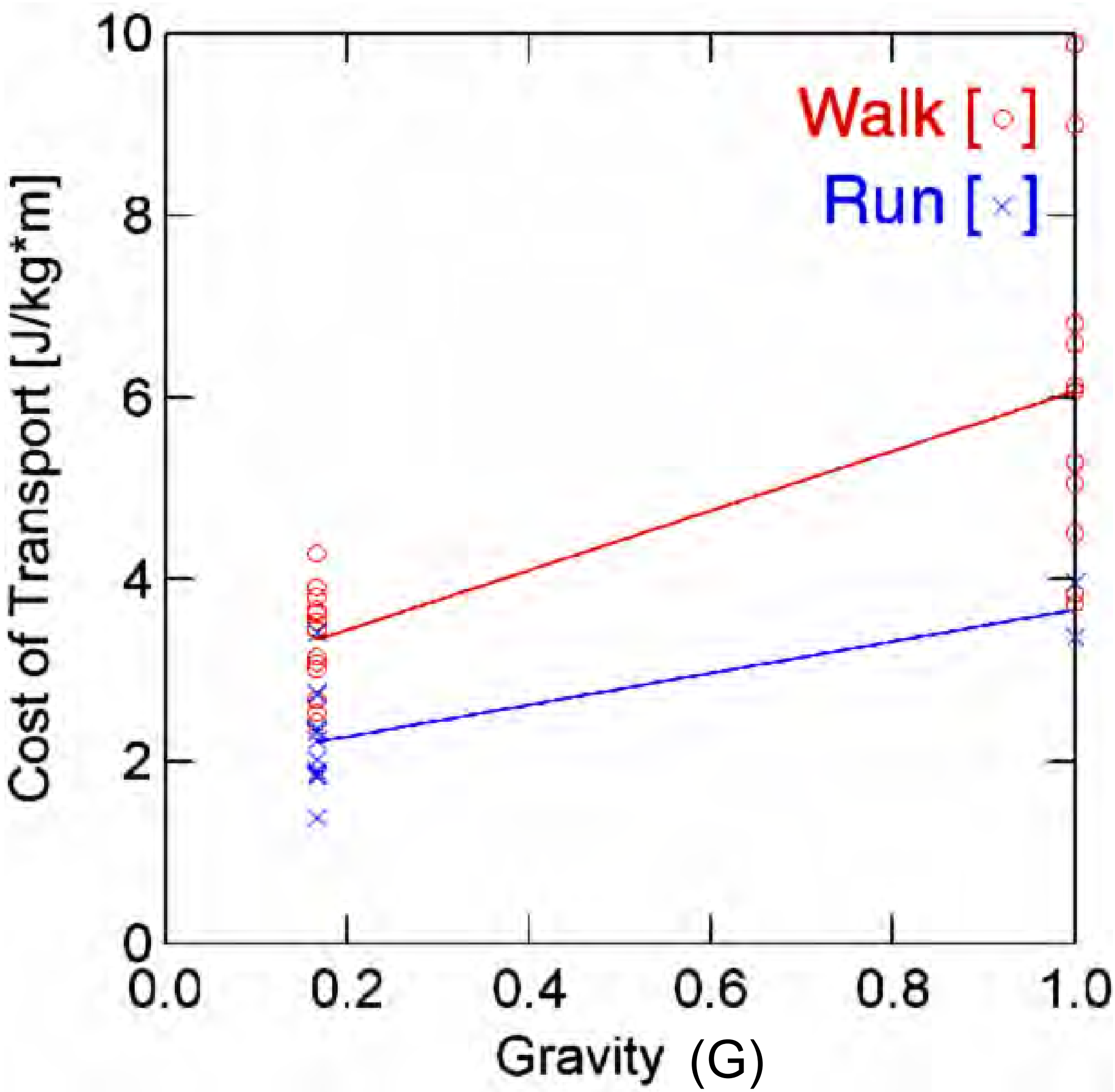


Exolocomotion: Cost of Transport [J/(kg·m)]



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

Suited Locomotion: Run, don't walk!

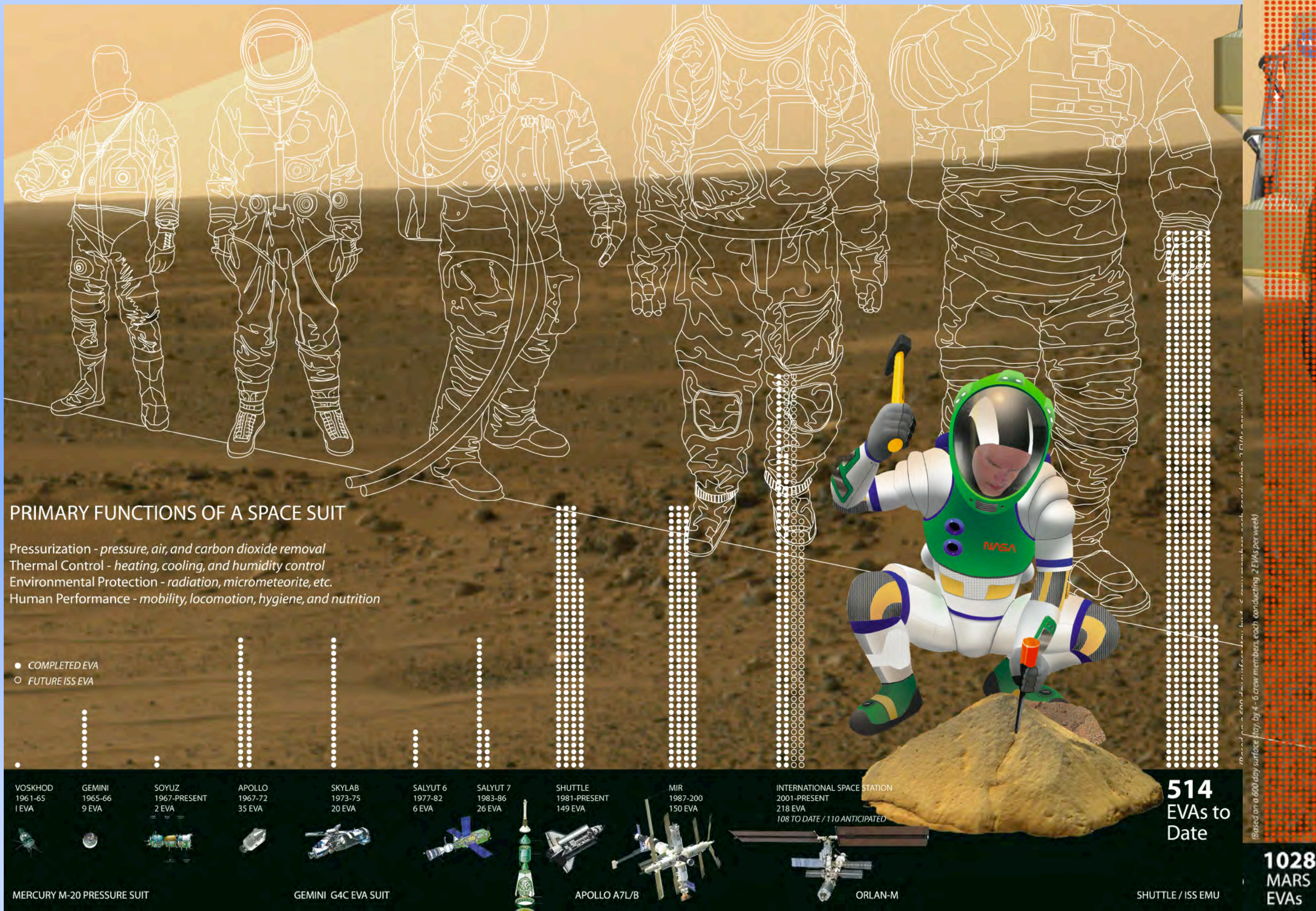


Carr & Newman (SAE paper 2005-01-2970).

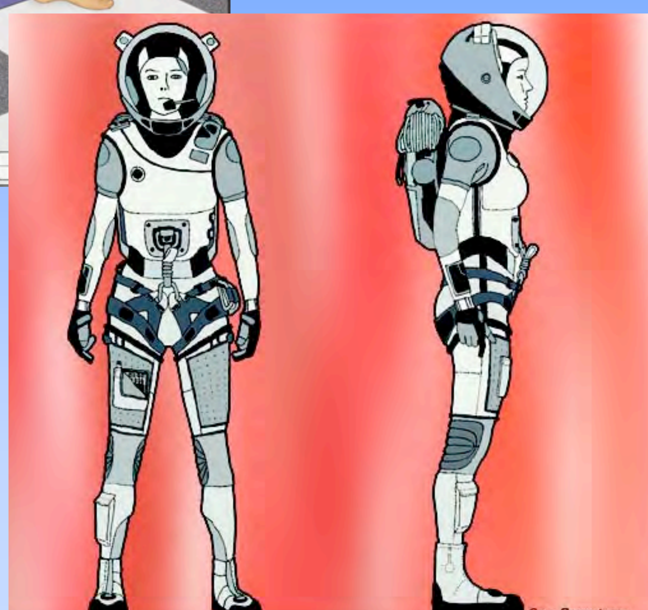
The Art of Engineering!

Creative Spacesuit Design

Human EVA History



Revolutionary Design: *Bio-Suit System*



Bio-Suit multiple components:

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

Systems Engineering: req's., design life, model, interchangeable components

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

$\Delta W = \Delta Wp + \Delta We$

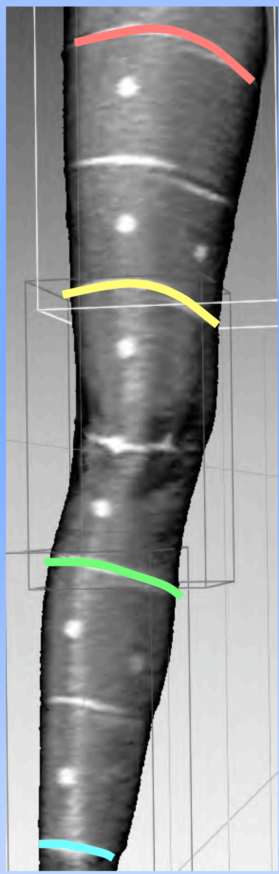
ΔWp - Minimize through MCP design

ΔWe - 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

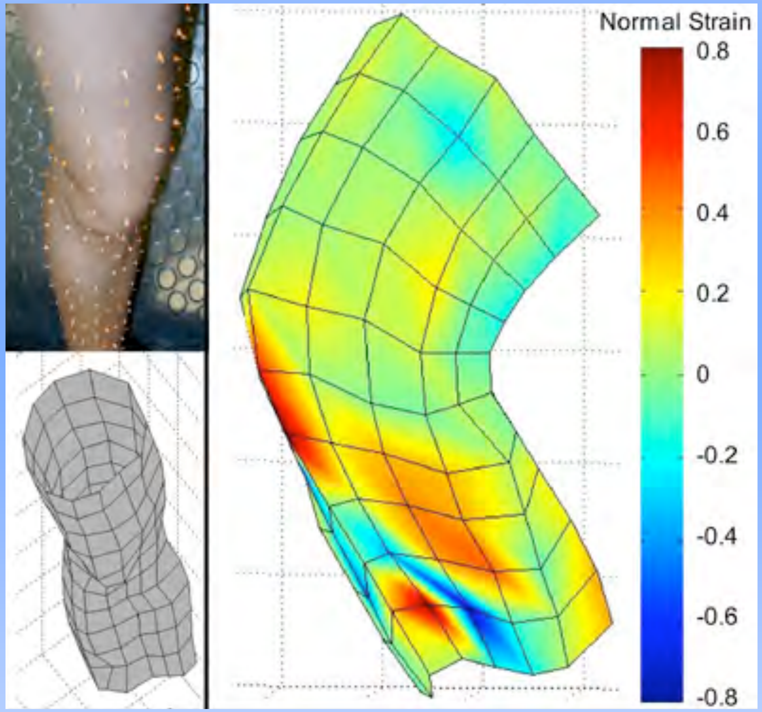
Knee Volume

18%

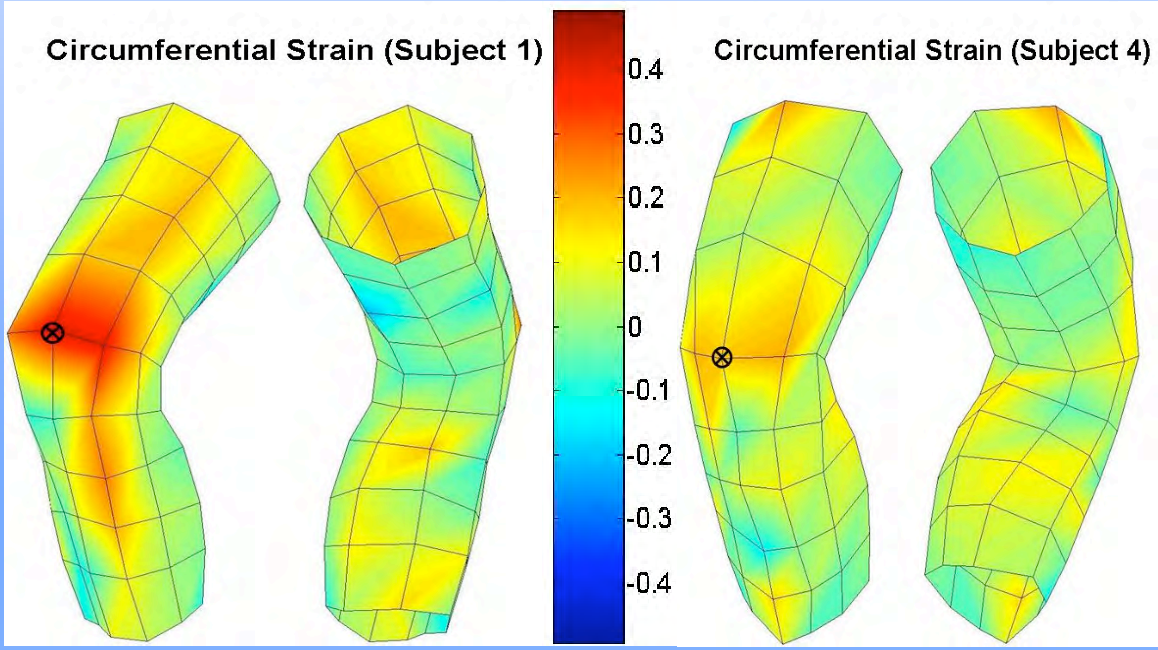
In knee region, when leg flexes from 0 to 90 degrees

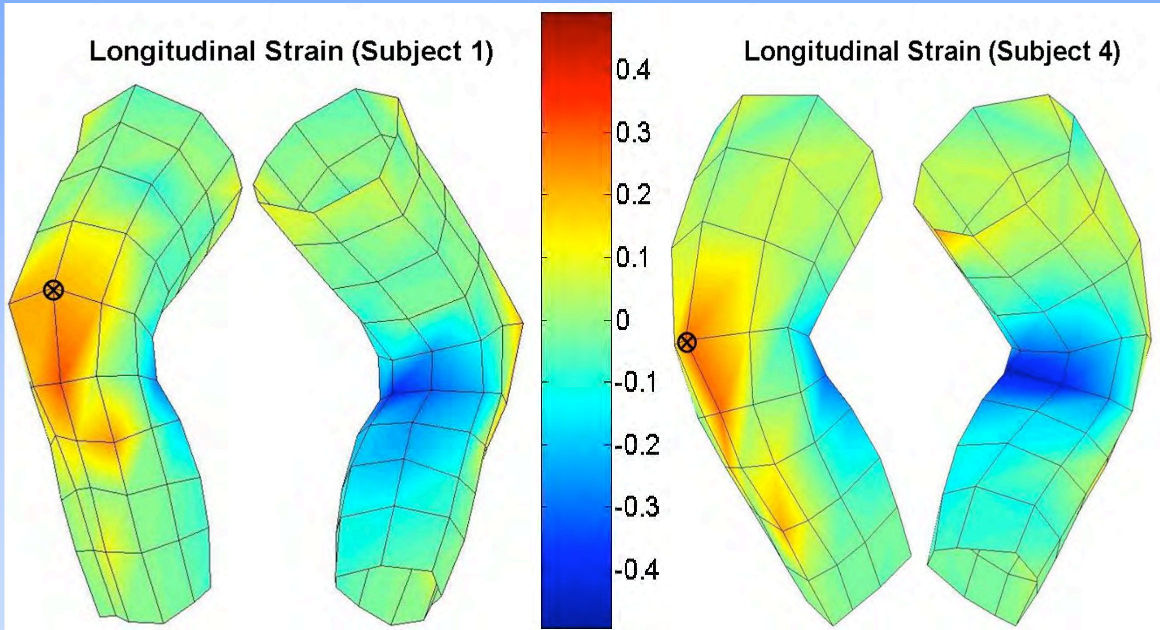
Skin Strain Field Mapping

Circumferential Strain

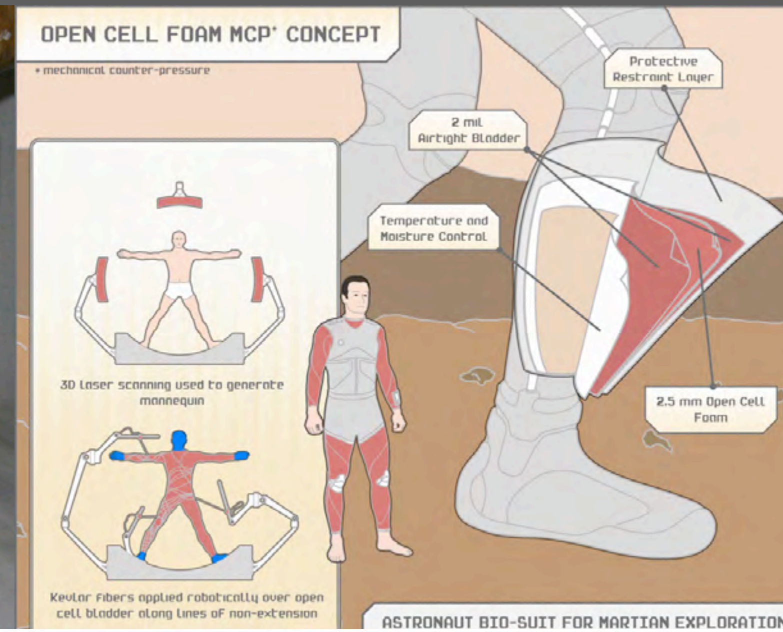


Bio-Suit Skin Strain Model

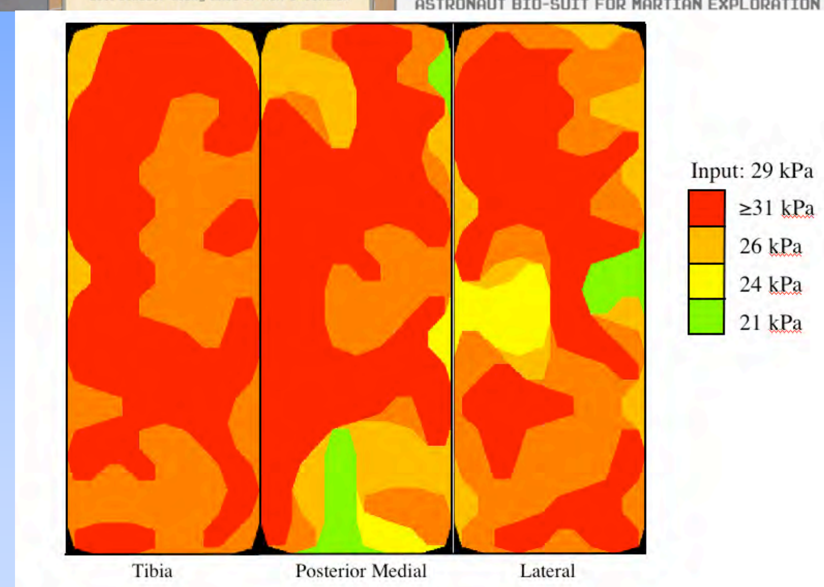




Results: MCP Initial Prototypes



Tibia Medial-Posterior Lateral



Results: Minimum Energy Bio-Suit

- Maximizing mobility
- Minimizing energy
  - (Strain energy, stress and modulus)







Results: MCP Elastic Bindings

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

- **Varying circumferential tension gives constant pressure as leg radius changes.**
- **Donning time ~5 minutes**

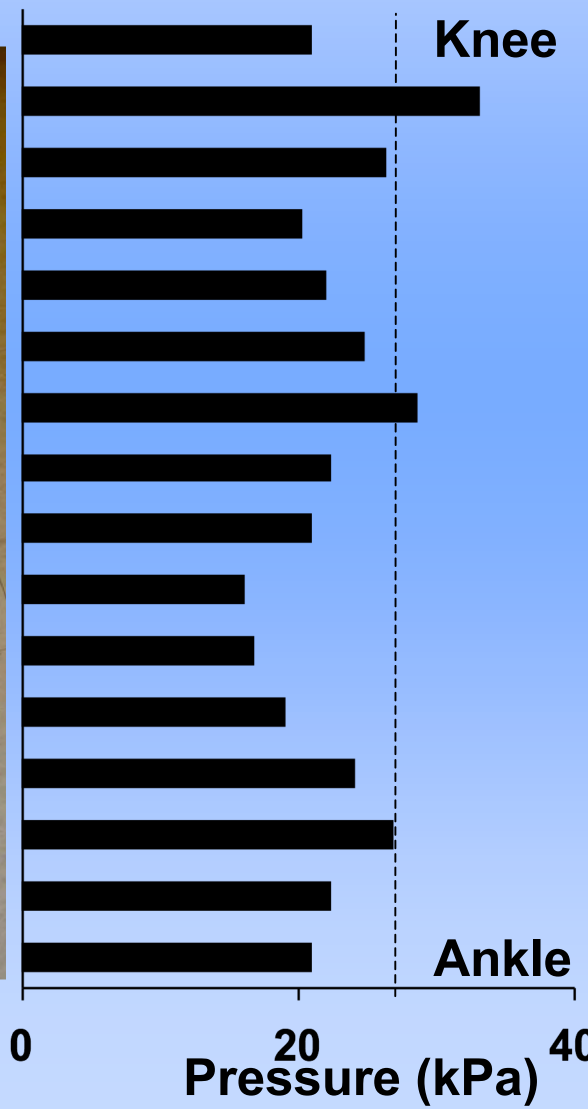
- **Knee flexion angle ~140^{o}**

Pressure Distribution Generated by the Elastic Bindings Varies from the Target Value

Prototype MCP generated on calf using Elastic Bindings

Front

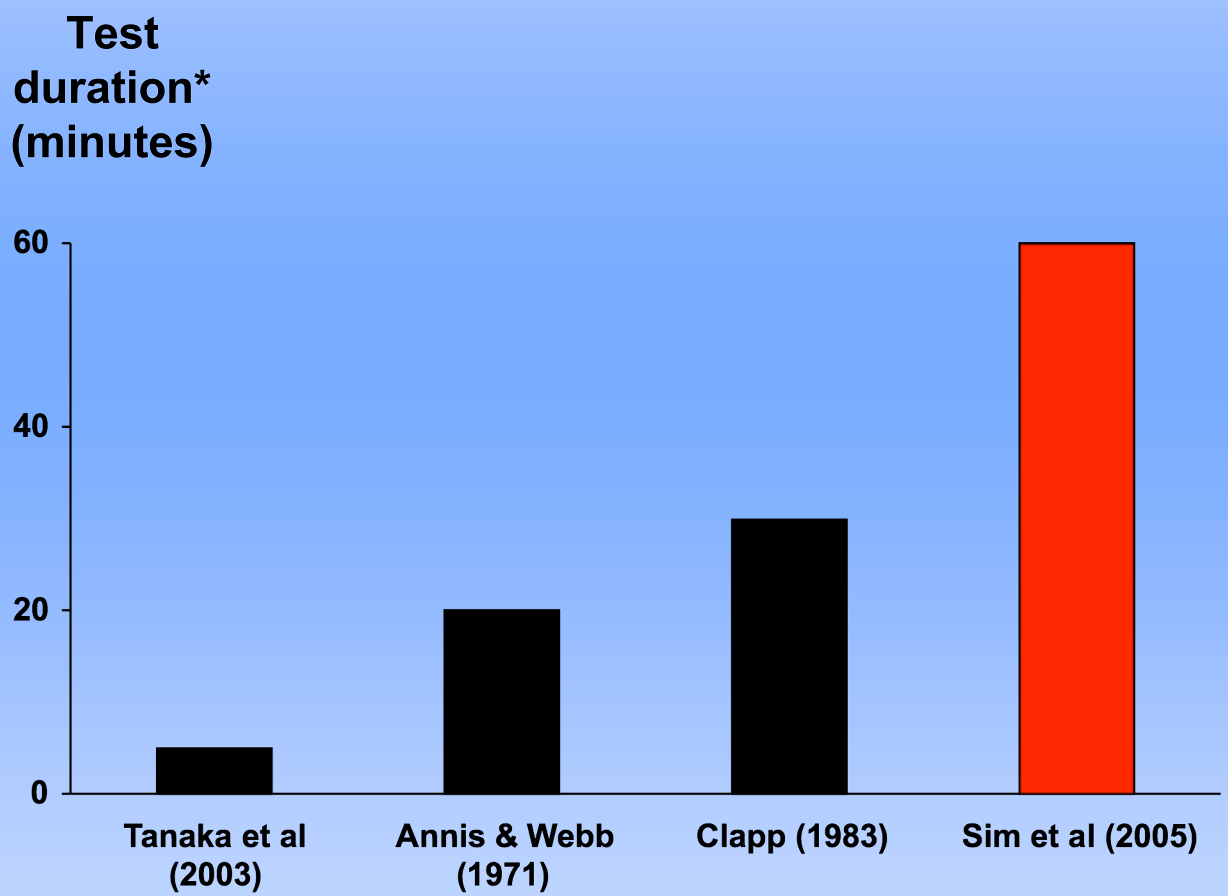
Back

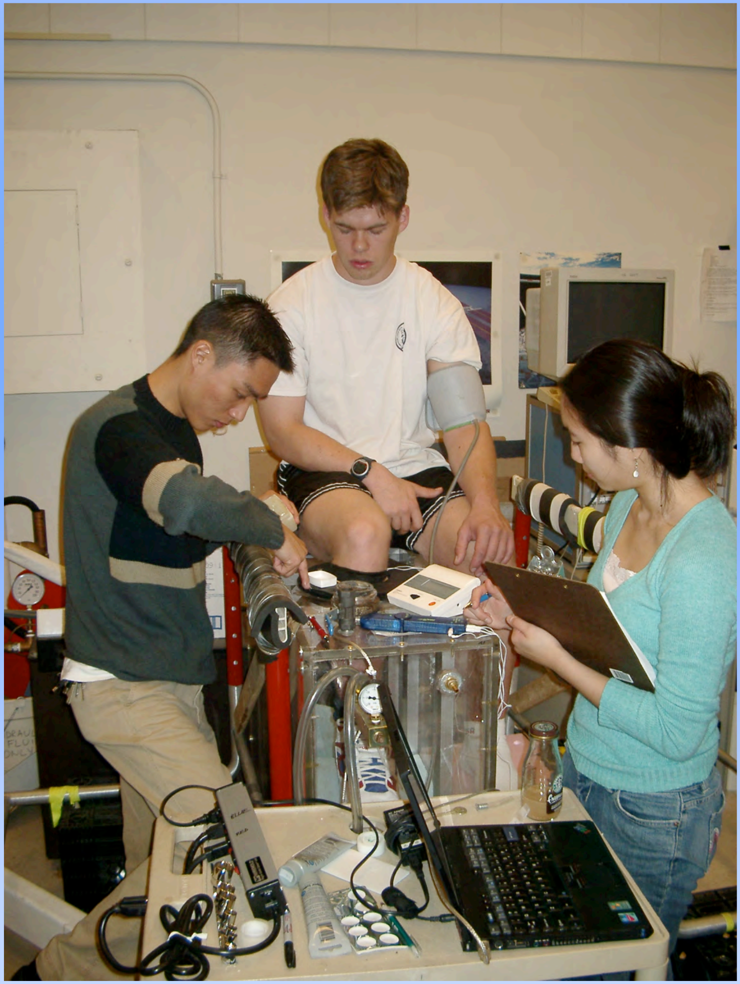


Successfully protected a human leg from the effects of external underpressure

ELASTIC BAND PROTOTYPES

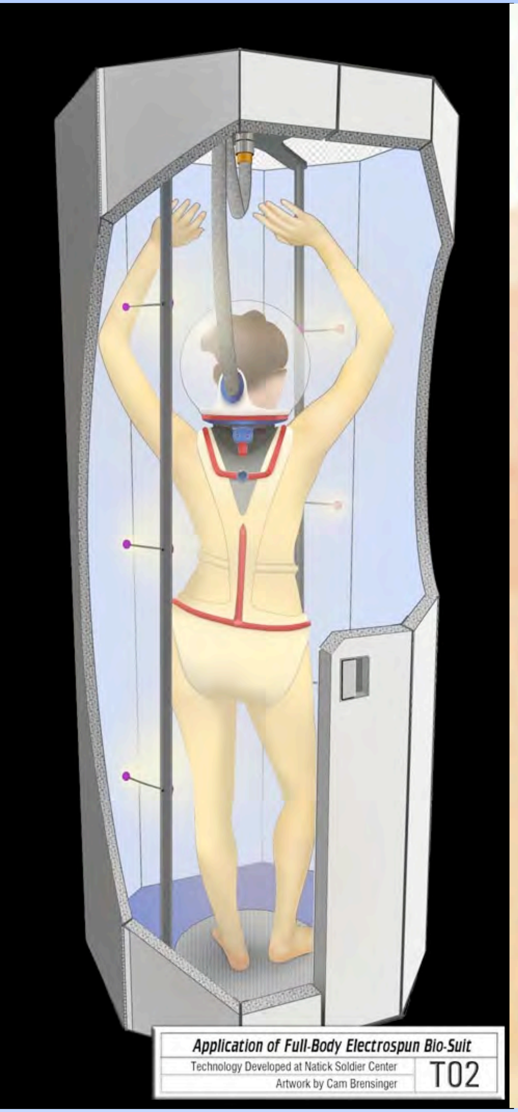
Human MCP Garment Trials in Low-Pressure Chambers





Note: * Excludes pressure ramp-down and ramp-up times

Technology Roadmap: Design



3D Laser Scanning

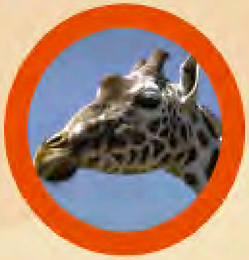
- ***D*** 1980 – Patented 3D rapid digitizing technology
- ***M*** 1990 – General purpose 3D scanning systems
- ***P*** 2005 – Bio-Suit analysis technique for skin strain field mapping

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

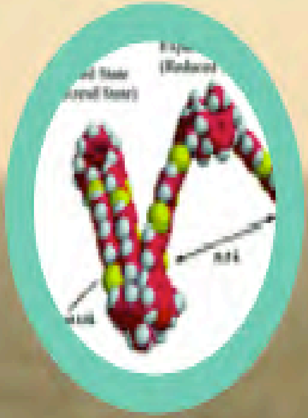
- ***D*** 1940 – Electrospinlacing proposed and patented
- ***M*** 2003 – Electrospun nano-fibers realized, anisotropic spray capability proposed
- ***P*** 2015 – 3D electrospun polymer Bio-Suit garment with specified mechanical properties



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.

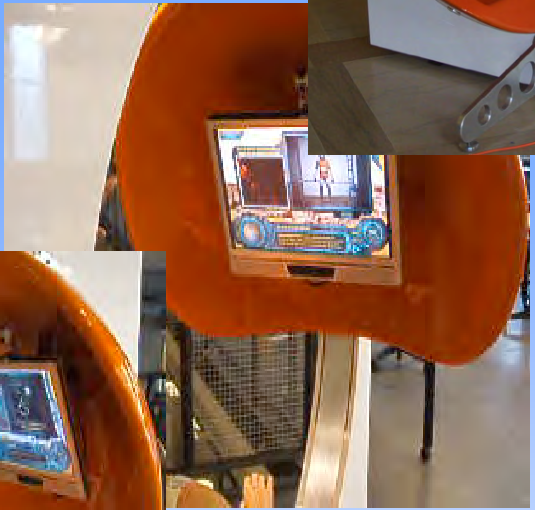
Learn about the world of NASA and NSBRI’s science and technology breakthroughs.

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



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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

References

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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.
4. Newman, D.J.,Bethke, K., Carr, C.E., Hoffman, J., Trotti, G., "**Astronaut Bio-Suit System to Enable Planetary Exploration**," International Astronautical Conference, Vancouver, B.C., Canada, 4-8 Oct 2004.
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10. Trevino, L. and Carr, C.E. **A First-Order Design Requirement to Prevent Edema in Mechanical Counter-Pressure Space Suit Garments**. Submitted to *Aviat Space Environ Med*, June 2005.