An Astronaut ‘Bio-Suit’ System for Exploration Missions

Professor Dava J. Newman, Ph.D.  ₵+
Professor Jeff Hoffman*, Kristen Bethke*, Christopher Carr**, Nicole Jordan*, & Liang Sim*
Norma Campos, Chip Conlee, Brendan Smith, Joe Wilcox

Guillermo Trotti¹

²Director, Technology and Policy Program
*MIT Department of Aeronautics and Astronautics
**Harvard-MIT Division of Health Science and Technology
¹Trotti & Associates, Inc., MIDÉ Technologies

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Industry Partners

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- South Pole Station
- Underwater Habitats
- Ecotourism. (Phase I and II)

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Dr. John Grunsfeld, NASA astronaut.
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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

Results: Partial Gravity Locomotion

MIT MoonWalker
1-G Simulation

MIT MoonWalker
Martian Simulation

Force

Normalized (Norm)

Absolute Time (s)

0 1 2 3 4 5 6

0 1 2 3 4

Normalized (Norm)

Absolute Time (s)

0 1 2 3 4 5

0 0.5 1.0 1.5 2.0
Space Suit Design: Motivation

• Extravehicular Mobility Unit (EMU)
  - Designed for weightlessness
  - Pressurized suit (29 kPa, 4.3 psi)
  - Life support system (O₂, CO₂, 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 degrees of freedom
- 9 complex motions:
  - Overhead reach
  - Cross-body reach
  - Low reach
  - Locomotion
  - Step up 15 cm (6 in)

M. Tallchief
Robotic Space Suit Tester (RSST)
The Art of Engineering!
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
Joint Torque: EMU & Exoskeleton

![Graph showing joint torque for EMU and exoskeleton with knee flexion angle and torque values.](image)
Exolocomotion: Cost of Transport

$[\text{J/}(\text{kg} \cdot \text{m})]$
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, micrometeorites, etc.
- Human Performance - mobility, locomotion, hygiene, and nutrition

Completed EVAs
- MERCURY M-20 PRESSURE SUIT
- GEMINI EVA SUIT
- APOLLO EVA SUIT
- SHUTTLE EVA SUIT
- ISS EVA SUIT
- MARS EVAs

Total EVAs to Date: 514
Total MARS EVAs: 1028
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

\[ W = W_p + W_e \]

\( W_p \) - Minimize through MCP design
\( W_e \) - Bending (design) and Strain Energy (min. or max E)
<table>
<thead>
<tr>
<th>MCP Tension</th>
<th>Knee Surface Area</th>
<th>Skin Strain Field Mapping</th>
</tr>
</thead>
<tbody>
<tr>
<td>~2 kN/m</td>
<td>16%</td>
<td>Circumferential Strain</td>
</tr>
<tr>
<td></td>
<td>In knee region, when leg flexes from 0 to 90 degrees</td>
<td>Normal Strain</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Knee Volume</th>
<th>18%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>In knee region, when leg flexes from 0 to 90 degrees</td>
</tr>
</tbody>
</table>
Results: MCP Initial Prototypes

Tibia Medial-Posterior Lateral

Input: 29 kPa
≥31 kPa
26 kPa
24 kPa
21 kPa
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

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

Electrospinning
D 1940 – Electrospinning 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
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.

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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
References


Thank You!