Supernumerary Robotic Limbs to Support Post-Fall Recoveries for Astronauts

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Erik Ballesteros[1], Sang-Yoep Lee[1], Kalind C. Carpenter[2], H. Harry Asada[1]

1. Massachusetts Institute of Technology 2. NASA Jet Propulsion Laboratory

Contact: *balleste@mit.edu, sangyoep@mit.edu, kalind.carpenter@jpl.nasa.gov, asada@mit.edu*

MOTIVATION

Extra-Vehicular Activities (EVAs) are considered one of the most dangerous tasks for an Astronaut to perform

- Space suits are large and cumbersome
- If an astronaut were to fall, they likely won't be able to recover

Fig. 1 - Apollo-era footage of astronaut falling during a lunar EVA.

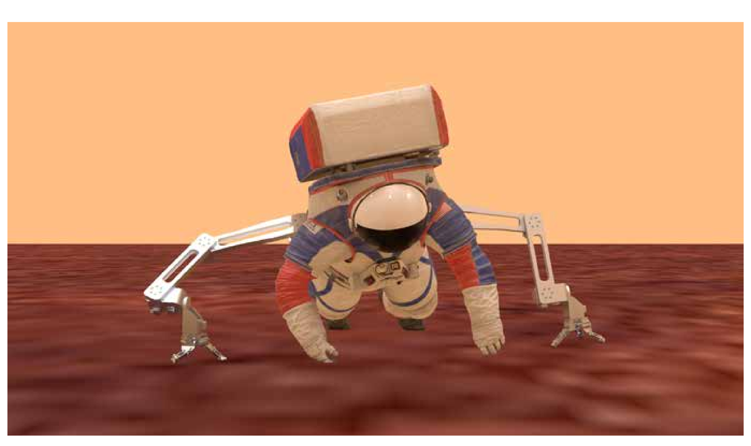


Fig. 2 - Rendering of SuperLimbs assisting an Astronaut in a Post-Fall Recovery.

- Supernumerary Robotic Limbs (SuperLimbs) can augment human capabilities
- **With SuperLimbs, astronauts can safely recover**

A **human study** was performed to better understand the challenges associated with post-fall recoveries (approved by the Massachusetts Institute of Technology Committee on the Use of Humans as Experimental Subjects, protocol number 2306001022)

Four test subjects
- Mass = 75.14 +/- 12.85 kg
- Height = 1.78 +/- 0.07 m

Three phases of experiments
1. Unconstrained human study
2. Partially Constrained human study
3. Suited human study with/without SuperLimbs assistance

PROBLEM DISCOVERY

Key Findings

- Adoption of sequence of waypoints to stand up
  - Large variations between waypoints across participants
- Sequence doesn't change when partially constrained
  - Smaller variations between waypoints across participants

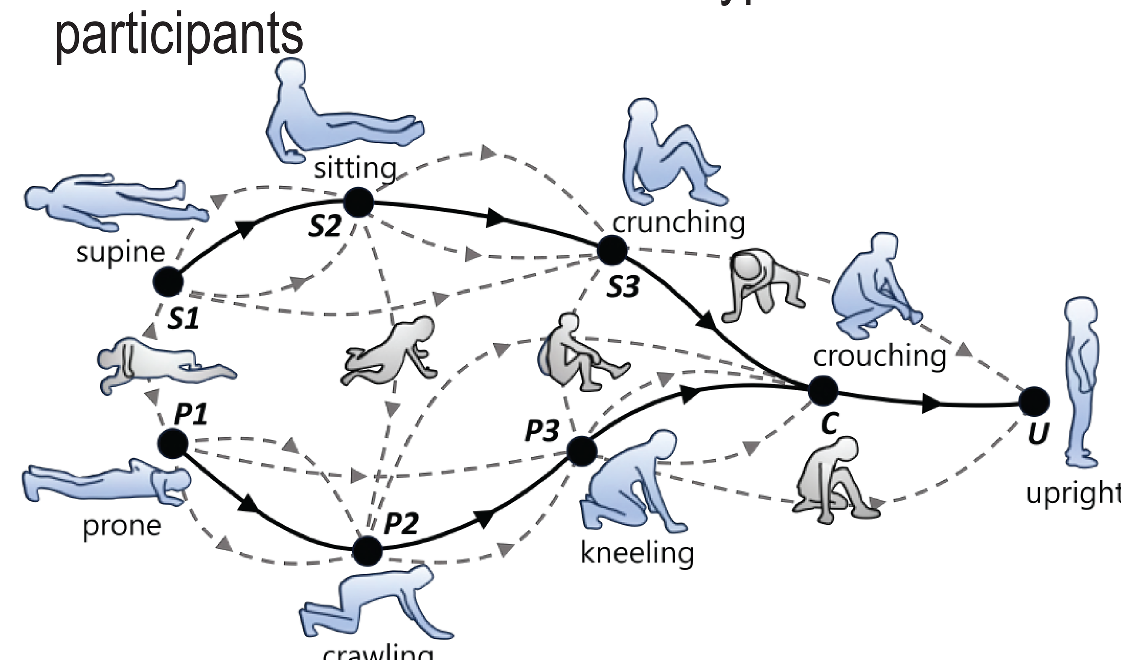
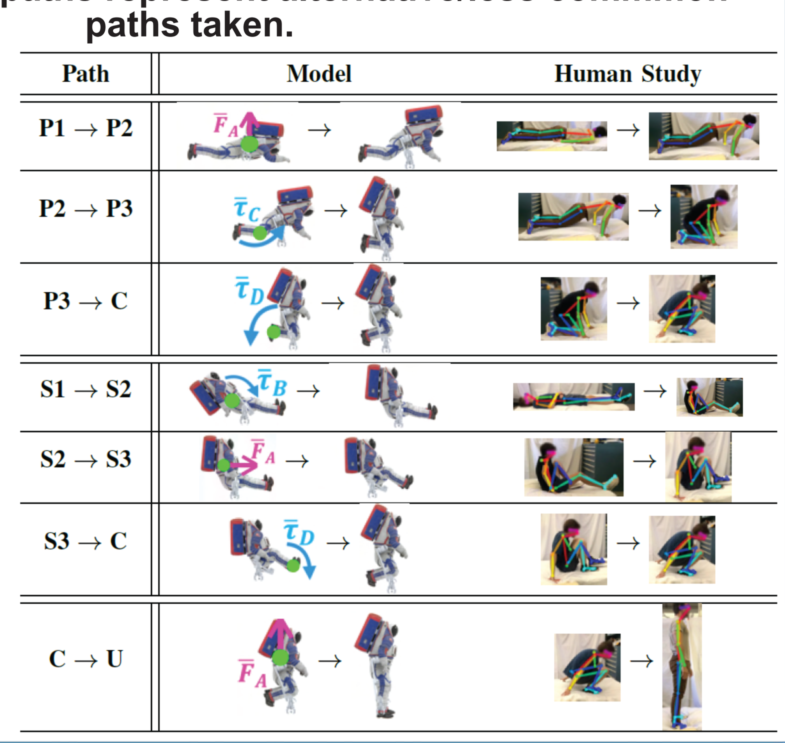


Fig. 3 - Representation of the sequence of waypoints (bolded) taken by humans to perform post-fall recoveries. Solid black paths are to represent the most straightforward/common paths taken, while dashed paths represent alternative/less commmon paths taken.

- A force/torque about a point on the astronaut's body can represent motion between waypoints



DESIGN & CONTROL

- An in-house space suit was developed to simulate mass/inertia and mobility of modern space suits
- Benchmark: NASA Exploration Extravehicular Unit (xEMU)

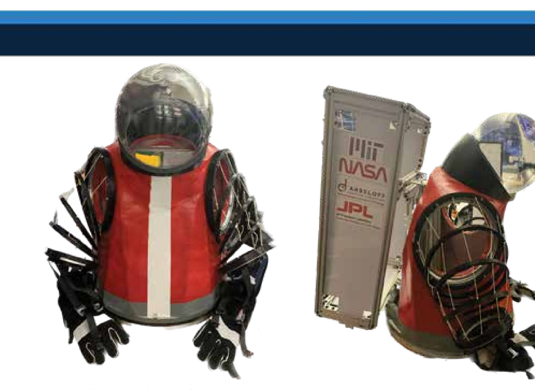


Fig. 4 - Supernumerary Robotic Limbs Extra-Vehicular Mobility Unit testing prototype (SuperEMU)

Control Design must take heed of the following:
- Overshooting of astronaut position due to large inertia
- Less braking effect due to low gravity
- Human hands and SuperLimbs can only apply downward forces
- Astronaut can only apply forces in limited range of postures
- Astronaut must be in-the-loop at all times, control authority to perform voluntary motion
- SuperLimbs must not impede astronaut's motion

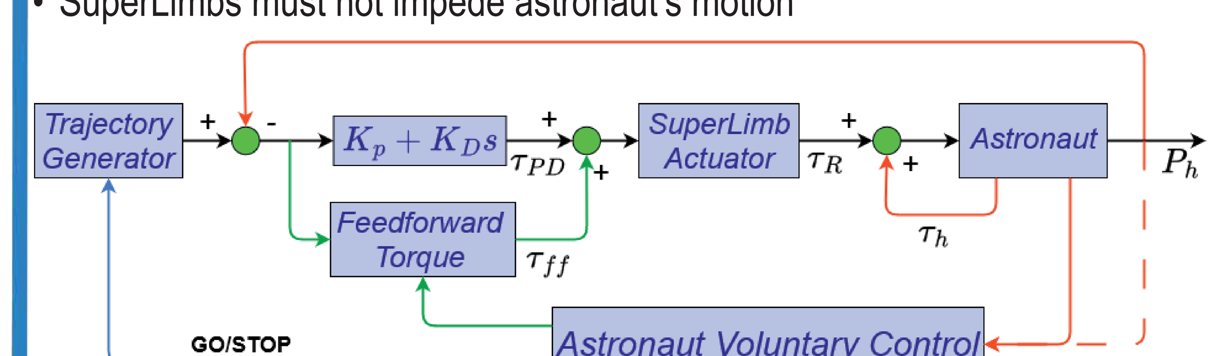


Fig. 5 - Block Diagram of Astronaut-SuperLimbs system where the human is supported with impedance and control the recovery process.

Control Features
- Torque to maintain a path from one waypoint to another
- Feedforward torque from explicit input from astronaut
- Explicit command from astronaut via space suit interfaces
- Trajectory plan for task-space impedance control

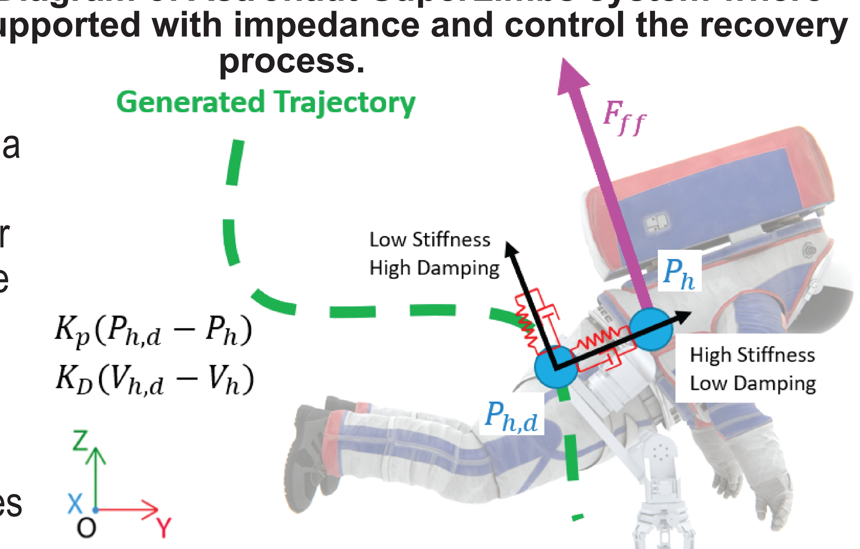


Fig. 6 - Representation of Astronaut-SuperLimbs system elements acting on Astronaut body along sagittal plane

RESULTS

The Astronaut-SuperLimbs system was realized via a Universal Robots UR10e with Real-Time Data Exchange (RTDE) communications

The following metrics were captured:
- **Position** of the participant's center of mass
- **Externally applied assistive forces** on the participants

Takeaways

- Success Rate - Participants showed 42.5% improvement with SuperLimbs
- Exertion - Energy consumption reduced 15.28% with SuperLimbs
- Tracking Accuracy - SuperLimbs reduced deviation by 38.13%

Observations

- Unassisted
  - Participants were forced to exert impulsive loads to move between difficult waypoint transitions
  - High effort AND instabilities
- Assisted
  - Participants who poorly fit the SuperEMU required larger assistance

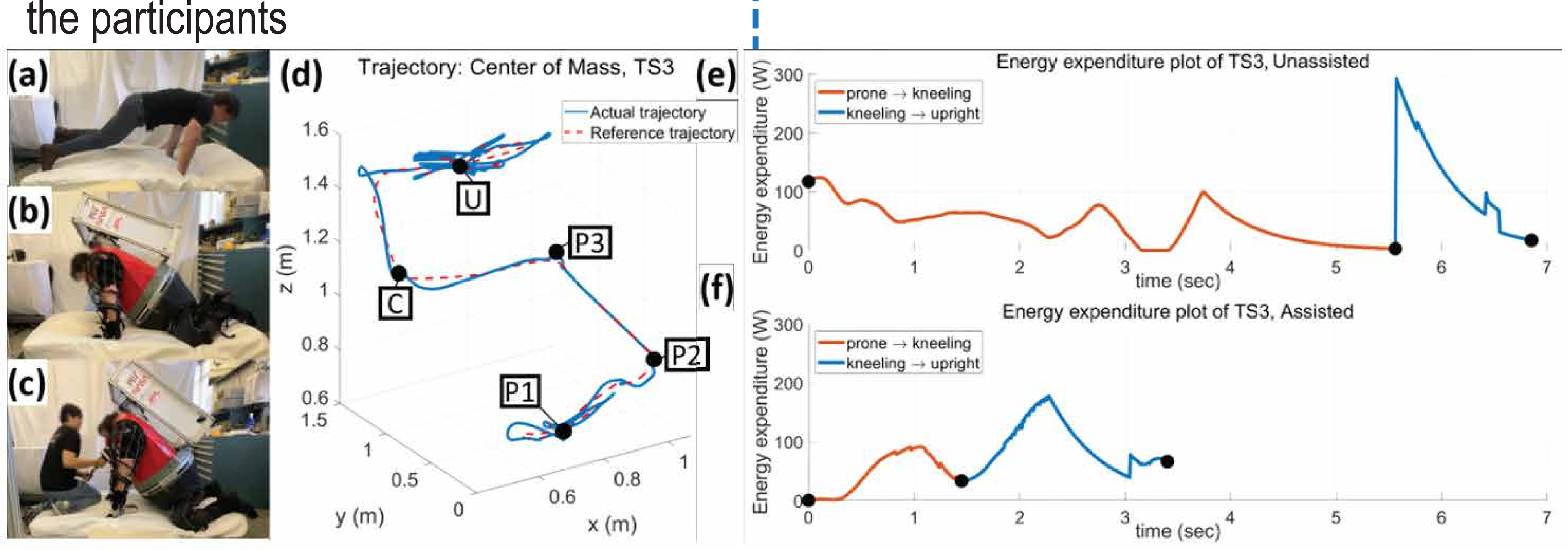


Fig. 7 - Experimental setup and representative results of a typical test subject, other subjects showed similar behavior. (a) Test subject performs voluntary post-fall recovery process without any restriction. (b) Test subject performs voluntary post-fall recovery assisted by a test operator. (c) Test subject performs human-assisted post-fall recovery wearing SuperEMU. (d) Spatial trajectory of test subject's center of mass while performing an unassisted post-fall recovery, overlapped with reference trajectory. Energy expenditure while performing post-fall recovery process when (e) unassisted and (f) assisted.

Test Subject	TS1	TS2	TS3	TS4
Level of Recovery Success				
Unassisted (%)	100 [U]	15 [P1]	100 [U]	50 [P3]
Assisted (%)	100 [U]	40 [P2]	100 [U]	100 [U]
Energy Consumption				
Unassisted (J)	376.88	47.43	391.07	335.77
Assisted (J)	363.133	32.497	301.94	325.115
Reduction (%)	3.65	31.49	22.79	3.17
Integrated Deviation throughout Sequence				
Unassisted (cm)	63.81	73.60	82.20	60.61
Assisted (cm)	51.61	35.23	33.80	47.05
Reduction (%)	19.12	52.13	58.88	22.37

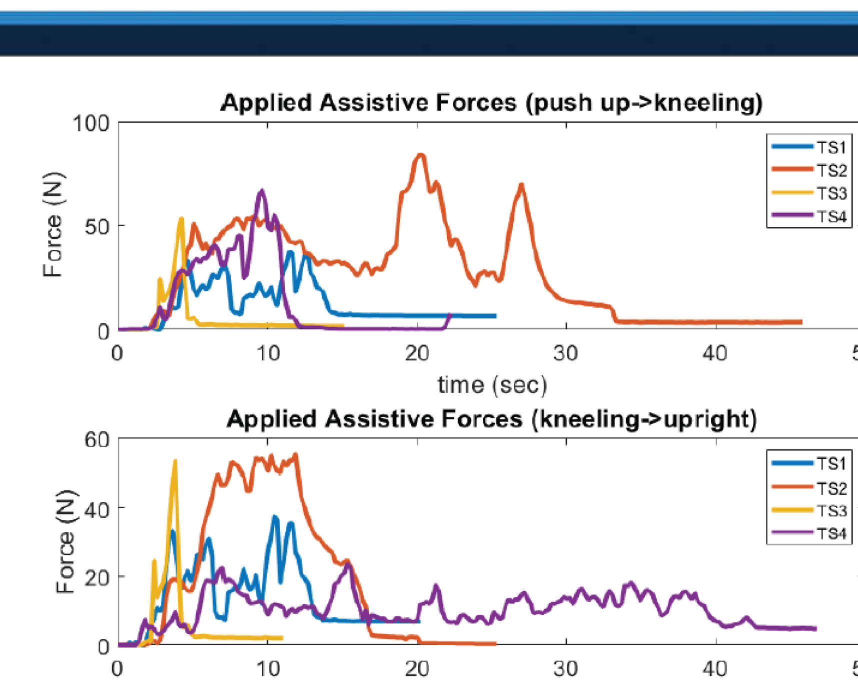


Fig. 8 - Profiles of assistive forces required for suited post-fall recovery.

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Reference

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'ARBELOFF ROBOTICS LABORATORY Massachusetts Institute of Technology

Jet Propulsion Laboratory
California Institute of Technology

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