Design of Supernumerary Robotic Limbs for the Augmentation of Astronauts Performing Partial-Gravity Extra-Vehicular Activities (EVAs)

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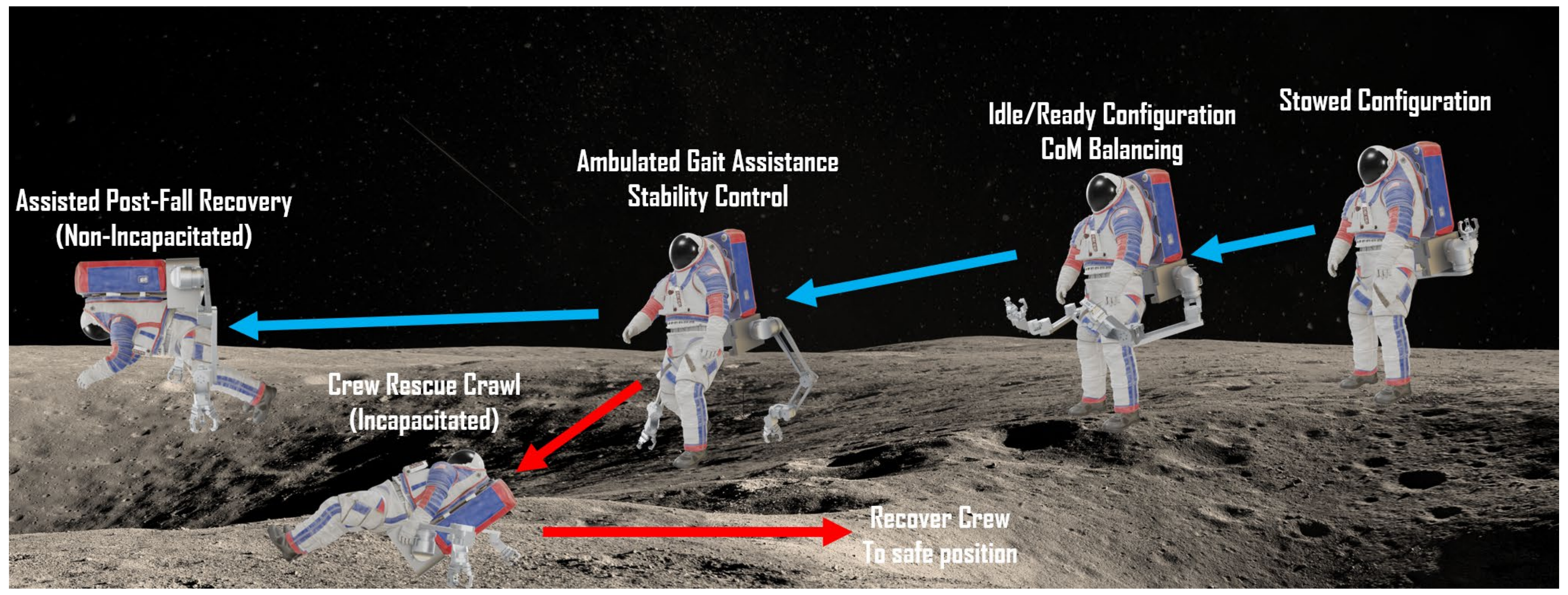
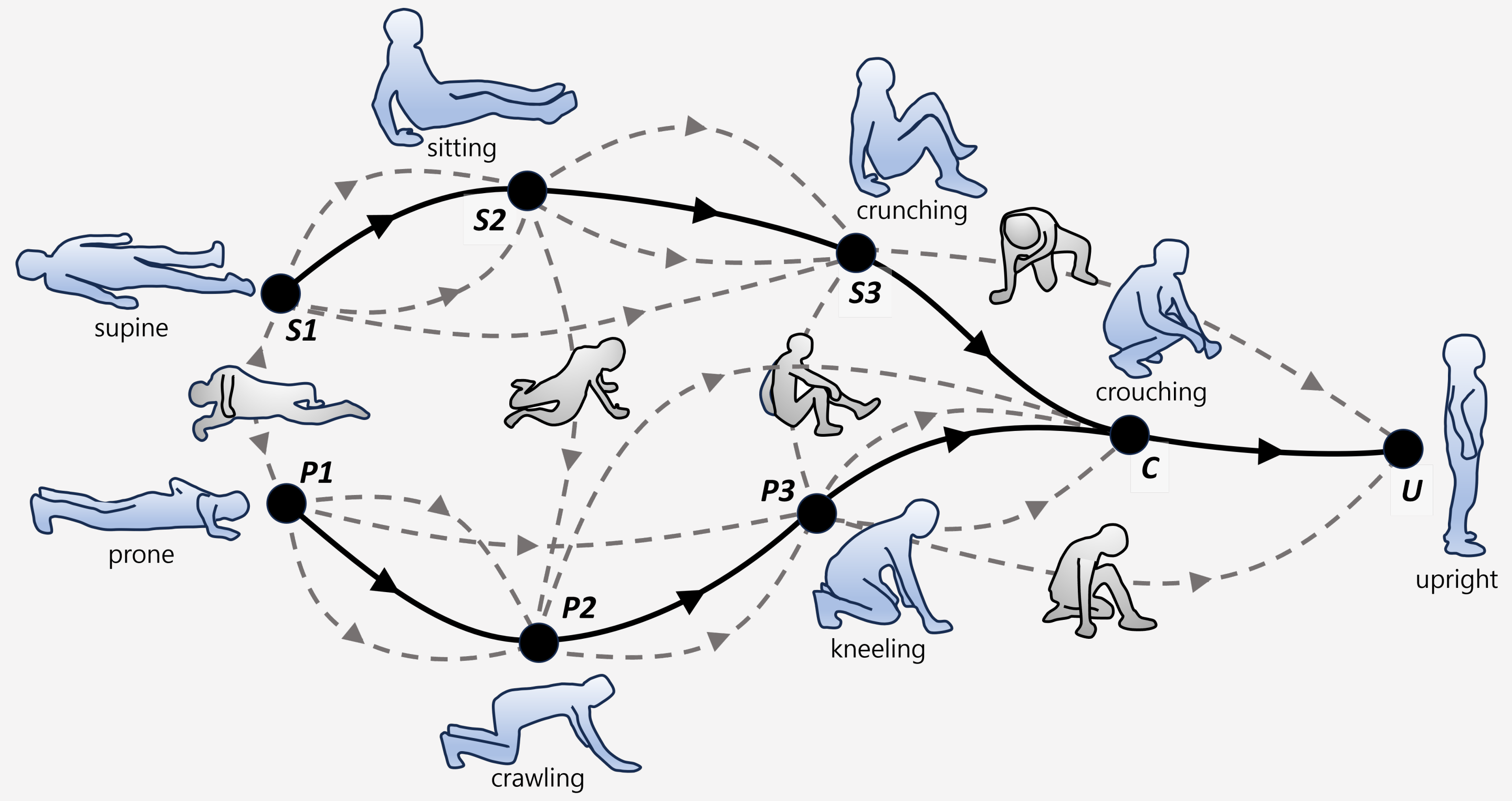


Motivation

- There is no standard method for designing wearable robotic manipulators
  - Most systems are tailored to specific experiments or use cases
- For astronauts, EVA tasks are highly variable, and pressurized space suits introduce significant ergonomic and safety challenges
  - **This motivates the development of versatile and effective Supernumerary Robotic Limbs (SuperLimbs)**

Modeling Astronaut Post-Fall Recoveries



- **Design for the worst-case EVA task -> cover all tasks**
- Space suits constrain recovery to a uniform stand-up strategy [Ballesteros et al. (2024)]
- Model recovery as sagittal, quasi-static pose transitions

E. Ballesteros *et al.*, "Design of Supernumerary Robotic Limbs for the Augmentation of Astronauts Performing Partial-Gravity Extra-Vehicular Activities (EVAs)," *International Journal of Robotics Research*, 2026.

Translating model into design requirements

- For each pose along the recovery path:
  - Maximum voluntary joint torques, $\boldsymbol{\tau_{max}}$, can be estimated by a biomechanics model [Anderson et al. (2007)]
  - Spacesuit-induced joint stiffness torques, $\boldsymbol{\tau_{SSA}}$, are estimated using a data-informed model [Diaz and Newman (2014)]
  - Bracing torques at the astronaut's joints are computed as

$$\boldsymbol{\tau_h} = \boldsymbol{J}^T m_h g$$

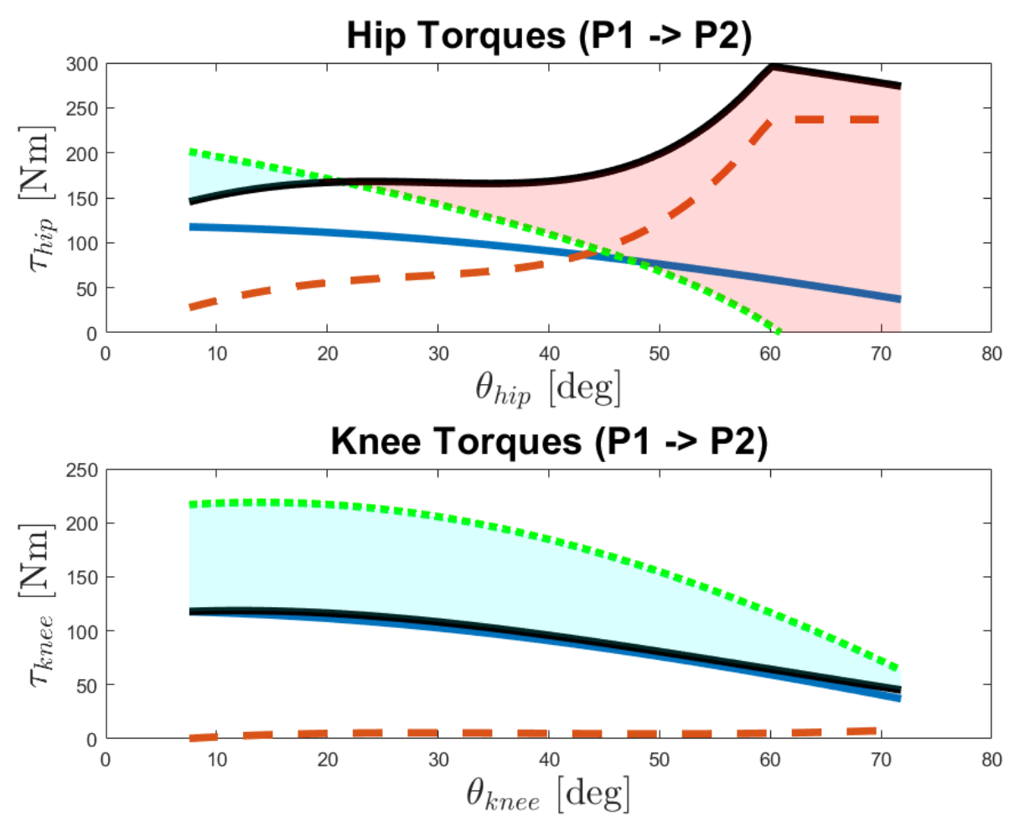
- Required torques that an astronaut must exert:

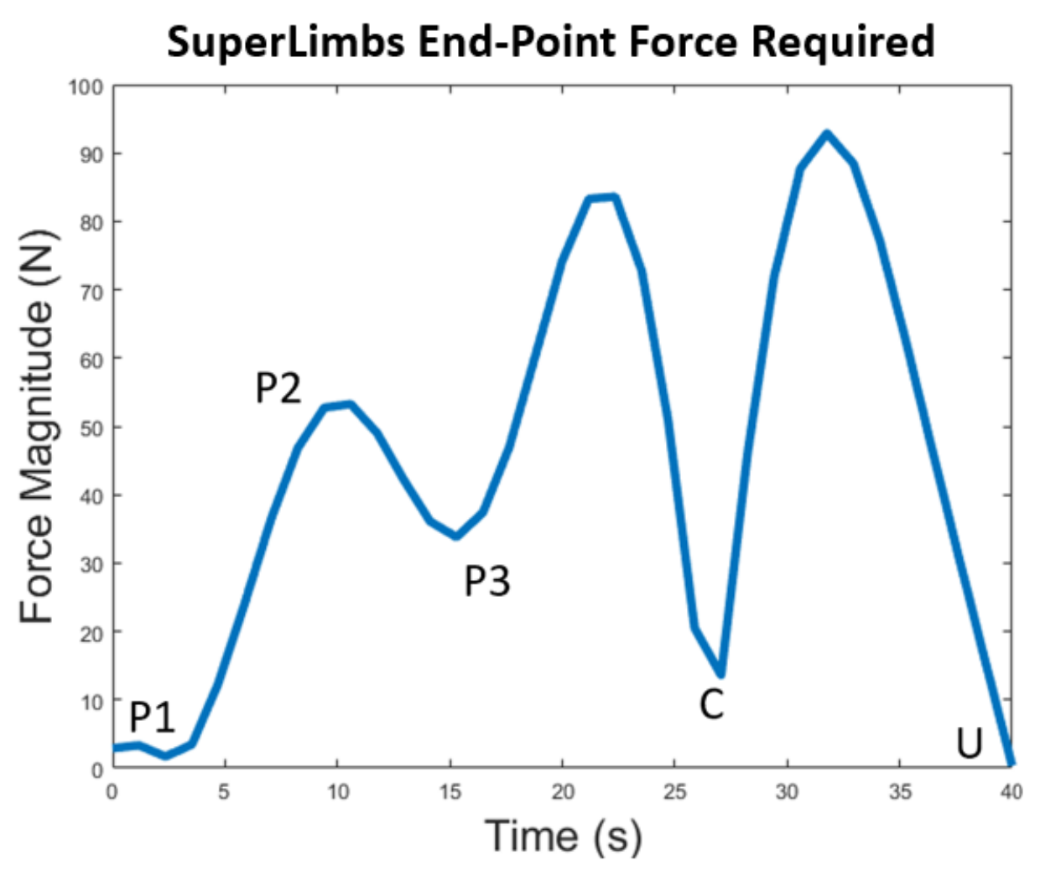
$$\boldsymbol{\tau_{req}} = \boldsymbol{\tau_{SSA}} + \boldsymbol{\tau_h}$$

- The **torque gap**, where the astronaut cannot generate sufficient joint torque, must be compensated by wearable robotic assistance

$$\boldsymbol{\tau_{gap}} = \max[\boldsymbol{\tau_{req}} - \boldsymbol{\tau_{max}}, \boldsymbol{0}]$$

- The torque gap, together with the astronaut's sagittal trajectory, maps into the robot's task space and defines its key design requirements





Finding the right design

SuperLimbs designs can be decomposed into:

- **Intrinsic** Design Parameters
  - Link Lengths, Joint Orientations, Gearing
- **Extrinsic** Design Parameters
  - Contact Point Location, Mounting Location

5.4 million design permutations

Phase 1: Coarse-Grid AI Search

- Simulate each robot design along the sagittal post-fall recovery trajectory
- Evaluate: *reachability*, *singularities*, *friction cone violations*, and *astronaut-robot collisions*
- Prune infeasible branches via backtracking in the design tree

252 vetted designs

Phase 2: Fine-Grid Localized Optimization

- Rank designs by:
  - Minimum actuator energy loss
  - Minimum contact normal forces
  - Maximum allowable shear loads
- Select the top design and perform local fine-grid optimization to minimize:
  - Total actuator energy consumption
  - Tracking error between astronaut recovery trajectory and robot task-space trajectory
- Iterate over design parameters until convergence

1 final design

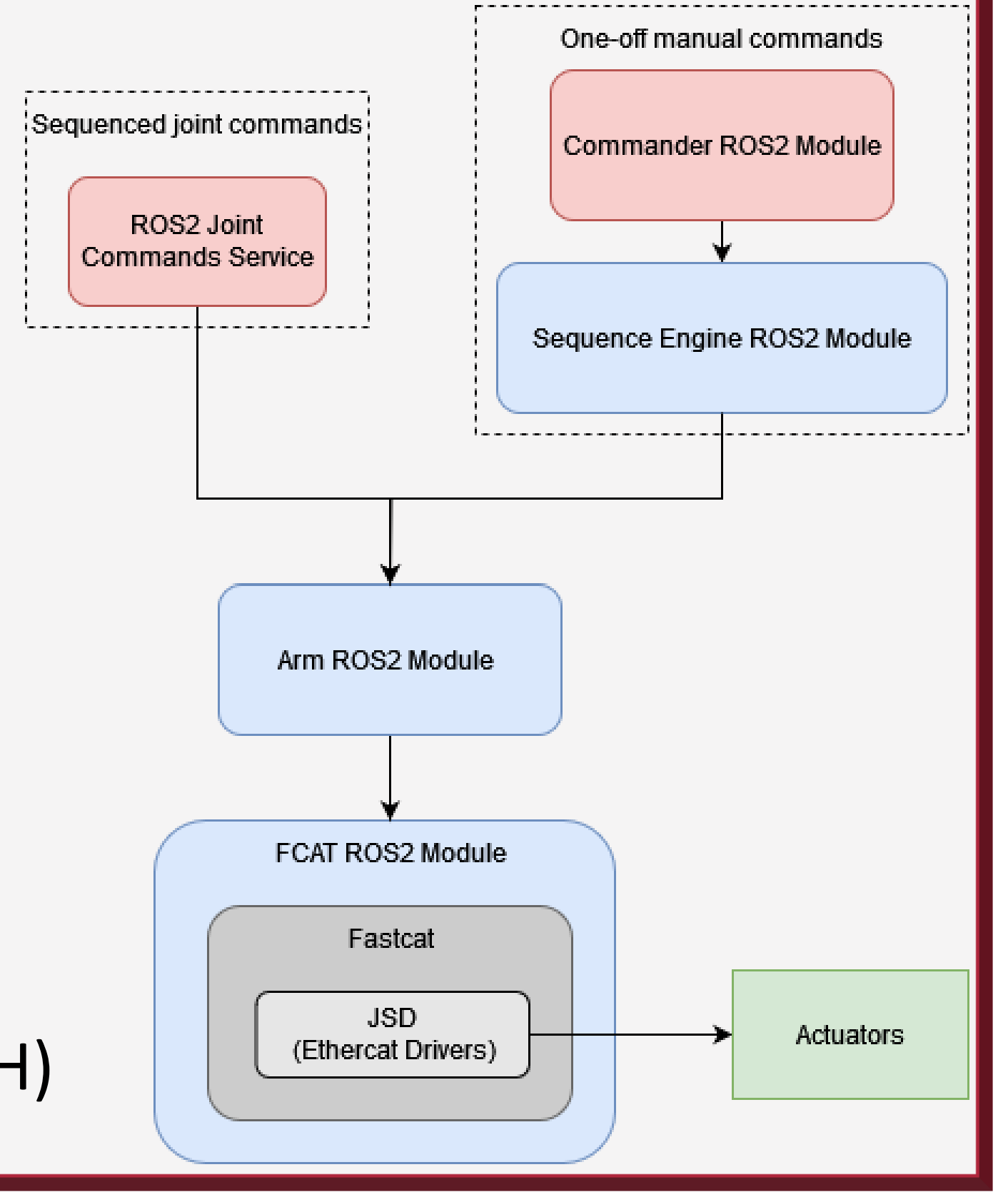
Functional Prototype: SuperLimbs-T1.0

Hardware Description

- Each SuperLimbs arm consists of 4 JPL EELS2.0 actuators
  - 400 Nm MPT (~100 Nm/kg torque density)
- Custom machined AL-6061 linkages
- AL-6061 Backpack frame housing Intel NUC PC

Software Description

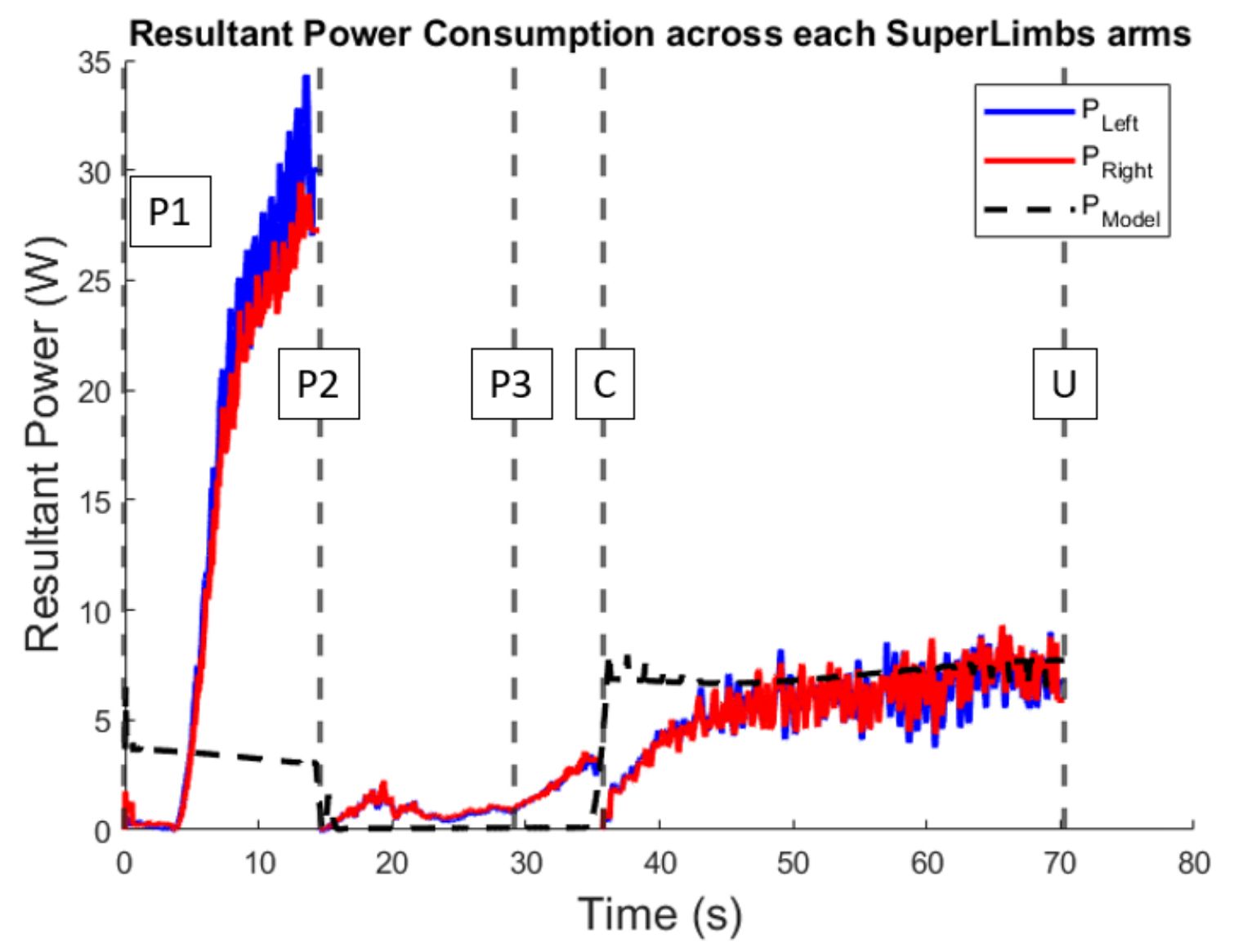
- Each actuator controlled by ELMO Twitter Platinum drivers
  - Communication over EtherCAT chain via Fastcat
  - Intel NUC is EtherCAT master
- ROS2-Based control architecture
  - Variant of JPL-internal Controls and Autonomy for Sample Acquisition and Handling (CASAH)



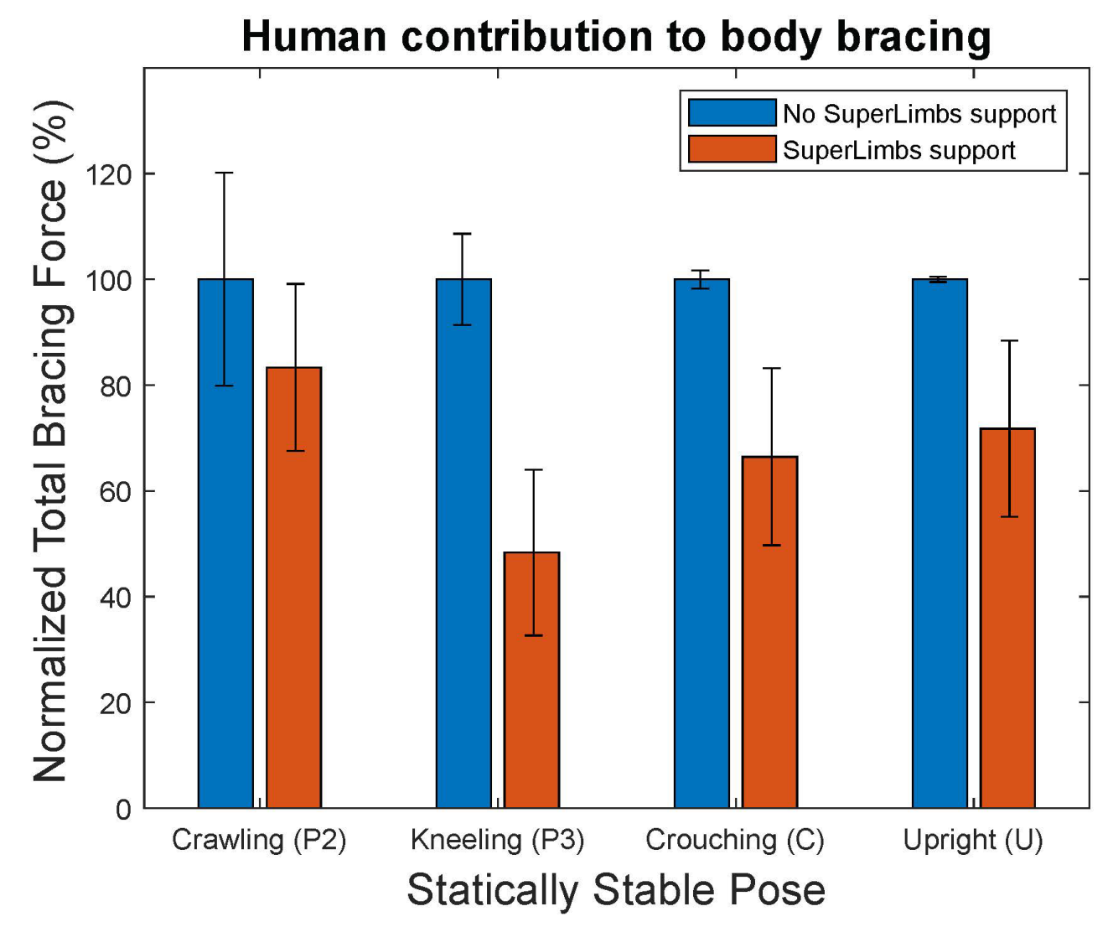
Testing & Validation

Mannequin Post-Fall Recovery Demo

- Nursing mannequin lifted from prone to standing position
  - Actuators performed well within operating range
  - **Aligned with design validation model**



Performance Metric	Model	Prototype
Max Act. Torque		
P1 - P2	105 Nm	310 Nm
P2 - P3	12 Nm	74 Nm
P3 - C	15 Nm	95 Nm
C - U	174 Nm	145 Nm
Max Resultant Pwr. Cons.		
P1 - P2	4 W	32 W
P2 - P3	1 W	3 W
P3 - C	1 W	4 W
C - U	7 W	7 W
Load Bearing Force		
P1 - P2	54 N	94 N
P2 - P3	53 N	51 N
P3 - C	83 N	55 N
C - U	94 N	103 N



Human Body Bracing

- Human participant braced mass of SuperLimbs-T1.0 and spacesuit at prescribed static poses in trajectory
- **SuperLimbs-T1.0 reduced nearly 55% of human loading contribution**