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Supernumerary Robotic Limbs to Support Post-Fall Recoveries for Astronauts

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***Abstract*—This paper proposes the utilization of Supernumerary Robotic Limbs (SuperLimbs) for augmenting astronauts during an Extra-Vehicular Activity (EVA) in a partial-gravity environment. We investigate the effectiveness of SuperLimbs in assisting astronauts to their feet following a fall. Based on preliminary observations from a pilot human study, we categorized post-fall recoveries into a sequence of statically stable poses called "waypoints". The paths between the waypoints can be modeled with a simplified kinetic motion applied about a specific point on the body. Following the characterization of post-fall recoveries, we designed a task-space impedance control with high damping and low stiffness, where the SuperLimbs provide an astronaut with assistance in post-fall recovery while keeping the human-in-the-loop scheme. In order to validate this control scheme, a full-scale wearable analog space suit was constructed and tested with a SuperLimbs prototype. Results from the experimentation found that without assistance, astronauts would impulsively exert themselves to perform a post-fall recovery, which resulted in high energy consumption and instabilities maintaining an upright posture, concurring with prior NASA studies. When the SuperLimbs provided assistance, the astronaut's energy consumption and deviation in their tracking as they performed a post-fall recovery was reduced considerably.**

***Index Terms*—Supernumerary Robotic Limbs, Human-Assistive Robotics, Human-Robot Interaction, Astronaut Ergonomics, Fall Recovery**

I. Introduction

In recent years, the space industry, particularly government agencies like NASA, ESA, and JAXA, have joined together to start sending humans back to the Moon and beyond, known as the Artemis Program [1]. As exciting as it is to see a resurgence in space exploration, there are significant challenges and risks. One key risk concerns that of falls during an Extra-Vehicular Activity (EVA). Astronauts, wearing an Extra-Vehicular Mobility Unit (EMU) experience reduced mobility and additional mass from the space suit. The mission could fail if an astronaut were to fall and be unable to stand back up [2–4]. During the Apollo Program, astronauts were able to adopt different, often awkward and strenuous techniques to recover to their feet following a fall [5]. These methods were viable because the astronauts were subjected to lunar gravity (1.62 m/s^2) and unencumbered. The same methods cannot be adopted for the Artemis Program, particularly due to the facts that:

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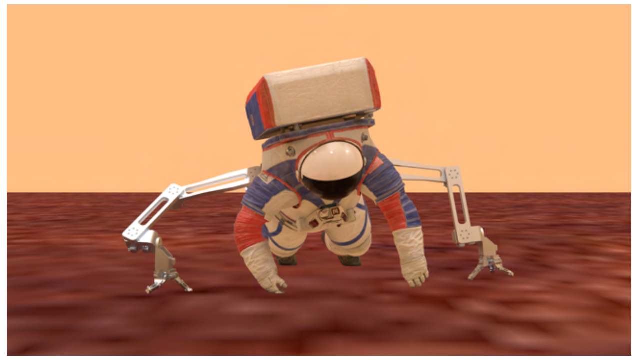


Fig. 1. Rendering of SuperLimbs assisting an Astronant in a Post-Fall Recovery.

- A permanent presence is to be established on the Moon (and eventually Mars) [1], astronauts will carry out rigorous construction tasks, requiring high exertion and effort, while wielding various tools and equipment.
- Martian gravity is greater than that of the Moon (3.71 m/s^2). On Mars, with current systems, it is highly likely astronauts won't be able to recover following a fall, leading to mission loss.

Supernumerary Robotic Limbs, or SuperLimbs for short, are a type of wearable robot designed to augment human capabilities in a plethora of specified activities [6]. SuperLimbs have been demonstrated to support the bracing of the human body for strenuous tasks [7–10], including that of astronauts in micro-gravity EVAs [11].
In this paper we will

- *Perform a human study* to gain insights into an astronaut's movements during post-fall recoveries and the assistance required to successfully perform a post-fall recovery when burdened with additional loads and reduced range of motion.
- *Devise a control scheme* built upon impedance control [12–14] with a trajectory generator and feedforward torque that is modulated by the astronaut. This scheme allows the astronaut to intuitively express intention while providing SuperLimbs with the assistive forces necessary to carry out a post-fall recovery successfully (Fig. 1).
- *Perform an empirical analysis* of the system where we evaluate the effectiveness of SuperLimbs with this control scheme on human test subjects wearing an analog space suit.

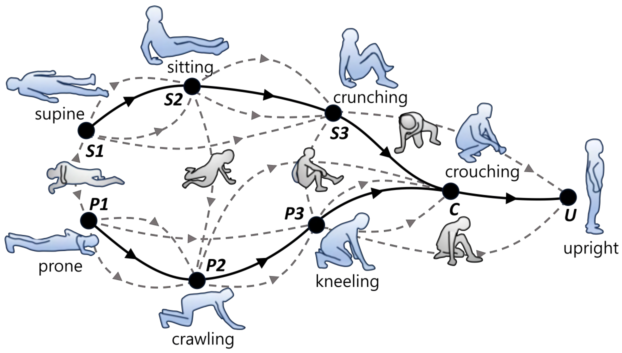


Fig. 2. Representation of the sequence of waypoints (bolded) taken by humans to perform post-fall recoveries. Solid black paths are to represent the most straightforward/common paths taken, while dashed paths represent alternative/less common paths taken.

II. Problem Discovery/Investigation

In order to best assist an astronaut following a fall, we must first understand how astronauts rise to their feet. To carry this out, we investigate how a human performs a post-fall recovery and the effects of additional loads and high joint stiffness. All human studies are conducted under the protocol approved by the Massachusetts Institute of Technology Committee on the Use of Humans as Experimental Subjects, protocol number 2306001022.

A. Unconstrained Human Study

Four test subjects ($weight$ = 75.14 $\pm$ 12.85 kg; $height$ = 1.78 $\pm$ 0.07 m) were asked to perform a post-fall recovery starting from both a supine and prone position. Using OpenPose [15] to analyze RGB video data, we observed the kinematic behavior of the test subject's movement throughout a post-fall recovery [16]. By analysis of the data, we were able to make the following key observations:

- **Waypoints:** As the test subjects performed a post-fall recovery, they moved from one pose that is statically stable to another, we called these "waypoints". Fig. 2 shows those waypoints observed. Mechanistically, a waypoint pose is one where a test subject's limbs can maintain that pose without significant muscular effort.
- **Adopting same sequence of waypoints:** The test subjects adopted a consistent sequence of waypoints during a post-fall recovery.
  - From a supine position (S1), 67% of test subjects adopted a strategy of sitting upright (S2), then proceeding to a crunch position (S3), where they would lean forward to crouch (C), and finally stand to their feet (U), as shown in Fig. 2.
  - The remaining 33% of test subjects would sit upright (S2) and proceed to a crunch position (S3). However they would instead roll their body to take a kneeling position (P3), then sit up into a crouch position (C) and finally stand (U), as shown in Fig. 2.
  - From a prone position (S1), 100% of test subjects began by pushing up into a crawling position (P2), then would sit back into a kneeling position (P3) and lean forward into a crouching position (C), then finally stand to their feet (U), as shown in Fig. 2.

Variations in the paths between waypoints were minor and likely attributed to each test subject's particular muscular strength and skeletal build. Based off these findings, we can safely assume human motion planning in a post-fall recovery is non-stochastic and can be directly modeled as a sequence of waypoints depending on starting position, with an optional switch between crunching (S3) and kneeling (P3) waypoints.

B. Partially Constrained Human Study

We had test subjects repeat post-fall recoveries but wearing a large trekking backpack (15.88 kg), to simulate a large off-centered load with bandages wrapped around the wrists, elbows, knees, and ankles to emulate the increased joint stiffness when wearing a space suit. Key observations from this experiment were the following:

- **Adoption of same sequence of waypoints as the unconstrained case:** Test subjects would follow the same sequence of waypoints as they did in the unconstrained case. We observed test subjects limiting the level of exertion in their joints constrained by the bandages. This led to test subjects adopting paths between waypoints where their limbs would be kept nearly fully extended.
- **Priority of stability over efficiency:** The inclusion of the large backpack shifted the test subject's center of mass. Test subjects were shown to move much slower than when unconstrained. Often test subjects would widen their stance with the ground to maintain balance. Additionally, all test subjects avoided taking a path from crunching (S3) to crouching (C), and instead rolled to kneeling (P3), then to crouching (C).

This preliminary human study offered great insight into the mechanics of human's bodies when they perform a post-fall recovery. However, this study comes with some caveats:

- Test subjects were able to utilize the flexibility in their waist to move between waypoints. The xEMU [17] consists of a Hard Upper Torso (HUT) and brief that restricts the ability to use one's waist for mobility.
- The mass of the trekking backpack (15.88 kg) is dramatically less than that of the xEMU (54.43 kg). The inertia that test subjects would need to overcome from a space suit are not considered in this preliminary study.
- The bandages used to increase joint stiffness could only partially simulate the stiffness of a pressurized space suit. The preliminary study lacked restraint on the shoulder and hip joints that are present on the xEMU.

III. Testing Platform Design

The analog space suit, known as the Supernumerary Robotic Limbs Extra-Vehicular Mobility Unit (SuperEMU) (shown in Fig. 3), is a testing platform we developed in-house, designed to simulate the mass/inertia and constrained ranges of motion of a modern space suit platform, utilizing the xEMU as a design benchmark [17–19]. Features of the SuperEMU are:

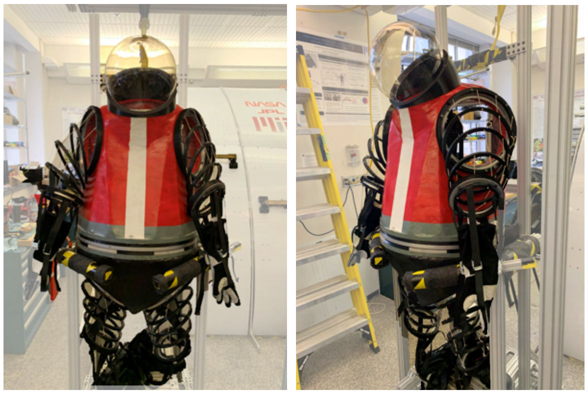


Fig. 3. Supernumerary Robotic Limbs Extra-Vehicular Mobility Unit testing prototype (SuperEMU).

- *Rotary bearings* positioned about the waist, shoulders, thighs, elbows, knees, wrists, and ankles.
- *A HUT and brief* constructed with fiberglass, enabling rigidity and impact resistance for extensive testing.
- *Sleeves* for the arms and legs that forms a bellows-like structure to simulate the xEMU's bulky pressure garment.
- *Boots and Gloves* with high joint stiffness.
- *A large backpack frame* to simulate the mass and volume of the Portable Life Support System (PLSS).
- *An internal structural frame* that offsets any mounted loads away from the body of the HUT and brief.
- *An integrated mounting harness* that distributes the weight of the space suit to the user's waist and shoulders.
- *Tracking markers* positioned at landmarks around the suit to capture pose data.

The total mass of the SuperEMU is approximately 40 kg. In addition to the SuperEMU mimicking the xEMU space suit, it was also designed as a testing platform with the intention of trialing different SuperLimbs in various partial-gravity EVA tasks. Particularly, the HUT and brief are capable of having payloads with high dynamic loads in various locations.

A. Control Platform

In the development of a control platform for the SuperLimbs, numerous design considerations must be taken into account. These include the attachment location of the SuperLimbs and the directional forces exerted on the human body in various postures. To empirically investigate these factors, a robotic arm with a high degree of freedom is required. In this study, we utilized the UR10e cobot from Universal Robots as a surrogate for the SuperLimbs to conduct our research. The base of the UR10e was anchored to the floor, while its end-effector was affixed beneath a large backpack frame. Control implementation was carried out through the use of Real-Time Data Exchange (RTDE), enabling precise and dynamic adjustments [14, 20].

IV. Control System

In order for SuperLimbs to be effectively utilized by astronauts for partial-gravity EVAs (specifically for post-fall recoveries), we must take heed of the following key considerations in the interest of human-robot interaction:

- The inertia of the astronaut wearing a space suit with a PLSS is large, resulting in overshooting of their position when they are trying to stop their motion.
- The gravity is low, resulting in less braking effect when standing up.
- The ground contact is unidirectional; both human hands and SuperLimbs end-effectors can apply only downward pushing forces, not upward pulling forces.
- The astronaut can apply a force on the ground only at a limited range of postures.
- The astronaut must be in-the-loop at all times so that he/she can adapt to contingencies and unexpected conditions. The astronaut must have the control authority to perform voluntary control.
- The SuperLimbs must not impede the astronaut's motion for recovering from a fall.

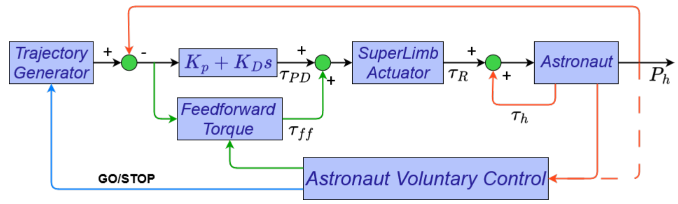


Fig. 4. Block Diagram of Astronaut-SuperLimbs system where the human is supported with impedance $K_p + K_D s$ and controls the recovery process.

A. Strategy and Architecture

To meet these working conditions and functional requirements, this paper presents the SuperLimbs control system shown in Fig. 4. The system consists of a trajectory generator, a PD + feedforward controller, and an astronaut's voluntary controller. To prevent an overshoot in a low gravity environment, this control system allows no large acceleration; the process is kept quasi-static. Yet, the astronaut's body is compliantly supported with low impedance, and the astronaut can control the waypoint-to-waypoint process and superpose or override his/her voluntary control command to the robot controller. The system is tuned as detailed below:

- The trajectory generator stores a series of waypoint-to-waypoint segments of trajectory, and provide each segment based on the astronaut's GO/STOP sign.
- The feedforward torque τ_{ff} is to compensate for a fraction of the gravity load of the astronaut and the space suit. Furthermore, the astronaut is allowed to control the SuperLimbs voluntarily by increasing or decreasing this feedforward torque τ_{ff}. The astronaut can also modulate the feedforward torque to adjust the level of support.
- A low servo-stiffness, trajectory control loop is formed to follow each segment of the trajectory. The proportional feedback gain K_P is kept low, so that the astronaut's voluntary motion with torque τ_h may not be constrained. Furthermore, the derivative gain K_D is high enough to

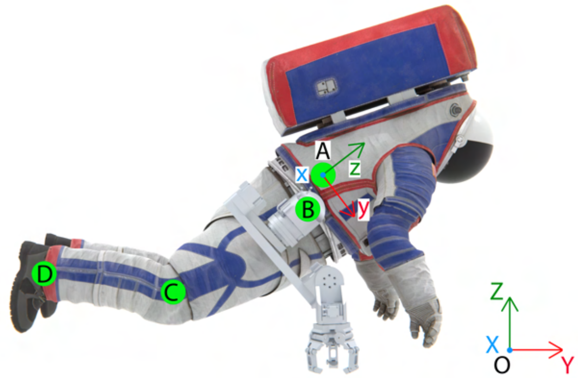


Fig. 5. Sagittal view of astronaut performing post-fall recovery.

reduce the deviation from a desired speed. This is to prevent overshoot and jerky motion from occurring.

B. Trajectory Generation

Based on our observations from the initial human study (Section II), we were able to categorize the waypoints into a set of consistent states of the astronaut body, as shown in Table I. Once the trajectory generator creates a reference path and the astronaut explicitly commands the SuperLimbs to execute movement, a task-space impedance controller drives the motion. The coordinate systems are shown in Fig. 5 represented along the sagittal plane. $O - XYZ$ is the inertial reference frame and $A - xyz$ is the reference frame tied to the astronaut's center of mass. Points B, C, and D refer to the positions of the waist, knee, and ankle joints, respectively.

Each path that traverses from one waypoint to the next in a sequence can be approximated by applying a single force or torque about a point on the astronaut's body along a particular direction, shown in Table I.

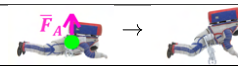
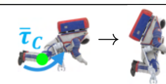
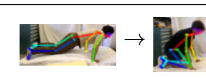
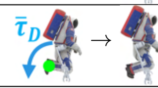
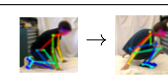
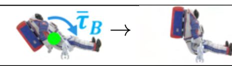
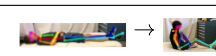
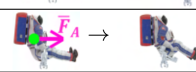
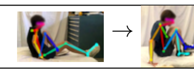
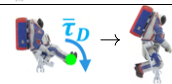
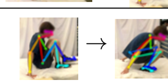
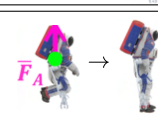
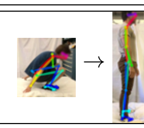
- **P1** $\rightarrow$ **P2**: A vertical force applied about CoM (Pt.A)
- **P2** $\rightarrow$ **P3**: A torque applied about knee joint (Pt.C)
- **P3** $\rightarrow$ **C**: A torque applied about ankle joint (Pt.D)
- **S1** $\rightarrow$ **S2**: A torque applied about hip joint (Pt.B)
- **S2** $\rightarrow$ **S3**: A horizontal force applied about CoM (Pt.A)
- **S3** $\rightarrow$ **C**: A torque applied about ankle joint (Pt.D)
- **C** $\rightarrow$ **U**: A vertical force applied about CoM (Pt.A)

C. Voluntary Control and Human Intention Detection

The commanded torque into the SuperLimbs is a superposition of both the torque to maintain a path from one waypoint to another, denoted as τ_{PD}, and the feedforward torque, τ_{ff}. τ_{ff} is to be modulated based upon direct explicit input by the astronaut user. Similarly, the astronaut can explicitly command the trajectory generator to initiate/terminate the motion from the SuperLimbs as a GO/STOP command. Explicit commands from the astronaut could be realized by use of the Display and Control Module (DCM) mounted on the xEMU space suit [19] or an alternative/more advanced astronaut interface [21–23].

In addition to the astronaut having explicit control over the initialization/termination of SuperLimbs assistance in post-fall recoveries, the astronaut is also to supply input into the

TABLE I
CHARACTERIZATION OF PATHS BETWEEN WAYPOINTS AND THE REQUIRED FORCES/TORQUES

Path	Model	Human Study
P1 $\rightarrow$ **P2**		
P2 $\rightarrow$ **P3**		
P3 $\rightarrow$ **C**		
S1 $\rightarrow$ **S2**		
S2 $\rightarrow$ **S3**		
S3 $\rightarrow$ **C**		
C $\rightarrow$ **U**		

trajectory plan for the task-space impedance controller. This is to be done implicitly, by capturing the state of the astronaut body (P_h), see [11].

V. EXPERIMENTATION

Once we completed development of the SuperEMU and SuperLimbs system, we executed a follow-up human study to validate the effectiveness of SuperLimbs on astronaut post-fall recoveries. The subject testing was divided into three phases:

- ***Phase 1*: Control/Baseline** - Observation of post-fall recovery without assistance.
- ***Phase 2*: Assistance Profiling** - Repeat of Control/Baseline with test operators applying external forces to assist test subjects with post-fall recovery.
- ***Phase 3*: SuperLimbs Realization** - Repeat of Control/Baseline with UR10e cobot acting as the SuperLimbs to assist test subjects in select stages of post-fall recovery.

During each testing phase, we captured the following metrics:

- **Position** of the test subject's center of mass (CoM) to profile their body motion through use of motion capture via the OptiTrack system.
- **Externally applied assistive forces** to the test subjects by means of a handheld load cell with an embedded Inertial Measurement Unit (IMU) (Phase 2 only) or the Force/Torque Sensor located on the end-effector of the SuperLimbs (Phase 3 only).

We asked each test subject from the initial human study (Section II) to assume a supine or prone position while wearing the SuperEMU. Then, we asked each test subject to attempt to rise to their feet. During Phase 2, a test operator would apply an assistive external force to the test subjects as they performed their post-fall recovery. During Phase 3, the UR10e would

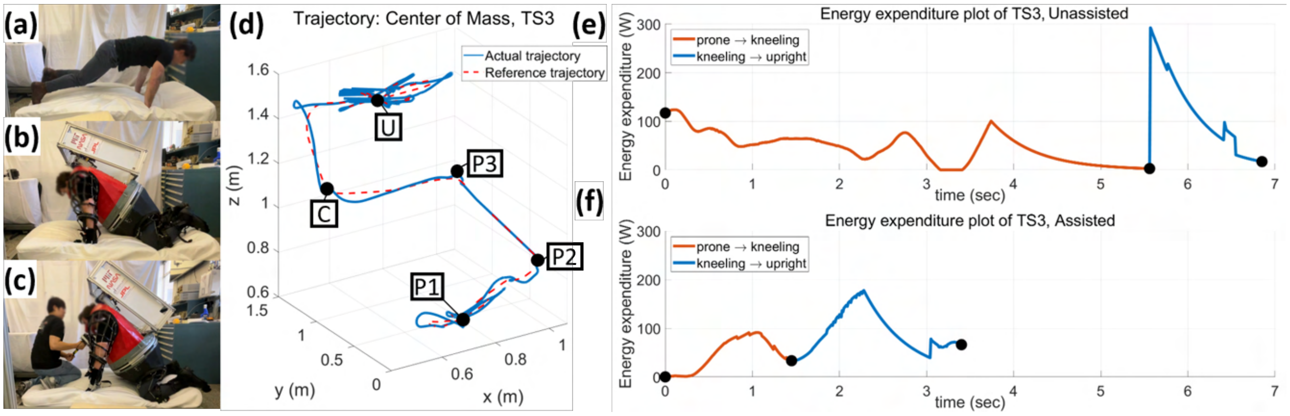


Fig. 6. Experimental setup and representative results of a typical test subject, other subjects showed similar behavior. (a) Test subject performs voluntary post-fall recovery process without any restriction. (b) Test subject performs voluntary post-fall recovery assisted by a test operator. (c) Test 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.

TABLE II
HUMAN SUBJECT PERFORMANCE FOR POST-FALL RECOVERIES

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

enact the SuperLimbs control system to apply the assistive external forces to the test subjects. A test operator with a joystick would drive the reference position of the robot.

VI. ANALYSIS/RESULTS

A. Success Rate Analysis

An astronaut being able to successfully perform a post-fall recovery is critical to the validation of SuperLimbs. The degree of how far along the post-fall recovery each test subject achieved (final CoM height with respect to upright CoM height) was quantitatively measured with the motion tracking system (Flex3; Optitrack). Table II shows the level of success of each test subject as a percentage. Without assistance, TS2 and TS4 were unable to successfully perform a post-fall recovery. With assistance, TS2 showed considerable improvement while TS4 was able to succeed in a post-fall recovery.

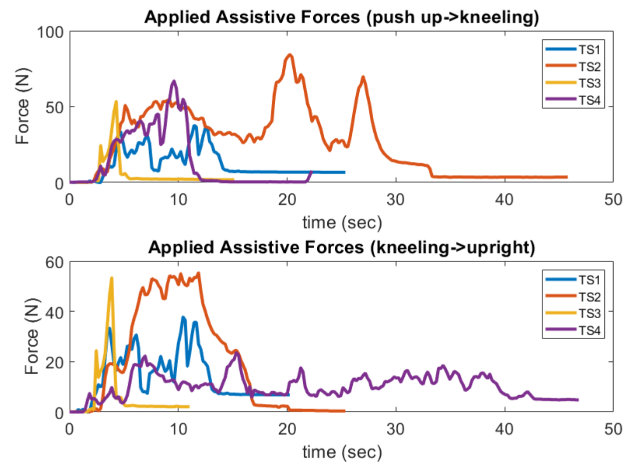


Fig. 7. Profiles of assistive forces required for suited post-fall recovery.

B. Exertion Analysis

The level of exertion can be quantified by work against gravity with respect to time [24, 25]. Fig. 6(e) and Fig. 6(f) depict the energy exerted by one of the test subject's when unassisted and assisted, respectively. We determined work by integrating the energy exertion throughout the post-fall recovery for each test subject, and the results are tabulated in Table II. Overall, on average test subjects with assistance reduced energy consumption by 15.28%.

C. Tracking Accuracy Analysis

When performing a post-fall recovery, one important evaluation criterion for SuperLimbs concerns the astronaut's upright stability. Using each test subject's motion tracking data, we evaluated the stability by quantifying the deviation in the position of their CoM [26–28]. Using a low-pass filter ($f_{cutoff} = 10Hz$), we could estimate the non-trembling reference trajectory. The integrated difference between that reference trajectory and the actual recorded positions were scored to measure stability, as shown in Table II and Fig.

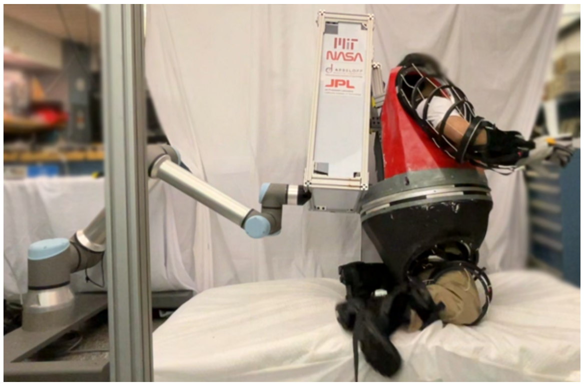


Fig. 8. Test subject wearing the SuperEMU performing a kneeling to upright transition with the assistance from SuperLimbs.

TABLE III
IMPACT OF FEEDFORWARD TORQUE ON ASTRONAUT PERFORMANCE

Feedforward torque support lvl (%)	100	75	50	25
Energy Consumption (J)	52.15	52.25	55.33	56.02
Energy Reduced (%)	6.92	3.17	1.24	0

6(d) [29]. When test subjects were assisted, deviations in their tracking reduced by an average of 38.13%, showing improvement in upright stability.

D. Observations

Unassisted test subjects struggled to stand to their feet from either a supine or prone position, this was especially obvious for TS2 and TS4. The restrictions presented by the SuperEMU forced test subjects to exert significant joint torques to overcome the inertia of their body and the space suit. This led to not only high effort, but also significant instability. Both of these conditions lead to high risks associated with partial-gravity EVAs identified by NASA [2–5]. What was also surprising was that between all test subjects, similar paths were adopted with minor variations. Effectively, every test subject who could successfully carry out a post-fall recovery chose the same sequence of waypoints as they recovered to their feet, in agreement with our earlier observations during the discovery/investigation study.

When assistive forces were applied to the test subjects wearing the SuperEMU, test subjects who were too small (TS2 and TS4) to properly fit the space suit required significantly larger supportive loads to successfully traverse from one waypoint to another, shown in Fig. 7. This is consistent with the observations that the fit of the astronaut to the space suit plays a crucial role in their physical performance [30, 31]. Test subjects who fit the SuperEMU (TS1 and TS3) were able to successfully carry out the post-fall recovery, regardless of assistance from the SuperLimbs; however like the other test subjects, energy consumption and stability were improved with assistance.

E. Control System Evaluation

Additionally, the study examined how variations in key parameters of the control system influenced the effectiveness of fall recovery assistance [32]. Specifically, we observed the effects of adjusting the feedforward torque, within the control algorithm applied to the UR10e cobot (Fig. 8). Our findings indicate that the most significant assistance, in terms of exertion by the test subjects, was achieved when the UR10e cobot was configured to offer maximum allowable support (Table III). Conversely, below a certain threshold, the assistive impact was found to be minimal. This suggests a critical dependency of assistance efficacy on the tuning of control parameters, illuminating the need for optimal parameter calibration.

VII. CONCLUSION

In this paper, we conducted an extensive study into the mechanics of post-fall recoveries. Starting with an unhindered/unsuited set of test subjects, we found that humans fundamentally move between a highly determined sequence of waypoints based off of starting position. When test subjects were hindered by additional mass and reduced mobility, the paths between waypoints would change to better accommodate unfamiliar inertia and lack of flexibility; however the sequence of waypoints remained consistent with the unhindered case. With this knowledge, we were able to devise a strategy to assist the test subjects by applying external forces along the same direction as the forces/torques required by the human to move between waypoints.

Once test subjects wore the SuperEMU, we found that the paths between waypoints were carried out by test subjects impulsively applying force along the path direction, leading to unstable motion and high effort, which aligned well with prior studies conducted at NASA. To combat this behavior, we devised a control scheme using task-space impedance control with high damping and low stiffness, which enables a set of SuperLimbs to apply assistive forces and allow stable quasi-static motion to the suited test subjects, while also providing them with significant control authority. Experimental data delivers promising results for the utilization of SuperLimbs to address astronaut post-fall recoveries. Future work should revisit this study, but in an environment that can mimic both lunar and martian gravity, such as the Active Response Gravity Offload System (ARGOS) at the NASA Johnson Space Center [33]. Additionally, use of a higher fidelity measurement test, such as the Peak Oxygen Consumption (VO_2pk) test [34], should be utilized to provide enhanced insight into astronaut exertion.

With the human study conducted in this paper, alongside the task-space impedance control developed and validated, a promising solution utilizing SuperLimbs can be integrated into future missions for human spaceflight.

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