Supernumerary Robotic Limbs to Augment Astronauts Performing Post-Fall Recoveries during Partial-Gravity Spacewalks

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This paper investigates the effectiveness of a type of wearable robot, known as Supernumerary Robotic Limbs (SuperLimbs) in assisting an astronaut performing partial-gravity Extra-Vehicular Activities (EVAs). SuperLimbs can directly address a key technology gap identified by NASA concerning that of incapacitated crew rescue devices during partial-gravity EVAs. To contextualize SuperLimbs in human spaceflight application, we start by reviewing other forms of wearable robotics technologies and perform a qualitative comparison with SuperLimbs. From there, we present a suite of operational modes that SuperLimbs is capable of delivering in a suited partial-gravity EVA. Within the operational mode suite, we selected the most urgent use-case: that of performing a post-fall recovery, and reviewed the results from a pilot-human study. To validate the effectiveness of SuperLimbs in providing the necessary assistive forces needed for a post-fall recovery, a series of validation experiments was performed with a prototype SuperLimbs system.

I. Introduction

Human spaceflight has emerged into an unprecedented age, where public interest has surged and a desire to innovate/push the boundaries of technological capabilities has swept across the aerospace industry. Commercial companies like that of SpaceX, Relativity Space, and Axiom Space continue to push the envelop of what is possible in human spaceflight. Additionally international agencies, like that of the ISRO and CNSA, are rapidly developing their human spaceflight programs and are poised to position themselves as leaders in the space industry [1]. The rapid growth within the space industry, both domestically and internationally, has pressured NASA to once again to make its' next giant leap: putting "boots on the moon" and establish a permanent human presence on the moon via the Artemis Program [2]. A program as ambitious as Artemis presents many challenges across a plethora of various fields. Technologically speaking, humans are complex systems highly sensitive to their environment, with micro-gravity and partial-gravity environments considered some of the most hazardous.
In order to combat the harsh environments present in spaceflight missions, astronauts must don a pressurized space suit, which protects their body yet restricts their mobility and utility, presenting additional risks [3]. The type of work and productivity we take for granted in a 1-G environment while wearing unrestricted clothing (such as walking, kneeling, etc.) are hindered significantly, which limits the level of productivity and breadth of work that astronauts can perform per EVA. *The EVA goals outlined by the Artemis Program may be jeopardized by an astronaut's loss of capabilities within a pressurized space suit*.

One solution to address the issue of human performance in suited EVAs is through the use of physical augmentation by means of wearable robotic systems. Particularly, we propose the use of a type of wearable robot, known as Supernumerary Robotic Limbs, or SuperLimbs for short. SuperLimbs, unlike an exoskeleton, can take on any shape

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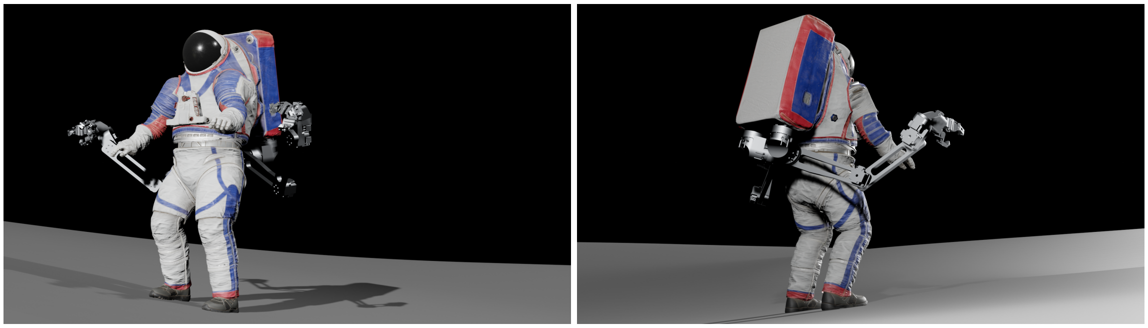

Fig. 1 Conceptual Rendering of Supernumerary Robotic Limbs mounted to a NASA xEMU space suit.

or size independent of the kinematics of the human wearer, taking the function of a second set of arms, legs, or a combination thereof; this allows designers to have high flexibility in the overall physical and operational design of the robot [4],[5],[6]. We propose that SuperLimbs can augment suited astronauts in a manner that offsets physical hindrances due to the pressurized space suit and presents a new paradigm of suited astronaut capabilities, possibly expanding the envelop of what astronauts can perform. Prior works have investigated the impact SuperLimbs has on astronaut productivity and ergonomics in a micro-gravity environment [7] and also begun to investigate human behavior in suited post-fall recoveries in partial-gravity environments [8].
This paper makes the following contributions:

1) Introduce SuperLimbs as a technological solution for human augmentation, comparing and contrasting it with existing wearable robot designs.
2) Contextualize the various use-cases of SuperLimbs in the utility of augmenting astronauts while they perform partial-gravity EVAs.
3) Perform an extensive analysis into performing a post-fall recovery: one of the key use-cases that addresses a technology gap identified by NASA.
4) Perform a follow-up human study demonstrating the effectiveness of SuperLimbs as a potential countermeasure to perform Post-Fall Recoveries.

II. Current State-of-the-Art in Robotic Human Augmentation

To better understand what SuperLimbs are and how they may benefit human spaceflight, we first must establish a conceptual foundation of what separates SuperLimbs from other wearable robotic systems. We begin by analyzing the most commonly adopted wearable robotic systems, providing a surface-level description of each system with examples of commonly accepted use-cases, then describe its' pros and cons. Finally, we introduce SuperLimbs as an alternative option for a wearable robotic system.

A. Exoskeletons

Exoskeletons are externally worn robotic devices that are tied directly to the body of the wearer [9]. Exoskeletons often are used to directly augment the physical performance of the human wearer's limbs. In order for exoskeletons to achieve direct user augmentation, actuators directly in line with the joints of the wearer are positioned such that the effective bracing/exertion torque by the user's joints is amplified or attenuated. Exoskeletons are worn normally by a series of fastening points around the body of the wearer (usually with straps or other means of soft mounting), however, mounting to the wearer will vary from one exoskeleton design to another.
Applications of exoskeletons vary significantly, ranging from military all the way to medical applications. For example, exoskeletons have been demonstrated to provide higher load-bearing support for shipping warehouse workers, where lifting boxes with large loads is paramount to their every day duties [10]. Similarly, exoskeletons have been shown to positively augment wearers with ambulated gait deficiencies due to neurological disorders, such as Parkinson's Disease [11].
Exoskeletons, in the context of wearable robotic devices, provides the following advantages:

- Exoskeletons provide direct augmentation/attenuation of human joints, making control intuitive from an operator perspective at the joints.

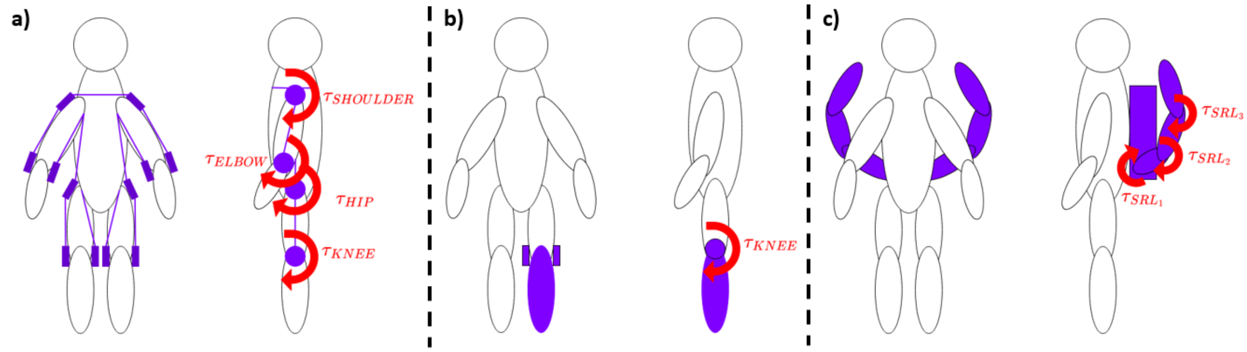

Fig. 2 Generalized representation of human augmentation via a) an exoskeleton (shown in purple). Exoskeleton actuators are attached externally to the joints of the wearer. Augmentation is provided by the actuators providing torque *in addition to* the torque of the wearer's preexisting joints, b) a prosthetic (shown in purple). Prosthetics are attached externally and serve as replacements for lost/missing appendages. Augmentation is provided by the actuators providing torque *in replacement of* the torque of the wearer's preexisting joints, and c) a set of SuperLimbs (shown in purple). SuperLimbs are attached externally and serve as additional appendages. Augmentation is provided by the actuators providing torques *in parallel to* the torques of the wearer's preexisting joints.

- Actuators on exoskeletons can be scaled, providing the wearer with significant augmentation capabilities.

Conversely, exoskeletons have the following shortcomings:

- Exoskeletons are constrained to the body of the wearer. The effectiveness of exoskeletons is heavily subject to the pose of the wearer's limbs. For supporting a human working on or near the ground, for example, exoskeletons are incapable of providing effective body bracing [12].
- Exoskeletons are large/bulky and often physically constraining systems for the wearer. Exoskeletons are composed of a series of actuators and linkages that must be tied to the joints of the wearer's body. This leads to additional mass and possible restrictions in range of motion to the wearer.

B. Prosthetics

Prosthetics are externally worn robotic devices that replace preexisting appendages of the wearer [13]. Due to the mere fact that prosthetics are replacements for human limbs, their applications are contained primarily within the medical field. Interestingly, prosthetics can be either passive [14] or active [15], allowing for a wide variety of prosthetics to be developed. Generally, prosthetics are designed such that they mimic the original appendage as closely as possible. For active prosthetics, actuators are mounted such that they directly overlap with the joint they are mimicking. Mounting of a prosthetic will vary based on the appendage it is serving to replace.

To this end, prosthetics provide the following advantages:

- Prosthetics generally are self-contained devices, in that all of the hardware necessary to power and operate are stored within a single package. This provides prosthetics with the advantage of being noninvasive in the wearer's every day activities.
- Prosthetics are widely used and accepted wearable robotic devices, leading to a plethora of options for wearers and the ability to routinely maintain/upkeep.

In contrast, prosthetics come with disadvantages:

- Prosthetics are highly customized to the wearer. In general, prosthetic devices must have custom fabricated interfaces to mount with the body of the user.
- Active prosthetics often require invasive surgery in order to integrate effective neurological sensors for control. Neurological sensors installed externally on the wearer's body are often highly noisy and can lead to control system instabilities.

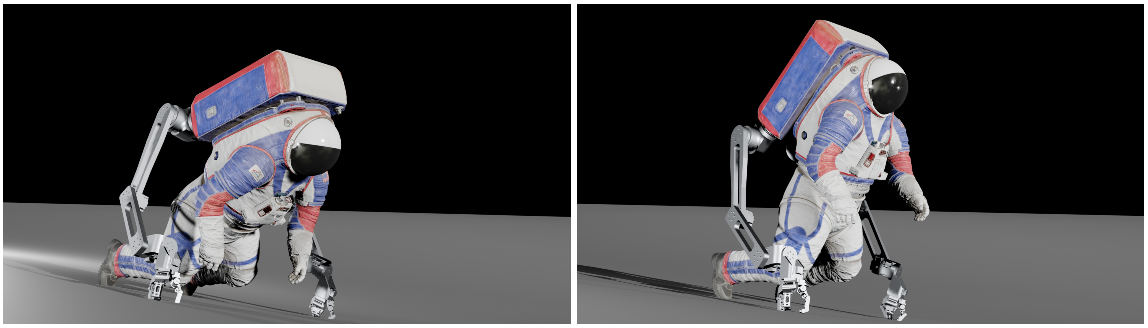

Fig. 3 Conceptual rendering of SuperLimbs performing a post-fall recovery, where the astronaut wearer is being navigated from a push-up position to a kneeling position.

C. SuperLimbs

SuperLimbs are externally worn robotic devices that provide additional appendages to the wearer [16]. SuperLimbs, due to their nature of not being constrained by the wearer's body, can provide augmentation in a plethora of ways. SuperLimbs can be thought of as a set of wearable robotic manipulators, where actuators are configured such that they follow an open-loop kinematic chain with a base tied at the wearer. For many SuperLimbs designs, the additional appendages can be used as a redundant set of legs, providing bracing support [12]. Alternatively, SuperLimbs can act as an entirely novel appendage, like that of a tail, used for balance control [17].

Applications of SuperLimbs has been explored in a wide variety of fields. The ability for SuperLimbs to act as additional appendages has also been investigated in providing novel new paradigms for package handling and navigating spaces when the wearer's arms are occupied [18].

SuperLimbs provide the following advantages:

- SuperLimbs can assume any structure independent of the wearer. This allows SuperLimbs to have an unconstrained design space in terms of physical makeup and control.
- SuperLimbs can be mounted and oriented on the wearer in any way deemed physically plausible. The wearer can be physically modified in a manner that can provide novel solutions to performing a variety of human tasks.

Alike the other types of wearable robotic systems, SuperLimbs too bear shortfalls that must be taken heed of:

- Communication and control of the SuperLimbs is highly challenging for the human wearer. Unlike an exoskeleton, which simply follows a wearer's joint motion, SuperLimbs need externally generated commands or controllers.
- SuperLimbs as wearable robotic appendages often bear significant mass that can shift the wearer's Center of Mass (CoM). Additionally, the externally mounted robotic appendages present a major safety risk, where the SuperLimbs can have collisions with the wearer. This is especially concerning for SuperLimbs with large load bearing capabilities.

III. Operational Modalities of SuperLimbs in suited partial-gravity EVAs

In order to provide an effective value-proposition for SuperLimbs augmenting astronauts during a suited partial-gravity EVA, we must determine a suite of use-cases that SuperLimbs can serve for the astronaut wearer. For this particular study, we identified three distinct use cases that a set of SuperLimbs can provide effective augmentation.

A. Post-Fall Recoveries

Prior observations during the Apollo Program found that astronauts occasionally fell during suited EVA operations on the moon. Falling was particularly prevalent when astronauts were tasked with performing several varying tasks, such as excavation and construction tasks [19]. Astronauts, when in a prone position, subjected to a large/bulky pressurized space suit, adopted the use of impulsive forces applied by their arms in order to dynamically lift their bodies back to an upright posture. This practice often led to astronauts falling back over and/or overexerting their muscles, risking injury. Observations from Apollo mission data and Artemis training data have led NASA to identify a technology gap associated with *Incapacitated Crew Rescue Devices* [20], where a need has been established to find technologies and methods capable of assisting astronauts in the event they become incapacitated during a suited EVA in partial-gravity environments. One of the principle operating modes for SuperLimbs is to directly address this technology gap.

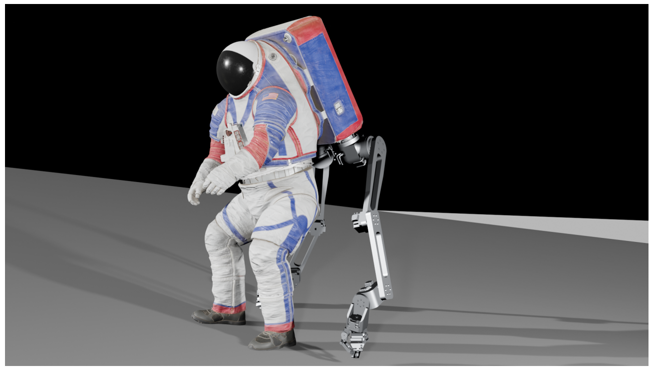

Fig. 4 Conceptual rendering of SuperLimbs acting as a set of redundant legs, where the astronaut wearer can leverage the forces exerted by the SuperLimbs to achieve higher gait energetics.

SuperLimbs is to provide leverage to the astronaut wearer and external assistive forces that can supplement their loss of mobility. The supplementation of assistive forces from SuperLimbs can provide an effective means to safely and reliably recover an astronaut from a fallen position. Furthermore, the SuperLimbs can be extended to navigate incapacitated astronauts into safe areas, where recovery may be possible.

B. Ambulated Gait Assistance

The NASA xEMU space suit has a mass of approximately 65 kg [21]. The space suit's mass in addition to being pressurized presents significant challenges for astronaut mobility and ergonomics. Historically, Apollo astronauts found that use of a "bunny hop" offered the best means of ambulation as they performed transfer operations during a partial-gravity suited EVA [22]. The use of the "bunny hop" was an effective gait to limit overexertion of joints in the legs while also taking advantage of the gravity effects. Human gaits can be approximated as a Spring-Load Inverted Pendulum (SLIP) model with a radius of rotation of r, as defined:

$$r = \frac{1}{g}\left(\frac{v}{Fr}\right)^2 \tag{1}$$

where g is the acceleration due to gravity, v is the tangential velocity of the human, and Fr is the Walking Froude number of the human ($Fr \approx 0.5$) [23]. Under lunar gravity conditions, in order for an astronaut to maintain a normal walking pace (approximately 1.2 m/s), they would need to adopt a gait with a height of $r = 3.56$ m.

A "bunny hop", although an effective means of traversal for an astronaut under partial-gravity, requires an astronaut to continuously launch their bodies for each gait cycle. Over repeated gait cycles, the risk for a loss of stability and falls increases, especially for long duration suited EVAs performed several times over an extended period of time, as profiled in proposed Artemis mission architectures [2]. Falls can lead to injuries and/or damage of critical life support equipment which may prove detrimental to mission success [24].

With the use of SuperLimbs, a set of redundant legs can be implemented, effectively modifying the astronaut to have quadrupedal locomotion. Specifically, SuperLimbs can aid in providing a wider Base of Support (BoS) for the astronaut. Astronauts would be have greater stability and would require less exertion from their joints to maintain an upright and stable posture. Additionally, the SuperLimbs can aid in arresting the momentum of the astronaut as they land from each hop, helping to reduce impact loading on the joints in their legs. This in effect would mitigate the risk of muscle strain as well as improve the overall ergonomics during transfer operations, leading to possibly expanding the length of time a safe suited EVA can occur.

C. Cooperative Manipulation

Future Artemis missions have proposed the construction and maintenance of a habitable infrastructure on the surface of the moon [2]. It is evident that astronauts will be required to perform a series of excavation, construction, and maintenance tasks during suited EVAs. As mentioned earlier, the pressurized space suit limits the mobility of the astronaut wearer, and thus reduces the working envelop available to the astronaut as they perform various manipulation-based tasks [25]. Numerous studies have been conducted demonstrating the criticality in the design of

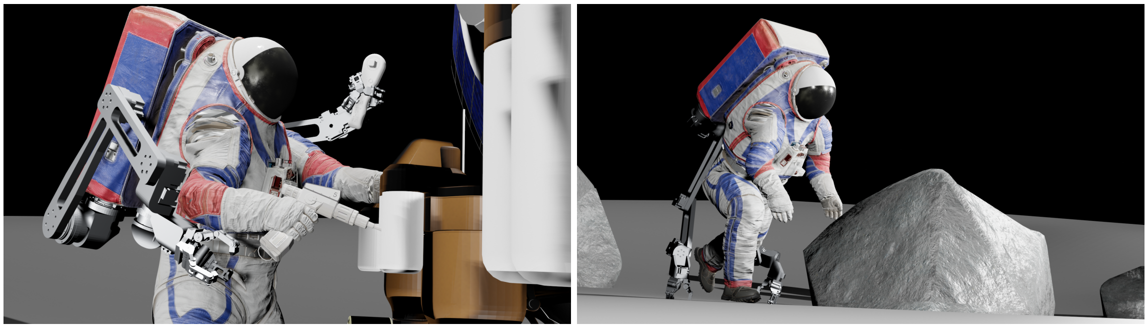

Fig. 5 Conceptual rendering of SuperLimbs performing cooperative manipulation tasks with the astronaut wearer. The SuperLimbs act as a set of redundant arms capable of holding/handling tools (Left) and bracing the body to give the astronaut use of both arms for more complex manipulation tasks (Right).

worksite tasks for astronauts to mitigate the risk of muscle fatigue and injury [7],[26],[27]. The limitations present by the space suit has limited both the astronaut's ability to carry out tasks we take for granted on Earth (such as hammering, drilling, lifting, grasping, etc.) and design of EVA tasks that can be performed. To this end suited EVAs, although a necessary means to construct, maintain, and perform critical tasks for any spaceflight mission, are heavily constrained by the space suit's design.

SuperLimbs can provide the unique ability to expand the capabilities of astronauts by changing the paradigm in how they perform manipulation tasks. The SuperLimbs can act as a set of redundant arms that can help to expand the working envelop of astronauts and provide additional appendages to stow tools, brace the body, and carry additional loads. Numerous SuperLimbs studies have investigated the use of SuperLimbs in augmenting worker tasks in fuselage assembly [12], general construction [28], and package carrying [18]. SuperLimbs can provide astronaut with better worksite ergonomics as well as provide astronauts with an expanded suite of manipulation capabilities that can greatly give suited EVAs more "bang-for-the-buck".

IV. Post-Fall Recovery Human Study

SuperLimbs, as already discussed, provides the unique capability for astronauts to improve their overall suited EVA ergonomics as well as expand the breadth of tasks that astronauts can perform. Since SuperLimbs are not physically constrained by the body of the astronaut, the design space is broad; numerous structured configurations and variations to design can be considered for meeting diverse needs. We adopt a "learn-first, design-later" approach, where we choose the most relevant human task and perform an ergonomics study to understand where there are physical exertion gaps. Specifically, we investigate what aspects of a given task requires the use of external assistance. From there, results from the ergonomics studies can inform the design of the SuperLimbs system. Based on NASA's technology gap pertaining towards *Incapacitated Crew Rescue Devices*, we decided to govern the physical design of the SuperLimbs for performing a post-fall recovery.

A. Review of Pilot Human Study/Key Observations

To better understand the effects of space suits on the ergonomics of the astronaut wearers, we developed an in-house analog space suit, which mimics the mass, inertia, and range of motion properties of NASA's xEMU space suit [21], dubbed the SuperEMU [8]. We asked test subjects to perform a post-fall recovery (stand up from both a prone and supine position) when wearing and not wearing the SuperEMU. Experiments were conducted based on an IRB-approved protocol [MIT Committee on the Use of Humans as Experimental Subjects protocol number 2306001022]. Based on preliminary observations from a pilot human study [8], two important observations were made concerning astronaut recovery following a fall:

First, humans, when unconstrained, can stand up from either a prone or supine position in various paths. Often the path selected by a human to perform a post-fall recovery bears high variability. However, when a human is constrained, particularly by that of space suit (high joint stiffness, joint bearings, mass/inertia offset), the path selected became uniform, where the entire sample population of test subjects took the same path to recovery. Fig. 6 represents the variability of paths a human can take to perform a post-fall recovery.

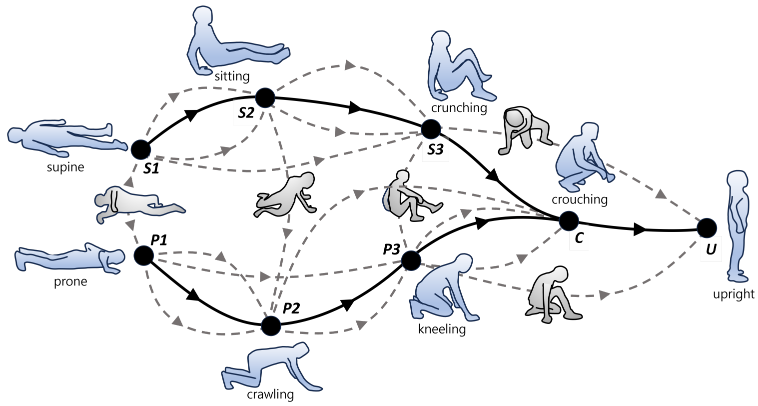

Fig. 6 Simple model representation of astronaut post-fall recovery (Left) and Representation of the sequence of waypoints (bolded) taken by humans to perform post-fall recoveries. Solid black paths are to represent the most straightforward/common paths taken (suited), while dashed paths represent alternative/less common paths taken (unsuited) (Right) [8].

Second, post-fall recoveries were categorized into a sequence of statically stable poses called "waypoints". From Fig. 6, waypoints are labeled as S1, S2, S3 (Supine waypoints), P1, P2, P3 (Prone waypoints), C (Crouch), and U (Upright). Paths between waypoints can be modeled by simple kinetic motion applied about specific points on the body. Provided this model of astronaut post-fall recovery, a trajectory of the astronaut's center of mass (CoM) can be generated which represents the most common path an astronaut would take when standing from a fallen position [8].

Representing astronaut motion to achieve post-fall recovery as the concatenation of simple kinetic motions between waypoints enables the generation of a task-space trajectory that the astronaut CoM must traverse, and consequentially the same trajectory for a pair of SuperLimbs.

Also discovered during the initial pilot human-study were regions along the trajectory where test subjects impulsively exerted themselves to dynamically traverse between waypoints. These observations align closely with NASA studies investigating post-fall recoveries of astronauts during the Apollo missions [19].

V. Validation of SuperLimbs as an Augmentation System for Post-Fall Recoveries

A. Experimental Setup

In order to develop an effective SuperLimbs system, capable of effectively providing assistive forces necessary for a post-fall recovery, we investigated the performance of the human body when augmented by a set of preliminary SuperLimbs. We identified several regions along the post-fall recovery trajectory where external assistance was required, based off the pilot human study. We asked test subjects to don a specialized SuperLimbs prototype, which consists of a Universal Robots UR10e cobot mounted to an extruded aluminum frame which mimics the volumetric makeup of the PLSS 2.0 [29], and a body-fitting suit to minimize compliance between the human wearer and the SuperLimbs physical interface. The boots of the suit are outfitted with linear force sensors measuring the ground reaction force in each foot. Pose data of the test subjects was captured using OpenPose [30]. For this particular experiment, we asked test subjects to perform a Crouch (C) to Upright (U) phase of recovery, where we measured the reactive forces exerted by their feet as they attempted to stand from a crouch position as well as the displacement of their body's CoM to determine stability.

The SuperLimbs prototype was developed with an impedance controller [8], where each treatment varied the gains. For each trial, test subjects (sample size: 4) were asked to begin standing up and use a push button on their right glove to switch the SuperLimbs from "follow mode" to "assist mode", where the SuperLimbs would apply the impedance controller to deliver assistive forces, determined by the impedance gains, to the test subject along a predetermined reference trajectory, as shown in Fig. 7 Approximately halfway through the crouch to upright transition phase, test subjects were asked to cease vertical motion and introduce a horizontal disturbance. Various gains of the SuperLimbs impedance controller would demonstrate the ability for the SuperLimbs to return the test subject's CoM back to the nominal crouch to upright trajectory. In order to quantify the SuperLimbs as a viable solution to being an *Incapacitated Crew Rescue Device*, we analyzed the effects on the human wearer as we tuned the gains of the impedance controller:

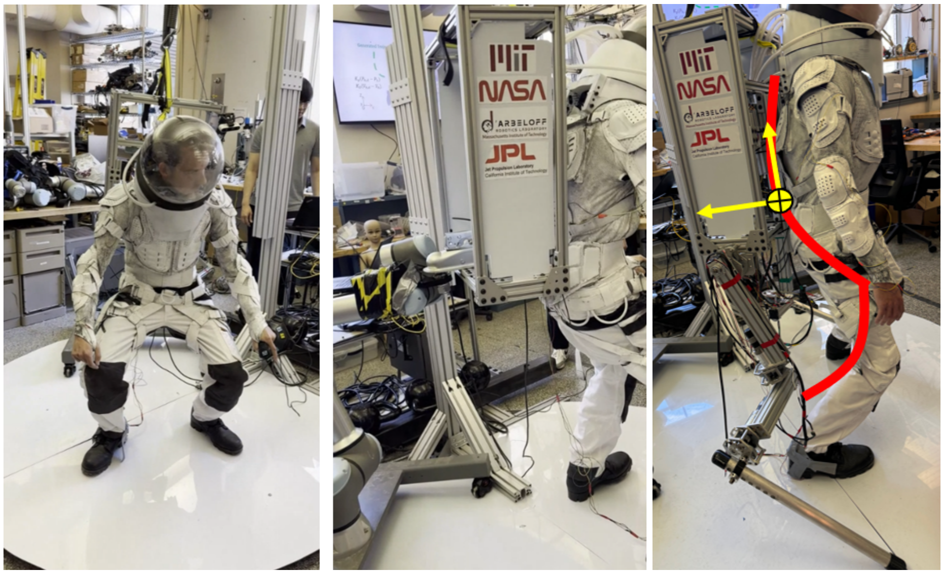

Fig. 7 SuperLimbs validation experimental setup. Test subjects wore a body-fitted garment which is rigidly tied to an extended aluminum frame which simulates the PLSS 2.0. A UR10e cobot is bolted to the lower-end of the PLSS 2.0 analog to act as a SuperLimbs system (Left/Center) and the test subject CoM trajectory path to be taken to profile a Crouch (C) to Upright (U) phase of post-fall recovery (Right).

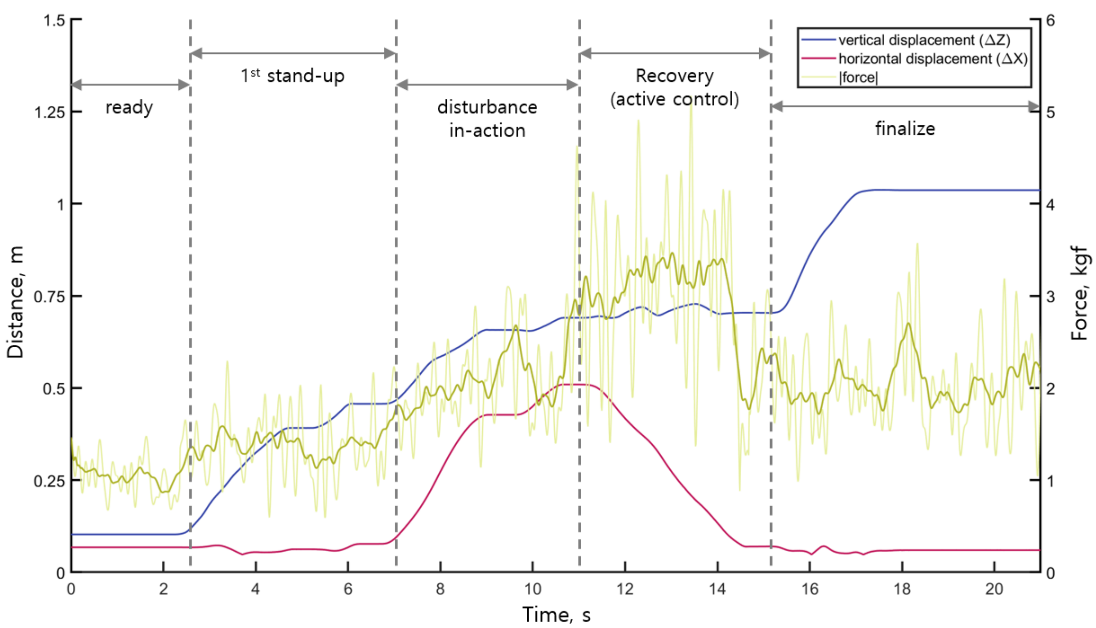

Fig. 8 Experimental data from one of the follow-up human testing trials. The solid blue line represents the vertical displacement of the test subject's CoM with respect to the crouching starting posture. The solid red line represents the sagittal horizontal displacement of the test subject's CoM with respect to the crouching starting posture. The solid lime line represents the average ground reaction forces exerted by the feet of the test subjects.

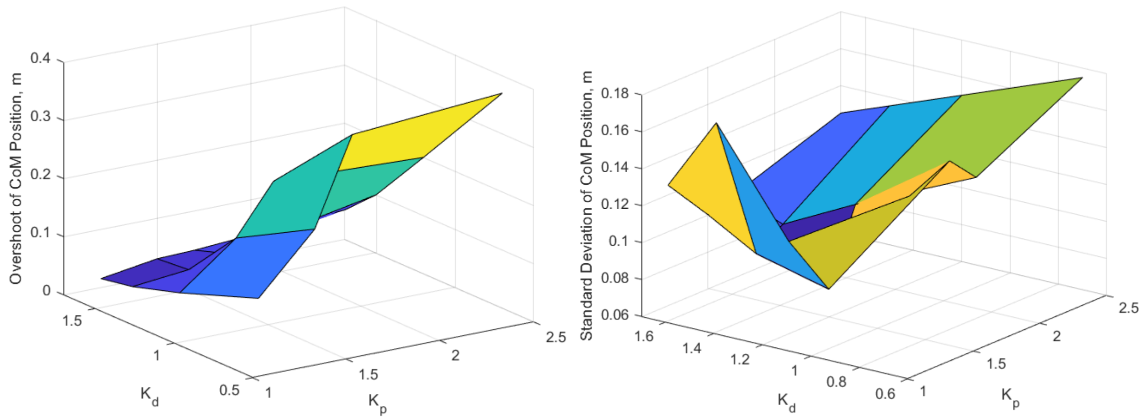

Fig. 9 Overshoot of Test Subject's CoM (Left) and Standard Deviation of Test Subject's CoM (Right) with respect to varying gains of the SuperLimbs impedance controller as they performed a Crouch (C) to Upright (U) post-fall recovery phase with respect to varying gains of the SuperLimbs impedance controller.

- **Overshoot Distance:** Determined from the measured deviation (length) from the recovery trajectory, shown in Fig. 7.
- **Stability:** Calculated by integrating the standard deviation across the entire trajectory between the nominal reference trajectory and the reported position of the test subject's CoM.

B. Human Performance (Validation) Experiments

Fig. 8 shows the experiment results for a trial with reasonable impedance controller parameters, where the SuperLimbs were capable of returning the test subject's CoM back to their original crouch to upright recovery trajectory. From extensive analysis of the two performance metrics, we were able to make the following conclusions:

- Overshoot of the test subject's CoM when recovering from horizontal disturbance was reduced as K_d increased and overshooting increased as K_p increased.
- There was an observed optimal K_p gain which showed minimal deviation in the astronaut's position throughout the entire recovery phase. Likewise, there was a maximum K_d gain that provided successful and stable recovery phases.

Test subjects, when subjected to assistive forces provided by the SuperLimbs, were able to successfully lift their bodies from the crouch to the upright positions. When unassisted, the mass of the fitted body garment and extruded aluminum analog challenged many of the test subjects in acquiring the proper leverage to stand upright. Half of the test subject sample population was able to successfully stand up, but required having to impulsively thrust their bodies while in a crouch position. This led to their bodies becoming highly dynamic and led to large instabilities and significant lack of balance to retain an upright posture. Fortunately, test operators on hand were able to safely stabilize test subjects and prevent any falls from occurring. Regardless, when unassisted, test subjects adopted recovery behavior highly similar to what was observed during the Apollo missions [19] and the pilot human study.

When SuperLimbs were implemented, all test subjects were able to successfully stand up with SuperLimbs assistance, where motions could be maintained as quasi-static. This allowed test subjects to maintain high stability in their CoM position as they performed a Crouch (C) to Upright (U) postural change, as shown in Fig. 8, where the position of the test subject remained relatively constant with no observed overshooting of their position.

The stability of the test subject's CoM under varying K_p and K_d provided great insights:

1) Low K_p effectively made the SuperLimbs passive as the test subjects introduced a disturbance in their recovery trajectory. This led to test subjects overshooting their position as they were required to pull themselves back into the nominal trajectory. Conversely, high K_p led to the SuperLimbs "pulling" the test subjects back into the nominal trajectory with its' own overshoot, leading to instabilities in CoM position. There was an optimal K_p (K_p = 1.5) which allowed the SuperLimbs to help pull the test subjects back to their nominal trajectory with minimal overshoot.
2) Low K_d forced the SuperLimbs to behave like a spring pulling the test subject's CoM back to their nominal trajectory. This led to high instability as the SuperLimbs worked to recover the test subject's CoM back to the

reference trajectory. As K_d increased, the SuperLimbs would promote quasi-static motion of the test subject's CoM. However, as K_d continued to increase, there was a threshold when the recovery motion from the SuperLimbs became uncomfortably slow for the test subjects. Test subjects would have to hold awkward intermediate poses as the SuperLimbs navigated their CoM back to the nominal trajectory. From these observations, an optimal K_d ($K_d = 1.2$) was found amonst the testing population.

Finally, test subjects reported a "phantom limb" effect that lasted for an average of 2 days following the testing campaign. Test subjects had feelings of an additional force pulling at their back where the SuperLimbs were mounted, which were exacerbated when test subjects would stand up from a chair.

VI. Conclusion/Future Work

This paper introduced a wearable robotics technology known as SuperLimbs in the context of providing augmentation to astronauts. SuperLimbs provides the unique capability of being able to assume any kinematic structure independent of it's wearer, thus enabling a wide breadth of utility that can promote astronaut safety and productivity when performing suited EVAs on the surface of a partial-gravity environment. As compared to exoskeletons, which are large and bulky wearable systems that are limited to the pose of the astronaut's body, and prosthetics, which are used as replacements for missing appendages and not appropriate for astronaut applications, SuperLimbs presents a significant opportunity to address several of NASA's current technology gaps pertaining towards risks of EVA injury and *Incapacitated Crew Rescue Devices*. SuperLimbs can serve to provide astronauts with the ability to perform a post-fall recovery, where astronauts can reliably and safety stand back up from a fall while in a pressurized space suit.

From the three possible use cases of SuperLimbs for astronaut augmentation, Post-Fall Recoveries directly address an important and immediate NASA technology gap and was determined to be the underpinning task to govern the design of the SuperLimbs system. A pilot human study found that humans, when constrained to a large and bulky space suit, take predictable and repeatable trajectories when attempting to stand from a prone or supine position. This observation led us to identify regions along the post-fall recovery trajectory where astronauts would require an assistive external force to have success. Provided a set of regions where external assistance is required for post-fall recovery, we performed a follow-up human study, where we had test subjects don a SuperLimbs prototype and perform a single phase of recovery identified as a crucial region requiring external assistance. We found a configuration of the SuperLimbs, being operated with an impedance controller, provided an effective means for post-fall recovery.

Future work is aimed at providing an extensive analysis of the trajectory and developing a torque gap identification model. With these models, the physical design of the SuperLimbs system is to be governed and determined. Finally, the observations from this study will serve as basis for determining the final SuperLimbs design, where a demonstration showing the SuperLimbs lifting an astronaut throughout the entirety of a post-fall recovery can be achieved. Additional future work will begin to investigate other operational modes in suited partial-gravity EVAs. For example, SuperLimbs can serve to provide energetics and stability to an astronaut's "bunny hop" gait as they traverse the moon's surface. Similarly, SuperLimbs can also provide themselves as redundant arms, capable of holding additional tools and bracing, allowing astronauts to have better worksite ergonomics and potentially expanding their working envelope.

Acknowledgments

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