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Designing and Developing the Mobile Gravity Suit for Long-Duration Spaceflight

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Designing and Developing the Mobile Gravity Suit for Long-Duration Spaceflight

A Thesis submitted in partial satisfaction of the requirements
for the degree of Master of Science

in

Bioengineering

by

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2020

The Thesis of Neeki Ashari is approved, and it is acceptable in quality and form for publication on microfilm and electronically:

Co-Chair

Chair

University of California San Diego

2020

DEDICATION

First and foremost, I would like to dedicate this thesis to my loving brother, Andrew Ashari. Without his fierce will and endless support none of this would have been possible. I would also like to dedicate this to my loving parents, Dr. Mahvash Yadegar and Hossein Ashari, for their unconditional support. Thank you for teaching me the essence of hard-work, passion, and perseverance. Lastly, I would like to dedicate this to my loving uncle, Dr. Parviz Ashari, for his endless encouragement and passion for medical sciences.

EPIGRAPH

“**Imagination** will often
carry us to worlds that
never were, but without
it we go nowhere.”
– Carl Sagan

“Look again at that dot. That's here. That's home. That's us. On it everyone you love, everyone you know, everyone you ever heard of, every human being who ever was, lived out their lives. The aggregate of our joy and suffering, thousands of confident religions, ideologies, and economic doctrines, every hunter and forager, every hero and coward, every creator and destroyer of civilization, every king and peasant, every young couple in love, every mother and father, hopeful child, inventor and explorer, every teacher of morals, every corrupt politician, every "superstar," every "supreme leader," every saint and sinner in the history of our species lived there-on a mote of dust suspended in a sunbeam.”
– Carl Sagan

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LIST OF ABBREVIATIONS

Lower Body Negative Pressure – LBNP

Ground Reaction Force – GRF

Cross-Sectional Area – CSA

International Space Station – ISS

Advanced Resistive Exercise – aRED

Intravehicular Activity Suit – IVA

Head-down Tilt – HDT

Force Balance Analysis – FBA

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ABSTRACT OF THE THESIS

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by

Neeki Ashari

Master of Science in Bioengineering

University of California San Diego, 2020

Professor Alan R. Hargens, Chair
Professor Pedro Cabrales Arevalo, Co-Chair

Spaceflight Associated Neuro-ocular Syndrome, bone decalcification, and muscle atrophy are among the most prevalent risks associated with long-duration spaceflight. Implementing the lower body negative pressure (LBNP) technique is a potential countermeasure for these risks. LBNP counteracts head-ward fluid shifts and generates ground-reaction forces (GRFs). GRFs are beneficial for maintaining bones and muscles by generating gravitational-like loads we experience on Earth. Currently, LBNP devices are large/bulky and require the subject to maintain a stationary position. However, the mobile Gravity Suit I designed is relatively small, untethered, and flexible. It is hypothesized that by designing and developing a mobile Gravity Suit, we can generate greater GRFs than an LBNP chamber. Static LBNP chambers achieve only one GRF on the subject. This can be expressed as $A_W(\text{LBNP}) = \text{GRF}$, where A_w = cross-sectional area (CSA) of waist seal. However, the mobile Gravity Suit may achieve an additional GRF using the following equation, $(A_F + A_W)\text{LBNP} = \text{GRF}$, where A_F = CSA of subject's feet. The additional force can be further expressed as $F1 + F2 = A_F \times \text{LBNP}$, where F1 = spinal loading force, F2 = waist shear force, and $A_F \times \text{LBNP}$ = the total downward foot force. While lying supine, GRF data were recorded in both devices using foot sole sensors and a weigh scale. The data show that the Gravity Suit generated a mean maximum bodyweight of 125% ± 22% whereas the LBNP chamber generated 91%± 24%. The mobile Gravity Suit demonstrates higher percent of bodyweight, due to the suit's novel biomechanical design.

INTRODUCTION

Spaceflight Associated Neuro-ocular Syndrome (SANS), previously known as visual impairment intracranial pressure (VIIP), is a major risk associated with long-duration spaceflight. During prolonged missions, studies show optic disk edema, posterior globe flattening, decreased near vision and hyperopic shifts (Zhang & Hargens 2008). This negative outcome stems from the lack of gravity, a necessary biophysical stress on the human body. As a result, astronauts experience a head-ward fluid shift. This physiological issue can be characterized as a pressure exerted by a fluid in the cephalic region, also known as intracranial pressure. Although SANS is critical, it is not the only physiological repercussion astronauts may endure. Long-term microgravity exposure is also responsible for the reduction of mechanical loads, which can greatly reduce bone density and muscle force generation (Akima et al. 2003). Studies show that an astronaut's movement between modules, aerobic activity, and extra-vehicular activity components are amongst the leading causes of musculoskeletal injuries (Scheuring et al. 2009). This becomes a major concern as astronauts return from space to weight-bearing environments, such as Earth or even potentially Mars. On Earth, gravity is responsible for supplying resistance in our everyday life (Khort et al. 2009). Most commonly, we experience resistance through the ground-reaction forces (GRFs) our bodyweight generates underneath our feet. GRFs are critical forces that help increase the rate of bone renewal and maintain muscle structure and function (Boda et al. 2000)(Witt et al. 2014). In order to minimize musculoskeletal injuries, it is essential to develop effective techniques that can simulate gravitational forces for microgravity conditions.

In order to better understand the negative effects of weightlessness on Earth, scientists employ a ground-based analog technique by using 6° head-down tilt (HDT) bed rest experiments

(Hargens et al. 2016). Lying supine and/or HDT minimize axial loading and may provide insights into the physiological effects of bed rest or simulated microgravity on bones and muscles (Hargens et al. 2016). According to this study, five subjects who endured 120-days of HDT bed rest reduced their bone volume by 6.3%. Although bed rest studies try to mimic weightlessness, bed is not a perfect simulation. Patients on Earth still experience posterior compression in the - G_Z direction, an effect that is absent in microgravity. However, bed rest studies still illustrate the adverse physiological effects from reduction of external forces.

Ensuring mechanical loads on the human body is an essential necessity for long-duration spaceflight missions. Studies show that bearing the mechanical load of your bodyweight serves as a fundamental stimulus for maintaining musculoskeletal health. In microgravity conditions, there is a lack of external forces, which inhibits bone tissue from experiencing changes in strain energy – an important fluctuation we experience on Earth (Vico & Hargens 2018). Without these changes, bones become more prone to breaks and fractures (Dadwal et al. 2019). Currently, the International Space Station (ISS) incorporates exercise regimens to simulate artificial gravity to generate GRFs. Unfortunately, treadmills generate minimal GRFs compared to those generated on Earth (Cavanaugh et al. 2010). Studies show that walking, running, and squatting in space generates a reduced GRF by 77%, 75%, and 65% (Cavanaugh et al. 2010). This staggering drop shares critical insight as to how skeletal changes occur without effective GRFs. However, the advanced resistive exercise device (aRED) is an actively used countermeasure device in the ISS. Through its dynamic characteristics, it can simulate inertial loading up to 2,675N (Sibonga et al. 2019)(Vico & Hargens 2018). Additionally, the aRED's load and weight-bearing features allow bone tissue to adapt to mechanical stresses. Studies show that consistent aRED usage maintains bone density and increases bone renewal (Smith et al. 2008). However, remaining stationary for several hours at a time sacrifices critical crew time for work-related tasks. Although a waste in crew time, the aRED's load increase highlights the importance of countermeasure devices that will ensure GRFs similar to Earth.

A common technique to potentially alleviate musculoskeletal and head-ward fluid shift issues is applying lower body negative pressure (LBNP). This vacuum-style technique (below ambient pressure) applies a gravitational-like stress onto the cardiovascular system and generates GRFs beneath the feet to simulate axial loading. These gravitational-like factors are imperative for maintaining bone density and muscle generation. Generally, LBNP devices come in the form of a horizontal chamber (Photograph 1).

The LBNP chamber is extremely robust, heavy, and bulky. Thus, it is excluded from any in-flight missions to the International Space Station (ISS). Due to the large volume of the chamber, it requires more power consumption when generating stronger pressures. Additionally, the chamber is completely static and requires the user to remain inside for extended periods of time. Currently, the Roscosmos (Russian Space Agency) has its own LBNP countermeasure device in the ISS, called the *Chibis* (Yaramanova et al. 2015). This countermeasure design supplies no mobility, requiring the user to always be connected to a stationary vacuum and wall-mounted power supply (Yaramanova et al. 2015). Nearing the end of their flight missions, cosmonauts use the *Chibis* to apply a stress onto their cardiovascular system. This prepares their heart to feel similar stresses upon their return to Earth's gravity. Lastly, none of these iterations feature a self-driven, safe, comfortable, and mobile solution.

However, I designed and developed a new LBNP device in the form of a wearable garment (trousers) – called the mobile Gravity Suit (Photograph 2, 3, & 4). The mobile Gravity Suit is a small, untethered, and flexible intravehicular activity (IVA) suit. This trouser-like suit is designed for astronauts to comfortably slip into and begin applying the LBNP technique without reducing crew time. The negative pressure is generated by its own portable vacuum system, ensuring full mobility. Due to the Gravity Suit's biomechanical design, the flexible exoskeletal membrane begins to axially contract under negative pressure. This mechanical and dynamic characteristic provides an additional force that the static LBNP chamber does not have. Additionally, the Gravity Suit's endoskeleton is fully equipped with its own pressure and thermal control system to ensure user-control, as well as three safety features.

In comparison to the LBNP chamber, the mobile Gravity Suit ensures a higher GRF on a safe, user-accessible, and fully mobile scale. Due to the suit's smaller volume and biomechanical design, it requires less negative pressure to achieve a desired GRF. It is hypothesized that by designing and developing a mobile Gravity Suit, we can generate stronger GRFs than an LBNP chamber (Figure 1). In this study, we compare the two devices' experimental GRF data and how their biomechanical design affects that relationship. The goal of this analysis is to ensure the effectiveness and advantages of the mobile Gravity Suit for long-duration spaceflight, such as the journey to Mars.

MATERIALS AND METHODS

Approval and Recruitment

This study was approved by the Institutional Review Board of the University of California, San Diego. Each subject read the consent form and provided informed, written consent. Our previous study collected Gravity Suit GRF data from eight healthy subjects (six females and 2 males) with an average age ± SD: 24 years ± 6 years, average height ± SD: 168 cm ± 6 cm, and average weight ± SD: 57 kg ± 8 kg (Petersen et al. 2019). As for the LBNP chamber GRF data, we recruited a total of six healthy subjects (three males and three females) with an average age ± SD: 23.3 years ± 4.3 years, average height ± SD: 170 cm ± 7 cm, and average initial weight ± SD: 64.4 kg ± 12.7 kg.

Gravity Suit and Model

Design and Development

I designed and developed the mobile Gravity Suit in the form of wearable trousers that is fully equipped with its own portable vacuum system, pressure and thermal control system, safety shut-off system, and spinal loading system. The suit's exoskeletal membrane envelops the user from the waist down, encapsulating the feet. Additionally, the exoskeletal membrane incorporated an airtight yet breathable Hyprotex fabric. This ensured pressure retention, all while maintaining the suit's temperature and humidity. The endoskeleton of the suit was structured using ¼" crosslinked polyethylene PEX tubing. This internal support structure was composed of repeated ring-shaped PEX tubing, which maintained several inches of clearance between the user and the suit. Each ring was placed into a double or triple tier ring structure to prevent warping and/or deformation under highly stressed negative pressure conditions. This particular design structure also reinforced the polyethylene's low elastic modulus and high tensile strength.

Between each set of rings, a few inches of free space were added to ensure enough tension in the rip-stop HyproTex fabric (exoskeleton) to prevent the fabric from collapsing/tightening around the user's legs. The ring sets were spaced evenly throughout the suit to maintain a flexible user environment and to promote accordion-like axial contraction. This novel biomechanical design ensured an additional dynamic force that a static LBNP box did not have.

The knee joint was designed to ensure zero skin contact at both static and dynamic positions. The knee joint employed a "pac-man" open-mouth shape, allowing for free space at the knee anterior. The knee joint was developed using PEX polyethylene tubing. The distance between the upper and lower ring at the knee anterior would ensure enough tension to retain the fabric's rigid properties. This spacing-technique would help prevent a collapse under negative pressure conditions. The back of the knee joint was tightly stacked together to allow the knee posterior to enclose around it when generating a full flex.

To ensure extra reinforcement of each ring-stack placement, a strongly bonded adhesive fabric was developed. The fabric was then layered over every square-inch of the endoskeleton, tightly retaining all ring-stacks. This detail provided aesthetic yet smooth surface properties for dynamic air-flow. At the waist of the suit, ⅜" polyethylene PEX tubes were used to develop two separate two-tier stacked rings to form the aperture. This aperture support structure used larger diameter rings that extend about 3-4 inches outward encompassing slightly below the user's iliac crest. The increased diameter around the waist ensures dynamic air-flow and less strain on the user's cardiovascular system.

Located at the waist, above the aperture, a vacuum docking port was placed. The docking port was fabricated/modified out of a Dyson accessory female counterpart, allowing it to match the hose's male counterpart accessory. Together, they would fully "click" into place. The "click" mechanism would allow for an ensured seal, preventing any chances of leakage. In the event of an emergency, the user would have free-control to unclick the hose to ensure immediate relief of the entire system. This also served as an additional safety mechanism (manual).

The suit is also equipped with a customized portable vacuum system. The portable vacuum was developed out of a 90 mm 12-blade metal-ducted brushless fan. The device was 2-1, which means the fan and motor are accommodated together. The 22.2 V fan motor was supported by a Lectron Pro 22.2V 5200 mAh LiPo battery and a Mamba Monster 2 ESC (electronic speed controller). Together, they produced a high performance value of approximately 80,000 RPMs and 3,620 grams of thrust to generate a strong negative pressure. The voltage of the vacuum can be scaled with a portable variable resistor. By doing this, negative pressure can be scaled to a desired amount inside the Gravity Suit. The vacuum itself is housed in a 3D-printed enclosed CAD casing designated on the user's right hip.

Near the suit's aperture, a fully installed ¾" mechanical safety relief check-valve was installed. This reversed ball-spring mechanism was configured to allow air flow-in when reaching a negative pressure threshold of -50mmHg (cut-off dosage). This would allow for controlled leakage in the event the suit reaches a dangerous negative pressure threshold for the user. The pressure sensor was a 2-1, which means it served as both a pressure and temperature sensor. Additionally, a single humidity sensor was also added. Each internal sensor was housed together in an internal safety pouch inside the suit. Once activated, it relayed information via Bluetooth to the LCD screen's Arduino nano. Once the Arduino nano received information from the internal sensors, this then relayed a digital output to the suit's LCD screen. The LCD screen was designated on top of the suit's aperture, which provided an aerial view for the user and to have control of the whole system. The LCD screen provided a digital output of pressure (mmHg), temperature (C), and humidity (%). Additionally, each ankle was equipped with a ¼” brass pressure relief check-valve. This reversed ball-spring mechanism could be configured to any sensitivity to achieve minimal inward air-flow. This feature was implemented to regulate the temperature inside the suit when engaging in dynamics.

Additionally, a spinal loading vest was added to connect to the waist of the suit. The shoulder pads employed an even distribution area. This equalized the applied mechanical load onto the user’s shoulders and spine. Once negative pressure was activated, a downward force in series would be generated with the waist seal of the suit. This feature aimed to simulate diurnal changes that we experience here on Earth.

Lastly, we implemented Crocs shoes to prevent compression at the bottom of the suit. Crocs provided a rigid, yet durable structure around the feet. The rubber material incorporated holes around the structure, which allowed negative pressure to flow through. The Gravity Suit without negative pressure activation is shown in Photograph 2, with negative pressure activation in Photograph 3, and side profile view in Photograph 4.

GRF Prediction Model

A static and force-balance analysis was conducted to target the applied and residual resulting forces on the device. Through this model, we could predict the GRFs generated under each individual. This can be expressed as:

$$(A_F + A_W)LBNP = GRF$$

Where A_w = cross-sectional area of the subject’s waist. The additional force could be further expressed as:

$$\boldsymbol{F1 + F2 = A_F \times LBNP}$$

Where $F1$ = spinal loading force, $F2$ = waist shear force, and $A_F \times LBNP$ is the total downward reaction foot force during axial contraction.

LBNP Chamber and Model

Design and Development

The LBNP Chamber was designed and developed by the Department of Oceanography at UC San Diego. This four-sided static chamber was developed out of 1-inch thick Plexiglas to sustain high negative pressures. The device was equipped with a vacuum docking port that connects to a standard shop vacuum. It was also fitted with a one-way pressure spout that tethers to a pressure transducer in order to read negative pressure measurements.

On the front panel, the LBNP chamber was fitted with a 182.8 cm circumferential elliptical aperture. In most cases, the aperture left about 9-inches of clearance between itself and the user. This aperture would permit each user to slip in and out of the chamber in a supine position. Around the aperture was a flexible neoprene waist to ensure zero leakage. Above the aperture, a raised steel-beam was placed to supports the friction-less backboard (Cavanaugh et al. 1992). To support the user when lying supine, leg, thigh, and hip bungee cord slings were installed inside the chamber.

GRF Model

The original force model for this device can be expressed as (Boda et al. 2000)(Hargens et al. 1991):

$$A_W \times \text{LBNP} = \text{GRF}$$

Where A_w = cross-sectional area of the subject’s waist

Experimental Design:

Gravity Suit

The Gravity Suit was suspended inside of the LBNP chamber in order to utilize a friction-less ground-based analog. This would ensure more accurate GRF data from the suit, as there will be less friction against the subject’s back. As the subject would don the suit, their legs, thighs and hips would be suspended using the LBNP chamber's bungee cord slings. The suit's negative pressure system would then be activated from zero – 40 mmHg of negative pressure, using 10 mmHg intervals. At each interval, the force was recorded using Tekscan Foot Sole Sensors.

LBNP Chamber

Each subject was instructed to lie supine in the LBNP chamber. Their legs, thighs, and hips were suspended with bungee cord slings. Their back was supported with a non-resistive backboard sling. A neoprene seal enveloped the subject's waist, maintaining a tight seal. All subjects engaged in negative pressures ranging from zero – 40 mmHg, using 10 mmHg intervals. At each interval, the force generated onto the scale was recorded (Figure 1.)

Measurements

Tekscan Foot Sole sensors were placed inside each sole of the Gravity Suit's shoes. Each sensor was graded with loaded cells to provide distributed force mapping underneath the subject's foot. This was then quantified into GRFs. However, the LBNP chamber used a calibrated digital scale that was vertically mounted inside the panel door (Figure 2), while the Gravity Suit used TekScan sensors. Each measurement tool was selected based on the device's restricted parameters.

Statistics

The means ± standard deviations for the Gravity Suit GRF were compared to the LBNP chamber. A two-tailed t-test was used to compared the two conditions to determine statistical significance for each average percent bodyweight generated. This was done by comparing the normalized weights of the Gravity Suit trials with the normalized weights of the LBNP chamber trials, demonstrating a significant difference (set at $P<0.05$) in the two conditions for each pressure interval.

RESULTS

All 14 subjects who participated in these studies produced reliable data and showed no pre-syncopal symptoms. Ordered measurements were similar to randomized measurements using LBNP. An average error of 1.3% was found when comparing ordered measurements to the randomized measurements (Graph 1). Consequently, ordered measurements were chosen to avoid long-term LBNP exposure, which can lead to syncope.

Following the Gravity Suit's protocol, eight healthy subjects generated a mean maximum GRF of 125% ± 22% of their total bodyweight at -40 mmHg (Petersen et al. 2019). This substantial increase was shown to be 25% higher relative to normal bodyweight when standing upright. In order to generate about a single bodyweight in the Gravity Suit, users had to implement approximately -35 mmHg. Furthermore, observational results displayed that subjects generated a comfortable 90° knee flexion at -20 mmHg, while still generating approximately 41% of their total bodyweight. At 20 mmHg for N=1, a subject generated a temperature and humidity of 23 ±1 C; 47±3 %, respectively, inside the suit (Petersen et al. 2019).

Following the LBNP chamber's protocol, six healthy subjects generated a mean maximum GRF of 91% ± 24% of their total bodyweight at -40 mmHg. In order to generate an average of about one bodyweight in the LBNP chamber, users had to implement at least -45 mmHg. This high negative pressure threshold was shown to be -10 mmHg higher than the Gravity Suit's negative pressure generation. The Gravity Suit generated a 37% higher mean maximum GRF of their total bodyweight with a statistically significant t-test ($P<0.02$). A previous study that used a larger pool of subjects showed that it takes around -100 mmHg to generate a single bodyweight. However, the Gravity Suit required substantially less to generate a single bodyweight. (Hargens et al. 1991.) A linear order regression of means between the Gravity Suit vs the LBNP Chamber can be seen in Graph 2.

The Gravity Suit's force balance analysis (FBA) illustrated where the resulting reaction forces are derived. When activating the portable vacuum, a downward force was generated at the spinal loading vest's shoulders and a downward force was generated at the flexible neoprene waist. Since the loading vest and neoprene waist seal were connected to each other, they supplied a downward force in series. In result, they produced an upward reaction force. At the same time of this occurrence, the bottom of the suit would begin to axially contract, supplying an upward force underneath the subject's feet. In result, the subject's feet counteracted the axial contraction, therefore supplying a downward reaction force. The behavior of both occurrences could be compared to an accordion-like mechanism. The diagram in Figure 1 shows an additional reaction force that the static LBNP chamber does not have.

The LBNP chamber's FBA also illustrated where the resulting reaction forces were derived. The subject's axial load supplied a downward force, which would then produce an upward reaction force. The FBA can be seen in Figure 2.

DISCUSSION

The Gravity Suit vs LBNP chamber

The primary findings of this study support my hypothesis that the Gravity Suit generates higher GRFs than the LBNP chamber. The suit's results show a significantly higher mean maximum GRF of total bodyweight in comparison to the chamber. Although there are only four data points of negative pressure for each protocol, the most significant is at -40 mmHg. As the negative pressure increases, the GRF difference between the Gravity Suit and LBNP chamber increases and the Gravity Suit's bodyweight values become more statistically significant. The rest of the suit's data points are higher in GRF in comparison to the chamber. However, they are not as significant (Table 1). This may be due to the shortage of subjects for each trial. In a previous LBNP chamber study with twelve healthy subjects, results show that it took around -100 mmHg to generate about one bodyweight (Hargens et al. 1991.) The suit's ability to generate a single bodyweight is significantly larger than the rigid box study.

We suggest the Gravity Suit's novel biomechanical design may be a primary reason for this GRF increase. Since the suit's flexible endoskeleton is composed of a repeated ring-shaped PEX tubing, this allows the structure of the suit to axially contract under negative pressure (Figure 1). This behavior is analogous to an accordion-like mechanism, extending and curtailing (Photograph 2 and 3). Furthermore, the shoe structure serves as a rigid platform underneath the user's feet. This dynamic feature supplies an additional force that the rigid LBNP chamber does not have. The LBNP chamber's robust yet strictly rigid structure only allows for one force in comparison to the Gravity Suit's dual force dynamic feature.

Additionally, the Gravity Suit's aperture has approximately 3-4 inches of minimal clearance between its user in comparison to the LBNP chamber's 9 inches of clearance. This may affect the waist shear force for each device. Under negative pressure, the flexible neoprene waist seal around each aperture inverts. As it inverts, it supplies a load onto the device and user. Since the Gravity Suit has a smaller area of clearance, we believe it supplies a much smaller load onto the device itself while the rest of the load is applied to the user. In a simple model, we approximate one fourth of the suction force is applied to the Gravity Suit, while three fourths of the suction force are applied to the user contributing to their higher GRF generation. However, the LBNP chamber's larger aperture clearance supplies a much larger load onto the rigid device itself. As the flexible neoprene waist seal around the larger aperture inverts, we believe it supplies a larger load onto the device itself while the rest of the load is applied to the user. In a simple model, we approximate that one half of its suction force is supplied onto the LBNP chamber, while the other half is applied to the user contributing to the user's minimal GRF generation. The Gravity Suit's flexible exoskeletal membrane and minimal aperture clearance supplies the maximum axial force contraction for higher GRF generation. This dynamic force supplies maximum GRF onto the user without limitations. However, the larger aperture sustains horizontal tugging due to the large elliptical diameter and rigid properties. This can limit the amount suction force applied to the user. These reasons may also explain why the Gravity Suit also generates stronger GRFs using minimal negative pressure compared to a previous LBNP chamber study that used -100mmHg (Hargens et al. 1991). According to that study, the LBNP chamber included a spinal loading vest. However, the Gravity Suit still ensures stronger GRF results. Due to the Gravity Suit's ductile material properties and biomechanical design, it ensures maximum GRF load onto the user rather than onto the device itself.

Force Models

The Gravity Suit

The force model is as follows, $(A_F + A_W)LBNP = GRF$, where A_F = cross-section area of feet and A_W = cross-sectional area of waist. Since the Gravity Suit is also equipped with a spinal loading vest, which is attached to the neoprene waist seal, their mechanical loads work in series. Thus, the force model can be further expressed as: $F1 + F2 = A_F(LBNP)$, where F1 = spinal loading force and F2 = waist shear force. In equivalence, the bottom of the suit's exoskeletal membrane axially contracts upwards causing a downward foot force, hence $A_F(LBNP)$. This additional force along with its strong F1 and F2 force supports the Gravity Suit's results for generating a stronger force than the LBNP chamber.

LBNP Chamber

According to a previous study conducted on the LBNP chamber, a force model was developed through an FBA (Boda et al. 2000). Since the LBNP chamber in our study does not implement a spinal loading vest and/or dynamical material properties, it only generates a single resultant force in comparison to the Gravity Suit dynamic force feature. Additionally, the LBNP chamber is completely rigid and lacks elastic prosperities. The force model for the LBNP chamber is as follows, $A_W(LBNP) = GRF$, where A_W = cross-sectional area of waist.

Slope Shift

As we look at the LBNP chamber's force model, $GRF = (A_W)LBNP$, it is in the same format as the mathematical straight line equation, $y = mx$. As this force model shifts to the Gravity Suit's equation, $GRF = (A_F + A_W)LBNP$, there is an additional slope variable. The extra variable in the suit's equation should provide an increase of slope, which is validated and shown in Graph 2. The only difference between the two conditions is the change of slope, which can be explained by the two force models. The increase in slope is due to the suit's additional slope variable. The decrease in slope is due to the LBNP chamber's single slope variable. This provides mathematical support of the Gravity Suit's stronger GRF results.

Material Properties

The Gravity Suit

The Gravity Suit's material properties ensure its lightweight yet fully mobile characteristics. The suit's small volume guarantees faster negative pressure generation than an LBNP chamber. Smaller volume ensures less suction output, whereas, the large volume has higher suction output. Additionally, the suit's repeated ring pattern warrants axial contraction, which allows the suit to experience circumferential volume changes. Under negative pressure conditions, the suit volumetrically deforms compared to its initial volume. This advantage allows the user to reach a desired GRF much faster without having to over-expend negative pressure. By this finding, we can conserve more power for the spacecraft while also supplying less stress to the user's cardiovascular system.

LBNP Chamber

The LBNP chamber's material properties ensure a rigid structure while maintaining a large volume. The chamber was originally designed and developed with the intent of simulating gravitational stress, hemorrhaging, alter preloading, and manipulating baroreceptors (Esch et al). Therefore, volume size and mobility was never a primary objective. The LBNP chamber can mimic effective loads, but not to the efficiency of the Gravity Suit. Additionally, the large volume of the LBNP chamber requires more negative pressure to be drawn in order to achieve the same GRF as the Gravity Suit. This requires more power and more stress applied to the subject's cardiovascular system.

Significant Gravity Suit Features

Safety Features

The Gravity Suit is specifically designed with three safety features to shut-off negative pressure. This is an advantageous feature that the LBNP chamber and *Chibis* do not have. Too much negative pressure exposure can redirect copious amounts of blood away from the subject's brain, causing them to suffer from syncope. Thus, having three safety features (manual, mechanical, and electrical) allows extra reinforcement for the subject in the event they begin experiencing pre-syncopal symptoms. Aside from being able to manually disconnect the portable vacuum hose, the user is also equipped with a pre-calibrated reverse ball-spring check-valve. Once the negative pressure reaches a particular threshold, the ball-spring mechanism inverts into the suit allowing for air flow-in. In the event both features fail to deliver, a non-interactive electrical safety algorithm is incorporated into the Arduino of the pressure sensor. Once the suit reaches a particular negative pressure threshold, the Arduino relays a signal shut-off to the portable vacuum.

Thermal Control

Aside from the Gravity Suit's built-in pressure/thermal control system, the ankles are equipped with pre-calibrated ¼" brass check-valves to maintain temperature and humidity during dynamics. In comparison to the experimental protocol's ambient room temperature, the suit was at 22.7°C during dynamic exercise. This temperature control probably relates to the suit's breathable fabric membrane and ankle check-valves. Additionally, these pressure/temperature/humidity values are relayed to the suit's built-in LCD screen for rapid user-accessibility.

Limitations

During the Gravity Suit's protocol (Figure 2), limitations include restricted parameter sizes due to the suit's tailored volume. Due to the suit's parameter constraints, primarily females with specific waist and height parameters were selected for participation. This caused a shortage of subjects and thus a smaller data set. To better accommodate, larger sized suits can be developed for larger subjects. In the event the suit is commercialized for active use in the ISS, each suit can be anatomically tailored in accordance with each user.

During the LBNP chamber's protocol, limitations include buckling of the legs, which may affect impact when recording GRFs on the scale. We tried to overcome this limitation by reminding the subject to keep their legs extended. However, it is possible that a few subjects did not maintain extension of their legs. Lastly, friction underneath waist was closely monitored, however, chances of friction may have occurred during the experimental trials. We aimed to minimize this by adjusting the subject's waist in the center of the aperture opening.

Future Directions

As we begin developing larger sized Gravity Suits, we will be able to significantly increase our sample size. This will provide us a much larger data set to compare to LBNP chamber data sets. Next, we will incorporate the granular data into the force models of each device. This will provide us with analytical outputs to compare to our experimental values. These comparisons will supply more results documenting each device's ability to generate GRFs. Additionally, preliminary data support this advantageous method as it predicts how much of a GRF each subject generates without having them actually use the device. Lastly, this analytical technique will provide irrefutable numerical values that will further validate the Gravity Suit's advantage in comparison to the LBNP chamber.

During this study, we also discovered that expanding the CSA of the user's waist would increase their GRF values. This technique was used in the LBNP chamber, since the larger aperture accommodated subjects with larger CSAs. These preliminary data support the force models for both devices, since the *CSA of the user's waist* are key variables. In the future, we will test larger CSAs of the waist inside the Gravity Suit to further increase GRFs without having to over-expend negative pressure. This will supply the suit with an additional advantage on top of its already power effective features. Next, we will do a cross-analysis of both devices to decipher each device's characteristics and advantages.

However, the next rigid foot structure iteration will be customized to ensure the same mechanical and bulk properties as the Crocs. We aim to target a much milder tensile strength to avoid high ductile properties. Lastly, the lithium polymer battery in the Gravity Suit will be examined for spaceflight use to ensure safety and adherence to the regulations set by the ISS.

Broader Impact

Overall, the Gravity Suit serves as a user-driven and mobile countermeasure that may maintain musculoskeletal health without sacrificing crew time. Astronauts will be able to float freely around the space station, while adhering to their every day tasks. Flexibility, mobility, and safety will ensure the comfort of each user. However, this device is not just relevant to astronauts. Once space travel becomes more commercialized, this device will ensure the musculoskeletal health for future civilian space travelers. With the great space race rapidly approaching, the future for humanity comes into question. The solution may not be simple, but finding habitable conditions to sustain terrestrial life will be a long voyage. It is important to develop effective devices, like the mobile Gravity Suit, that simulate the very conditions terrestrial life depends on. This innovation may be pivotal for the journey to Mars.

FIGURES

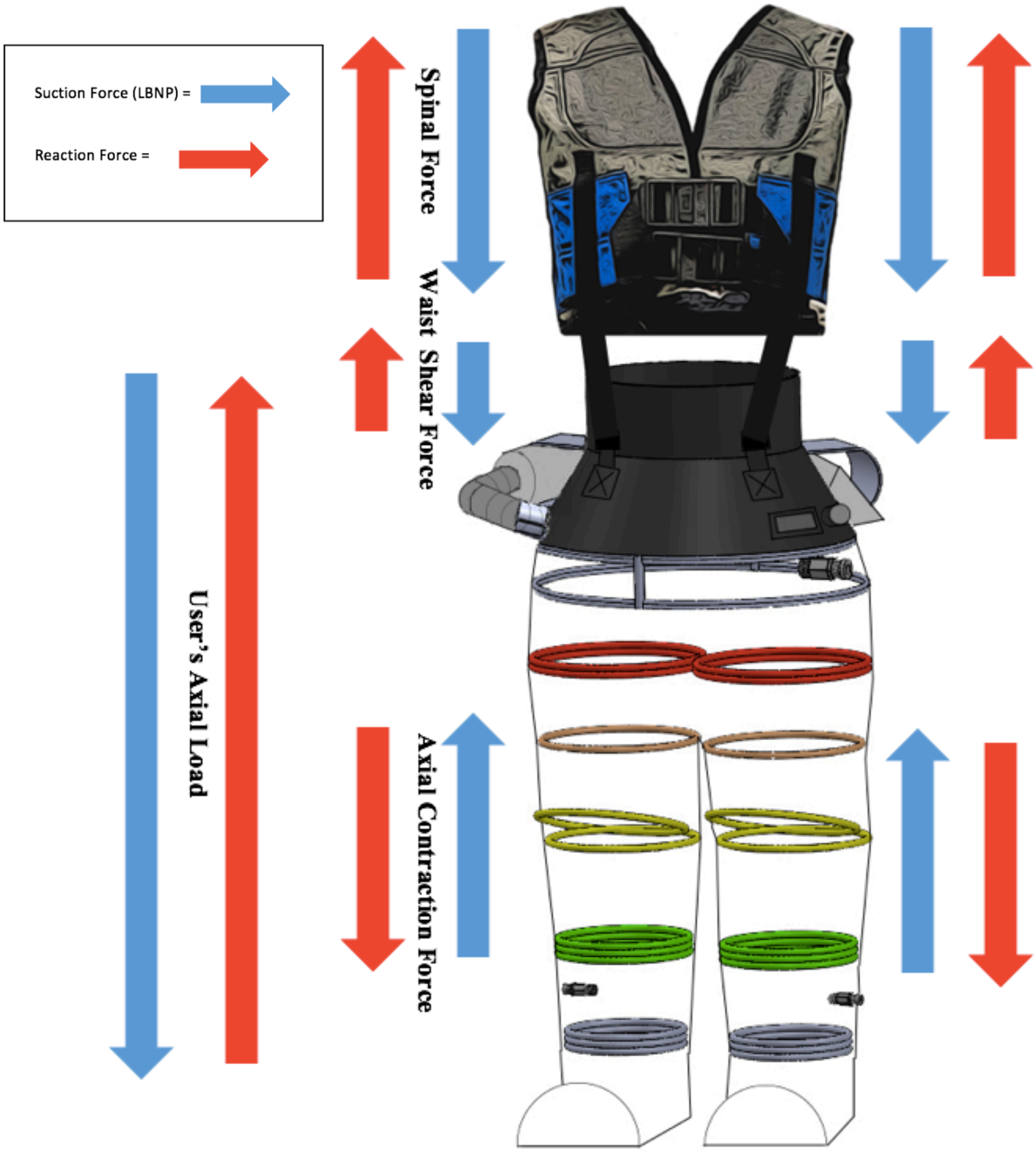


Figure 1. Mobile Gravity Suit Force Balance Analysis

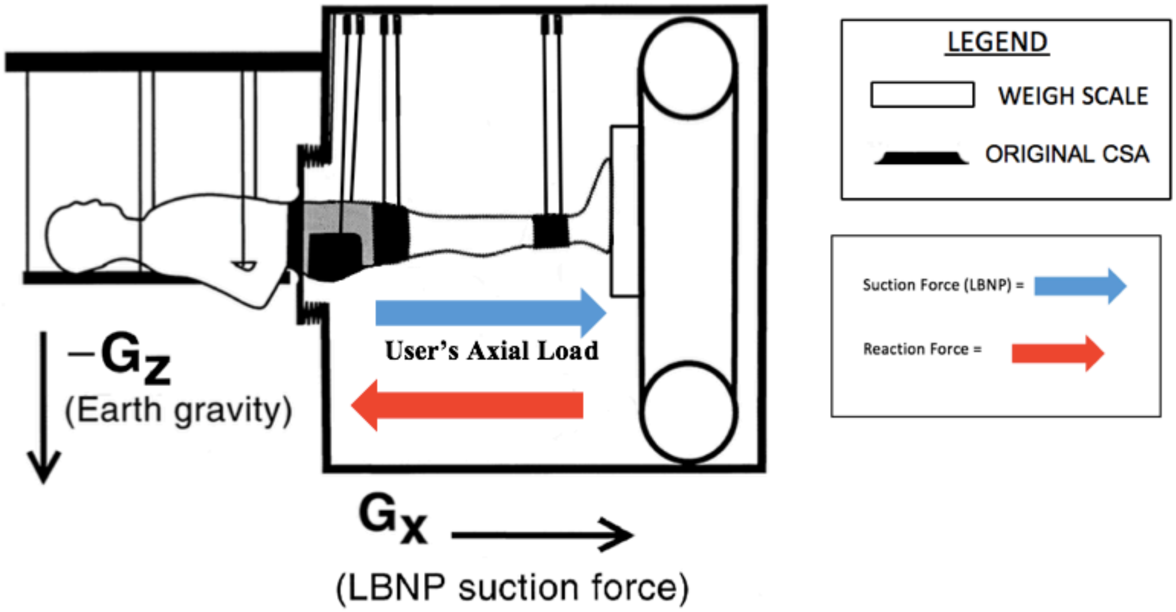
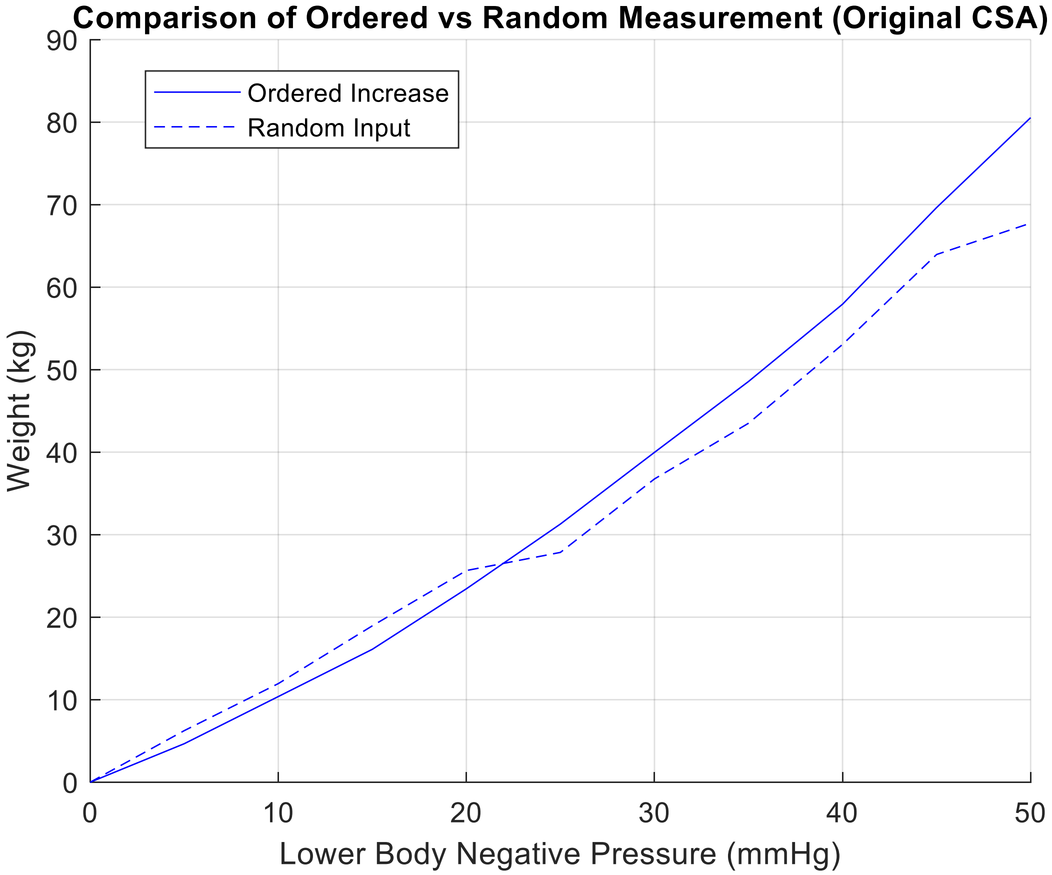


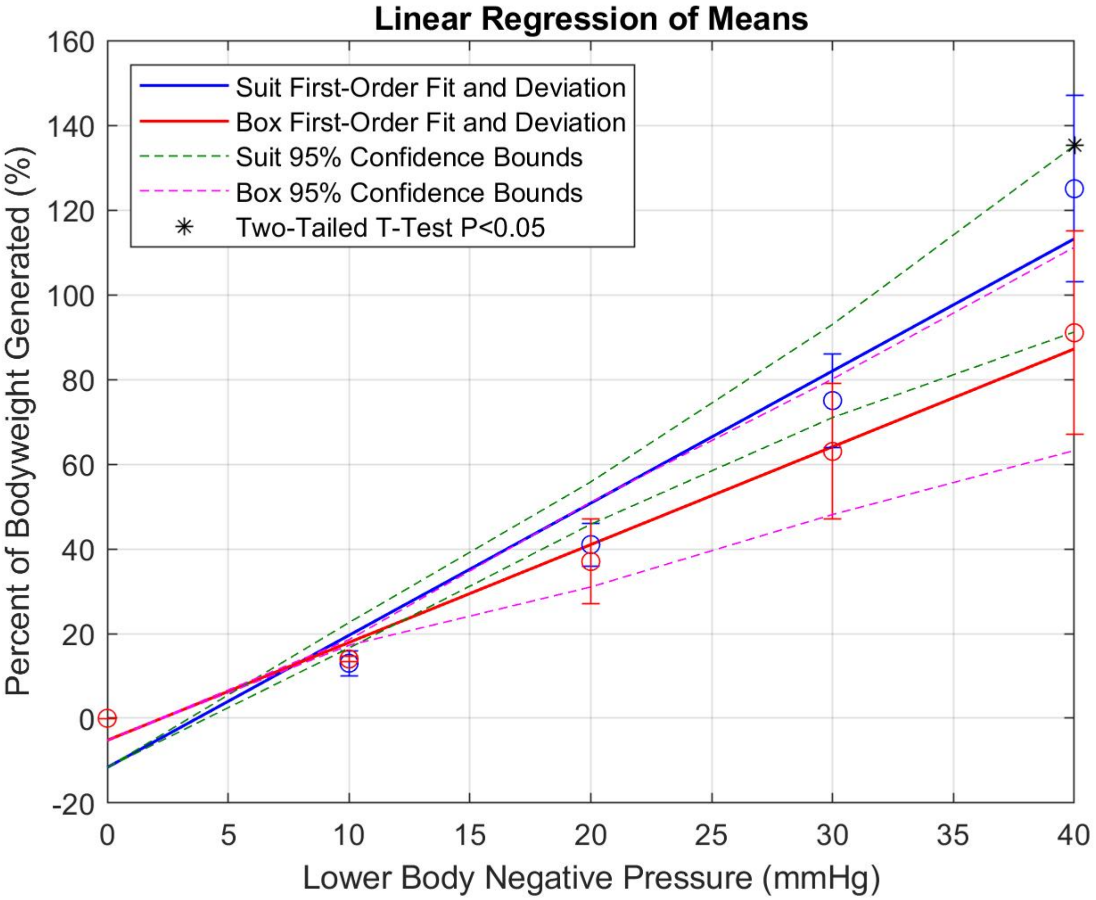
Figure 2. LBNP Chamber Force Balance Analysis

GRAPHS

Graph 1. Randomized vs Ordered Measurements



Graph 2. Percent of Bodyweight Generated (Gravity Suit vs LBNP Chamber)



TABLES

Table 1. A two-tailed t-test was used to compare the two conditions to determine statistical significance for each average percent bodyweight generated.

Negative Pressure (mmHg)	P-Value (P<0.05)
0	N/A
10	P<0.40
20	P<0.40
30	P<0.07
40	P<0.02

PHOTOGRAPHS

Photograph 1. LBNP Chamber with a user suspended in a supine position.

Photograph 2. Mobile Gravity Suit Without Negative Pressure Activation

Photograph 3. Mobile Gravity Suit During Negative Pressure Activation

Photograph 4. Profile View of Mobile Gravity Suit

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