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Generating waist area-dependent ground reaction forces for long-duration spaceflight

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ABSTRACT

Prolonged microgravity exposure greatly weakens the bones and muscles of astronauts. This is a critical biomechanical issue for astronauts as they may be more prone to bone fractures. To combat this issue, lower body negative pressure (LBNP) is a concept that generates artificial gravitational forces that may help strengthen bones and muscles during long-term spaceflight. Negative pressure, defined as below ambient pressure, is applied within a chamber that encompasses the lower half of the body. By increasing the negative pressure, more ground reaction forces (GRFs) are generated beneath the subject's feet. We hypothesize that increasing the cross-sectional area (CSA) of the subject's waist will generate greater GRFs beneath the subject's feet. Six healthy subjects volunteered to participate under two different experimental conditions: 1) original CSA of their waist and 2) larger CSA of their waist. In both conditions the subjects were suspended in a supine position (simulated microgravity) along with a weight scale beneath their feet. Negative pressures ranged from zero to 50 mmHg, increasing in increments of 5 mmHg. At −50 mmHg, original CSAs generated 1.18 ± 0.31 (mean ± SD) of their normal bodyweight. Subjects generated about one bodyweight at −45 mmHg using their original waist CSA. At −50 mmHg, larger CSAs generated 1.46 ± 0.31 of their normal bodyweight. Subjects generated about one bodyweight at −35 mmHg using their larger waist CSA. These data support our hypothesis. This novel technique may apply less stress to the cardiovascular system and conserve power for exercise in the spacecraft.

1. Introduction

Loss of bone and muscle strength are critical issues that occur during prolonged spaceflight (Sibonga et al., 2019). As a result of bone and muscle atrophy, studies show that an astronaut's movement between modules, aerobic activity, and extra-vehicular activity components are among the leading causes of musculoskeletal injuries (Scheuring et al., 2009). On Earth, bones and muscles are strengthened by the force of gravity which can be simulated by treadmill and resistive exercises in space (Cavanagh et al., 2010; Gene et al., 2010; Kohrt, 2008; Smith et al., 2012). Most commonly, we experience these impact forces through the ground-reaction forces (GRFs) our bodyweight generates under our feet. In return, GRFs help increase bone and muscle hypertrophy as astronauts spend more time in microgravity (Boda et al., 2000; Witt and Ploutz-Snyder, 2014). Therefore, it is imperative to develop effective techniques that will generate high GRFs under microgravity conditions to maintain musculoskeletal strength and health.

The loss of gravity becomes a major issue during long-term microgravity exposure. Studies show that mechanical loading generated by bodyweight serves as a critical stimulus to maintain musculoskeletal health. Thus, the lack of external forces in space prevents bone tissues from experiencing changes in strain energy (Vico and Hargens, 2018). This makes bones more susceptible to fractures when returning to weight-bearing environments (Dadwal et al., 2019; Vico and Hargens, 2018).

Lower body negative pressure (LBNP) exercise is a method that may potentially address these issues before a human centrifuge is available for spaceflight (Lee et al., 2014; Macias et al., 2005; Smith et al., 2008; Vico and Hargens, 2018; Zwart et al., 2007). This

Abbreviations: LBNP, Lower Body Negative Pressure; GRF, Ground-Reaction Force; CSA, Cross-Sectional Area; ANOVA, Analysis of Variance.

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vacuum-based method (below ambient pressure) generates gravitational-like forces underneath the user's feet similar to those experienced on Earth (Boda et al., 2000). Depending on the amount of force a user needs to generate, the user may increase or decrease the amount of negative pressure inside the LBNP device. Although LBNP techniques are known to generate full bodyweights of each user, it requires substantial negative pressure. A previous study that used a larger pool of subjects showed that it takes around −100 mmHg to generate a single bodyweight (Hargens et al., 1991). This means more stress applied across the subject's cardiovascular system. It may be beneficial to increase the mechanical loads across the subject's musculoskeletal system without having to increase their cardiovascular stress. This technical challenge can be mitigated by non-invasively increasing the cross-sectional area of the subject's waist.

The goal of this study is to test if the cross-sectional area of the subject's waist affects the ground-reaction force (GRF) generated while using the LBNP chamber. If successful, this will guarantee greater GRFs without having to use very high LBNP levels. This technique will limit stress across the user's cardiovascular system, conserve power, and can easily be added to other LBNP devices (large or small). The force model of the LBNP chamber is $A_W \times$ LBNP = GRF, where A_W is the CSA of the user's waist (Boda et al., 2000; Cao et al., 2005): the force is directly proportional to the cross-sectional area under constant pressure. Thus, in theory, increasing the area by a given amount will likewise proportionally increase the force (Leech, 1966). We hypothesize that increasing the CSA of the subject's waist will generate greater GRFs beneath the subject's feet.

2. Methods

2.1. Subjects

Before conducting this study, approval was granted by the Institutional Review Board of the University of California, San Diego. A power-analysis was conducted using the software, G*Power, which computed a sample size of six subjects. This calculation was performed by inputting a one tail test, 0.6 effect size, one independent variable, and a 0.05 significance level.

Each subject read the consent form and provided informed, written consent. Next, each subject's information (name, age, etc.) was recorded. A total of six healthy subjects (three males and three females) were used with an average age, average height, and average initial weight of 23.3 years ± 4.3 years, 170 cm ± 7 cm, and 64.4 kg ± 12.7 kg, respectively. Each of the six subjects were exposed to two conditions. The first condition used the subject's original CSA of their waist with an average CSA ± SD: 467.7 cm^2 ± 69-cm^2. The second condition used artificial cushioning to produce a larger CSA of the subject's waist with an average CSA ± SD of 1451 cm^2 ± 331 cm^2. The artificial cushioning was 1.4 kg and therefore, contributed minimally to generated GRFs. These second condition measurements are comparable to astronauts' anthropometric proportions, noting that astronaut BMI of male and female astronauts are 23.6 ± 1.9 and 20.8 ± 2.2 respectively and falls within one standard deviation of this study's male and female subjects, which are 24.3 ± 2.5 and 19.4 ± 2.1 respectively (Hamm et al., 2000).

2.2. Experimental protocol

This entire protocol was entirely static as each subject remained in supine position. During each 2-minute trial, all subjects experienced negative pressures ranging from 0 to 50 mmHg, in 5 mmHg intervals. At each interval, the force generated beneath the subject's feet was measured by a weight scale and recorded (Fig. 1A). This trial was repeated three times per subject for each of two conditions. Each subject participated in the trial with their normal waist size as the first condition. Subsequently, each subject had their apparent waist size increased using circumferential cushioning (approx. 50.8 cm circumferential increase) in the second condition (Fig. 1B). A total of six trials per subject was conducted, taking, in total, 1.5 h per subject.

2.3. Instrumentation and measurements

For the two conditions, each subject was instructed to lie supine in a custom-built LBNP chamber that was built by the Scripps Institute of Oceanography machine shop (Fig. 1). Their legs, thighs, and buttocks were suspended with sling straps. Their back was supported with a non-resistive backboard sling. Attached around the LBNP chamber's aperture (opening) was a neoprene seal manufactured by Seattle Fabrics. This neoprene was then wrapped around each subject's waist to ensure a tight seal within the chamber. The previously-calibrated, digital scale was vertically mounted, and the door of the LBNP chamber was closed to ensure a seal. A digital pressure transducer was connected to the LBNP chamber to measure the negative pressure. Each subject was closely monitored to prevent discomfort and/or syncope. Original CSA and larger CSA measurements were taken using measuring tape. Additionally, for a single subject, a random order of negative pressures from 0 to 50 mmHg was generated and a trial following the random order list was performed (Fig. 2). The GRFs generated were then compared to an ordered trial that incrementally increased from 0 to 50 mmHg to see if there was a significant difference in the two measurement approaches. Because the randomized pressures took 5-minutes per trial while the chronological pressures required 2-minutes, the shorter time approach was chosen for all subjects to avoid pre-syncopal symptoms (fainting).

Regression curves were used to show the polynomial behavior of GRF as a response to changes in negative pressure.

2.4. Data analyses

Weight Scale. The output forces generated by the subjects were recorded for analyses in both conditions. Each force output was compared to the initial weight as a ratio to analyze individual bodyweight generation.

Statistics. A script was developed to plot raw data, means, and deviations using MATLAB R2018a. Fit lines were also included in addition to their calculated 95% confidence intervals. One-way ANOVA test at each interval of negative pressure was the chosen method for testing because the original CSA and larger CSA data are two independent sample groups. The homogeneity of variances was proven by accepting the alternative hypothesis of Levene's test to demonstrate a normal distribution of measurements and meet the conditions for the ANOVA test. The means ± standard deviations for each enlarged CSA GRF was compared to the control condition (original CSA). A one-way analysis of variance (ANOVA) test was used to compare the two conditions to determine if statistical significance was present. A correction for multiple comparisons adjusting for the total number of statistical tests was not done because the analyses were planned before they were conducted. Additionally, all comparisons among means were considered to be of substantive interest a priori.

3. Results

All six subjects who participated in this study produced significant data (ANOVA $P < 0.05$) and showed no pre-syncopal symp-

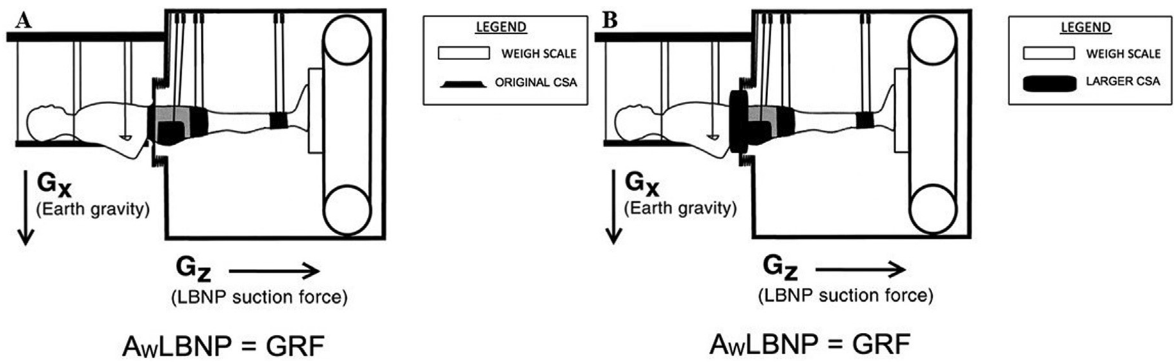

Fig. 1. (A) LBNP chamber for original CSA supine positioning. A_WLBNP = GRF, where A_W = CSA of user's waist; **(B)** LBNP chamber for larger CSA supine positioning. A_WLBNP = GRF, where A_W = CSA of user's waist.

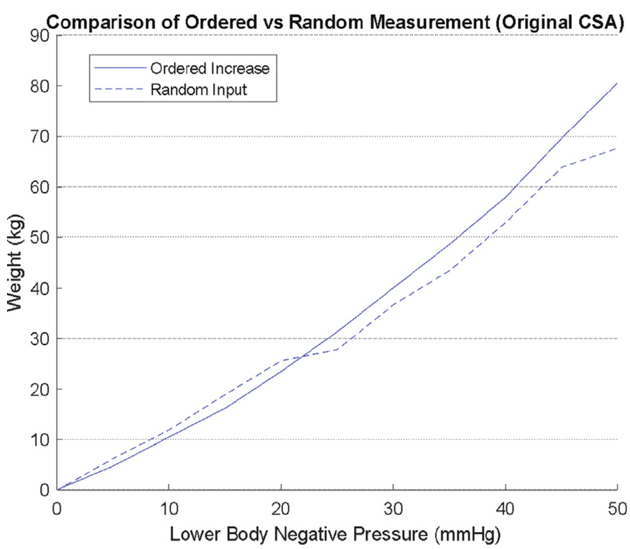

Fig. 2. Comparison of measurement methods for GRF #1 (original CSA) justifying ordered increase of negative pressure.

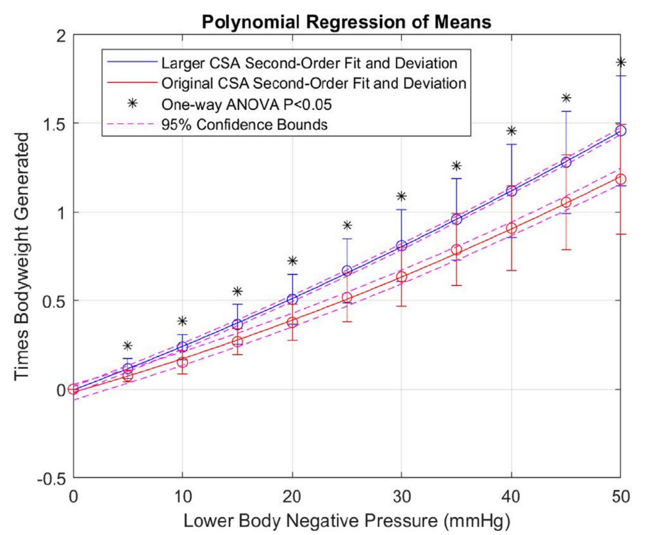

Fig. 3. Means of number of bodyweights generated by each subject at varying pressures with second-order polynomial regression curves, deviation of means, and 95% confidence intervals for best-fit lines; red is original CSA and blue is larger CSA. The standard deviations of each averaged measurement are displayed as error bars.

toms. The randomized forces were very similar to the forces produced in the ordered measurement of negative pressures with a Pearson correlation of 0.996. The adequacy of fit of regression was calculated to have a sum-squared error of 3.7e-4 (R^2 = 0.9989) and 1.87e-3 (R^2 = 0.9998) for larger CSA and normal CSA trials respectively. The p-values for Levene's test were all $P > 0.05$ (the p-values are 0.58, 0.86, 0.05, 0.23, 0.26, 0.32, 0.60, 0.81, 0.99, and 0.95 for averaged measurement of each subject from 5 to 50 mmHg in 5 mmHg intervals of negative pressure respectively).

3.1. Original CSA GRFs vs larger CSA GRFs

In the first condition (original CSA), subjects generated a mean maximum GRF of 73.1 kg at 50 mmHg (1 mmHg = 133.3 Pa) of negative pressure. In the second condition (larger CSA), subjects generated a mean maximum GRF of 90.8 kg at 50 mmHg of negative pressure. Overall, there was a clear increase in weight generated with an original CSA compared to a larger CSA (Fig. 3). The normalized weights of original CSA trials compared with the normalized weights of larger CSA trials and demonstrated a significant difference with $P < 0.05$ (the p-values are 0.026, 0.001, 0.005, 0.002, 0.005, 0.002, 0.003, 0.002, 0.001, and $P < 0.001$ for averaged measurement of each subject from 5 to 50 mmHg in 5 mmHg intervals of negative pressure respectively). The averaged raw GRF measurements for all six subjects in both test conditions are shown in Fig. 3.

3.2. Number of bodyweights generated and significance

Polynomial regression curves show the increase in the number of bodyweights (LBNP weight/initial weight) generated in larger CSA compared to original CSA trials. The difference in bodyweights generated between the two conditions increases with greater negative pressure. In the first condition (original CSA), subjects generate one bodyweight within 45 mmHg of negative pressure and a mean bodyweight of 1.18 ± 0.31 at 50 mmHg of negative pressure. In contrast, subjects under larger CSA conditions generate one bodyweight within 35 mmHg of negative pressure and a mean bodyweight of 1.46 ± 0.31 at 50 mmHg of negative pressure. Results illustrate that increasing the subject's average CSA (471 cm^2 to 1452 cm^2) similarly increases the average bodyweight generation by 24% at 50 mmHg of negative pressure. The average bodyweights generated between the original and larger CSA are compared in Fig. 3.

3.3. Number of bodyweights generated at varying CSAs

The number of bodyweights generated does not illustrate a directly proportional trend with CSA. This was due to the differences in bodyweights of each subject, which resulted in varying degrees of GRF generation. A low Pearson correlation coefficient of 0.169 for all measurements at 50 mmHg of LBNP supports this finding. The results instead conclude that the amount of increase in generated bodyweight depends on each individual subject and their individual CSA increase. The average bodyweights generated at various CSAs can be seen in Fig. 4.

4. Discussion

The primary findings of this study support our hypothesis that by increasing the CSA of each subject's waist, a higher GRF is produced beneath their feet. Statistical analysis demonstrates a significant increase in generated GRFs for larger CSA conditions compared to those generated under original CSA conditions (ANOVA $P < 0.05$ for all pressures). On average, a user with a larger CSA can reduce the necessary negative pressure by approximately 10 mmHg to generate about one bodyweight. Therefore, increasing the CSA reduces the power needed to achieve the same negative pressure with an original waist size. This new and useful method may be important as it reveals that LBNP devices can generate higher bodyweights at equivalent pressures. Also, generating a higher GRF with less negative pressure potentially reduces stress applied to the subject's cardiovascular system.

4.1. Bodyweight ratio

The data show that lighter subjects generate higher bodyweight ratios than heavier subjects with a comparable CSA. This is because the bodyweight ratio depends on initial weight as a denominator, hence higher ratios for lighter subjects. Therefore, lighter subjects can use minimal negative pressure to reach a single bodyweight. However, there was no clear linear correlation between changes in waist CSA and the resulting GRF.

4.2. LBNP chamber postulation of GRF generation

The LBNP chamber is equipped with a 182.8 cm^2 elliptical aperture, which allows users of various sizes to fit through. A flexible neoprene seal spans the gap between the user's waist and the chamber's aperture (opening; Fig. 1A), preventing air leakage. Based on careful analysis of the construction of the LBNP chamber, we propose a likely mechanism of the waist seal's contribution to GRFs. During applied negative pressure, the flexible neoprene seal in between the user and the aperture is drawn inward into the LBNP chamber. This applies a force both onto the subject and the LBNP chamber wall at the aperture dependent upon the area of the seal. When switching a user's CSA from their original size to a larger size, the areal size of the neoprene seal available to be drawn inward during negative pressure is reduced. In a simple model, we approximate that one half of the suction force generated by the neoprene seal's deformation is applied onto the LBNP chamber, while the other half contributes to the user's GRF. Increasing the CSA reduces the deformable area of the neoprene seal, reducing the associated suction force that is split between the subject and the LBNP chamber. More of the vacuum load is instead applied to the subject due to the greater CSA, producing stronger GRFs.

4.3. Limitations

There are possible errors in measuring the CSA of each subject's waist for both conditions. This may explain the large spread of data seen in Fig. 3. We attempted to overcome this limitation by taking multiple measures for each subject and averaging them. It was observed that buckling of the legs may reduce impact when recording GRFs. 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, contact and friction against the LBNP aperture of the larger CSA waist was closely monitored and avoided, though the flexible waist seal may have added some minor resistance during the experiments. We minimize this by adjusting the subject's waist into the center of the aperture opening.

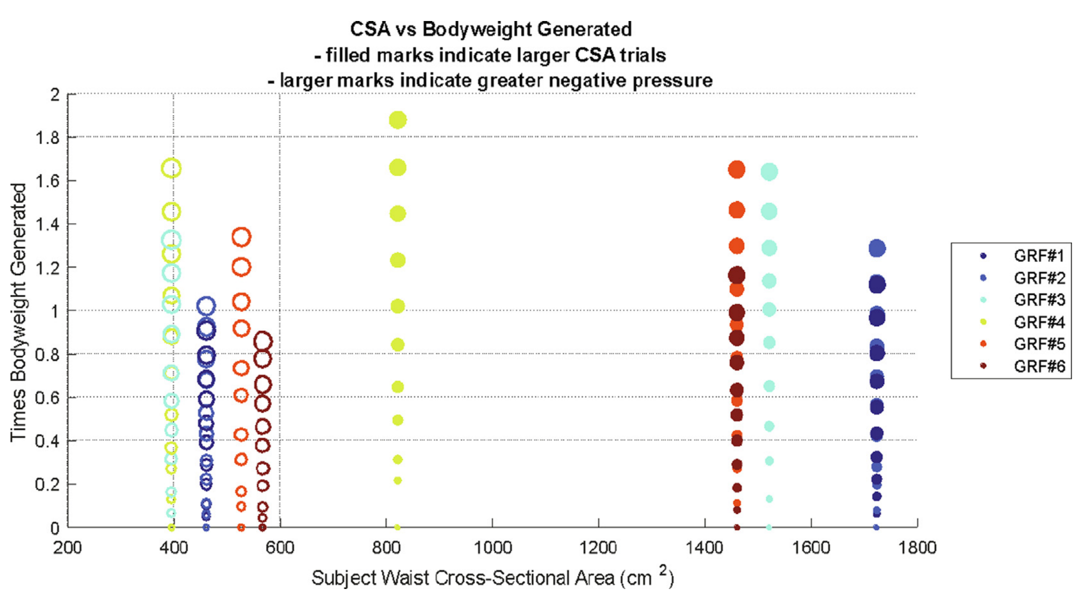

Fig. 4. Number of bodyweights generated for various subjects, separated by color; filled marks indicate larger CSA trials while empty marks indicate original CSA trials. Marker size increases with increasing negative pressure; the largest marker indicates −50 mmHg and the smallest indicates zero mmHg.

5. Conclusion

For a future spaceflight exercise device, this study explores the novel and important relationship between the cross-sectional area of a subject's waist and the resulting ground reaction forces beneath their feet. Our data demonstrate, on average, increasing the CSA of an individual's waist significantly increases the individual's GRF. This reproducible CSA-dependent increase of GRF provides valuable insight into static and dynamic LBNP exercise. However, further experimentation is required to determine the precise mathematical definition of this relationship and whether the increase in CSA is related to the generation of increased weight or the generation of an increased bodyweight ratio.

Considering future applications, this area-dependent technique may play a role in redesigning LBNP exercise devices. Standard seals in LBNP exercise devices will only provide the GRF for each user's original CSA. However, by simply incorporating a more robust waist seal that expands the waist CSA, LBNP users can slide in with comfort and generate stronger GRFs than that of a standard seal. Moreover, this new technique is advantageous because it requires nearly 10 mmHg less of negative pressure to generate one bodyweight. Using these new findings, less negative pressure and power will be required for space exercise. Thus, this concept will apply less cardiovascular stress and aid design of future development of countermeasures for prolonged microgravity exposure.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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