Hypergravity resistance exercise: the use of artificial gravity as potential countermeasure to microgravity

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Hypergravity resistance exercise: the use of artificial gravity as potential countermeasure to microgravity. J Appl Physiol 103: 1879–1887, 2007. First published September 13, 2007; doi:10.1152/japplphysiol.00772.2007.—The aims of this study were to 1) determine if hypergravity (HG) squats can produce foot forces similar to those measured during 10-repetition maximum (10RM) squats using weights under normal 1-G condition, and 2) compare the kinematics (duration and goniometry) and EMG activities of selected joints and muscles between 10RM and HG squats of similar total foot forces. Eight men and six women [27 yr (SD 4), 66 kg (SD 10)] completed ten 10RM [83 kg (SD 23)] and 10 HG squats (2.25–3.75 Gz). HG squats were performed on a human-powered short-arm centrifuge. Foot forces were measured using insole force sensors. Hip, knee, and ankle angles were measured using electrogoniometers. EMG activities of the erector spinae, biceps femoris, rectus femoris, and gastrocnemius muscles were also recorded during both squats. All subjects were able to achieve similar or higher average total foot forces during HG squats compared with those obtained during 10RM squats. There were no differences in total duration per set, average duration per repetition, and goniometry and EMG activities of the selected joints and muscles, respectively, between 10RM and HG squats. These results demonstrate that HG squats can produce very high foot forces that are comparable to those produced during 10RM squats at 1 Gz. In addition, the technique and muscle activation are similar between the two types of squats. This observation supports the view that HG resistance training may represent an important countermeasure to microgravity.

Space Cycle; squats; space; spaceflight; human centrifuge

IT IS WELL KNOWN that the virtual absence of gravity (microgravity) in space can produce significant deconditioning of key physiological systems, including the musculoskeletal, cardiovascular, and vestibular systems (1, 14, 17, 29, 32, 35, 38). With respect to skeletal muscle, the losses in muscle mass and function occur rapidly and can be large in magnitude. For example, short-duration (≤3 wk) spaceflights have been shown to produce 5–15% losses in muscle mass and 10–20% reduction in muscle strength (1, 17). Following 6 mo of space mission, losses as high as 40% in muscle strength has been observed (1). From a cardiovascular perspective, it is well known that microgravity produces a rapid and significant loss of orthostatic tolerance that impacts ~20% to 64% (7, 31) of all astronauts during short-duration spaceflight and as many as 83% (31) during long-duration spaceflight. Although the loss of bone mass does not occur rapidly, the magnitude of bone loss during long-duration space missions is a major concern, because average rates of bone loss ranging from ~1.5 to 3.0% per month have been observed (28, 29). Such rates of loss are equivalent to the bone loss in menopausal women in a year without intervention (33) and may increase the risk of fracture on returning to Earth or when landing on other planets (29). Collectively, these adverse health effects of microgravity must be prevented if we are to send astronauts on long-duration missions to Mars and beyond, and this places a premium on developing countermeasures that effectively maintain and protect key physiological systems (11).

Numerous countermeasures have been developed to combat the negative effects of microgravity. Artificial gravity represents a somewhat intuitive but poorly studied countermeasure that may benefit multiple physiological systems, specifically protecting the musculoskeletal and cardiovascular systems (11). We have developed a unique human-powered centrifuge, the Space Cycle (SC; Ref. 26), which can be powered to 7 Gz (head-to-foot direction) or more. A key feature of artificial gravity is that it not only can be used to replace Earth’s 1-G environment but also can be used to generate hypergravity (HG) conditions, which might minimize the exposure time required to achieve the same training benefits against the effects of microgravity.

In a previous study (37), we reported that subjects could perform squats under high-G (HG) loading conditions without experiencing motion sickness or illusory motion. In the present study, we extended these initial findings by comparing the foot forces produced during 10-repetition maximum (10RM) and HG squats. The aims of this study were to 1) determine if HG squats can produce foot forces similar to those measured while performing 10RM squats using weights under normal 1-G condition, and 2) compare the kinematics (duration and goniometry) and electromyographic (EMG) activities of select joints and muscles, respectively, between 10RM and HG squats of similar total foot forces. We hypothesized that HG squats can produce total foot forces similar to those measured while performing 10RM squats (foot force hypothesis). We also hypothesized that under this condition of similar total foot forces, the kinematics [duration and range of motion (ROM)] of the selected joints (kinematic hypothesis) and EMG activities of the selected muscles (EMG hypothesis) will be similar between the two types of squats. Importantly, the results suggest that HG squats are comparable to 10RM squats. Collectively, the findings of our previous (37) and present studies represent important foundations for future studies designed to test the hypothesis that HG can be used as a loading modality to prevent the loss of muscle mass that occurs in microgravity.

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Innovative Methodology

MATERIALS AND METHODS

Subjects. Fourteen young, healthy, nonsmoking subjects (8 men and 6 women, Table 1) participated in this study. Subjects were either sedentary or recreationally active except for one female and two male subjects who did heavy resistance training. All subjects were given oral and written information about the experimental procedures and potential risks before giving their informed consent to participate in this study. This study was approved by the Institutional Review Board and the Advisory Committee of the General Clinical Research Center (GCRC), University of California (UC), Irvine. All studies were performed in the SC Laboratory of the UC Irvine GCRC.

SC configuration for HG squats. All HG squats were performed on the SC using the squat configuration described in details in a previous study (37). Briefly, the SC is a human-powered centrifuge with two short centrifuge arms. One arm was constructed with a gondola/cage-like structure, which allows subjects to stand and perform squats. Subjects wore a full-body safety harness (model FB1100, Robertson Mountaineering, Henderson, NV) attached to the struts of the gondola during all HG squats. The harness can be adjusted to allow unrestricted squatting movements while protecting the subject. The other arm of the centrifuge is a cycle ergometer that allows a person to pedal and power the SC. As the cyclist begins pedaling, the centrifuge starts rotating, pushing the centrifuge arms outward and away from the center pivot. Artificial gravity is generated from the centripetal acceleration of the rotating centrifuge, and \( g_z \) is the inertial resultant to acceleration in the head-to-foot direction (\( g_z \)-axis) in multiples of the magnitude of the acceleration of gravity, \( g \), with \( g_z = 1 \, g \) under normal Earth’s gravity. All \( g_z \)s hereafter refer to the \( g_z \) at the feet unless otherwise stated. The SC was allowed to decelerate to a complete stop after each trial of HG squats by modulating the pedal RPM. A mechanical disc brake is also available for controlling the work rate and faster deceleration of the SC.

Experimental design. This study consisted of four separate sessions. In the first session, subjects were given instructions on how to perform conventional (i.e., on the ground under normal 1-G, condition using weights) back squats, using a standard 20-kg Olympic bar on their shoulders behind their necks. Additionally, subjects were required to ride the SC and perform squats at various \( g_z \)s to determine subject tolerance to HG squats.

In the second session, subjects performed 10 HG squats at each progressively higher \( g_z \) (1.5, 2.0, 2.5, and 3.0 at the feet/base plate) in one trial. Foot forces using insole pressure sensors (cf. Foot force measurements) and kinematic data (cf. Instrumentation) were recorded during the trial. The goal of this session was to determine the relationship between foot forces and \( g_z \) for each subject. This relationship was subsequently used in the fourth session to predict the \( g_z \) required to produce foot forces similar to those observed during conventional 10RM squats. Because of the contrasting loading modalities between HG squats, which rely on G-forces, versus conventional 10RM squats, which use weights, we used foot forces as a common measurement of loading condition between the two types of squats. The intensity of the HG squats was quantified by expressing the foot forces measured during HG squats as a percentage of the foot forces measured during the 10RM squats.

In the third session, the subjects’ 10RM was determined ~1 wk before the last session. The purposes were to predict 1) the 10RM during the final session (thereby reducing the number of attempts needed to achieve the 10RM and conserving strength during the final session), and 2) the \( g_z \) needed during the final session to produce foot forces similar to those in the 10RM squats. Subjects began squatting with a standard 20-kg Olympic bar after warming up with only their own body weight. The mass on the bar was progressively increased with each successful set until subjects could no longer maintain proper form and/or complete the set at the given mass. The 10RM was defined as the maximum mass that the subject could squat 10 times. One repetition is defined as from the standing position to a squat position with a knee angle of \( \sim 90^\circ \) (eccentric phase) and back to the standing position (concentric phase). A 2-min rest interval was given between each set of squats. Following 5–10 min of rest after the 10RM, subjects also performed a brief session of three HG squats at each \( g_z \) of 1.5, 2.0, 2.5, and 3.0 to prepare them for the fourth and final session (cf. below).

The goal of the final session was to determine if HG could be used to produce foot forces equivalent to those produced during 10RM squats. This session consisted of two phases: 1) 10RM test for conventional squats; and 2) HG squat test. Subjects first completed a 10RM assessment followed by 15–20 min of rest before performing HG squats. Each subject was instructed to maintain the same technique, including stance and squat depth, during both types of squats (10RM vs. HG squats). Left and right foot forces, goniometry of the right hip, knee, and ankle joints, and EMG activities of the left and right rector spinae (ES), biceps femoris (BF), rectus femoris (RF), and gastrocnemius (Gas) were collected during the 10RM and HG squats. The rate of perceived exertion (RPE) following each type of squat was assessed using a modified Borg RPE Scale that ranged from 0 to 10. Subjects first warmed up with 10 repetitions \( \times 20 \, kg, 5 \times 50 \% \) 10RM predicted in the 3rd session (10RMpred, 7 \times 70 \% 10RMpred, and 10 \times 90 \% 10RMpred) before attempting the 10RM. The load and number of sets and repetitions during the warm-up sets were adjusted if necessary according to each subject. For the HG squats, subjects performed a warm-up set of three squats at low \( g_z \), followed by two to three sets of 10 repetitions of HG squats at \( g_z \)s that were predicted to correspond to \( \sim 90–110\% \) of the 10RM based on the relationship between foot forces and \( g_z \) calculated from the data.

Table 1. Subject characteristics

<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>SD</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age, yr</td>
<td>26</td>
<td>4</td>
<td>22</td>
<td>33</td>
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<tr>
<td>Body mass, kg</td>
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<td>8</td>
<td>56</td>
<td>86</td>
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<tr>
<td>Height, m</td>
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<td>0.08</td>
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<td>1.85</td>
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<tr>
<td>10RM, kg</td>
<td>99</td>
<td>13</td>
<td>80</td>
<td>114</td>
</tr>
<tr>
<td>( G_z ) (at the feet) of HG, g</td>
<td>3.25</td>
<td>0.35</td>
<td>3.00</td>
<td>3.75</td>
</tr>
<tr>
<td>Avg total HG FF, %10RM</td>
<td>104</td>
<td>5</td>
<td>95</td>
<td>109</td>
</tr>
<tr>
<td>Peak total HG FF, %10RM</td>
<td>99</td>
<td>4</td>
<td>91</td>
<td>103</td>
</tr>
<tr>
<td>10RM/body mass</td>
<td>1.39</td>
<td>0.25</td>
<td>1.16</td>
<td>1.91</td>
</tr>
<tr>
<td>10RM RPE</td>
<td>10</td>
<td>1</td>
<td>8</td>
<td>10</td>
</tr>
<tr>
<td>HG RPE</td>
<td>9</td>
<td>1</td>
<td>8</td>
<td>10</td>
</tr>
</tbody>
</table>

10RM, 10 repetition maximum; HG, hypergravity; Avg total FF, average total foot force; Peak total FF, peak total foot force; RPE, rate of perceived exertion; Min, minimum; Max, maximum.
collected in the previous sessions. The set of HG squats that produced average total foot force that most closely matched that of the 10RM squats was selected for further analyses and comparisons.

**Instrumentation.** The instrumentation on the SC itself included an on-board computer, data-acquisition (DAQ) modules, accelerometers, a torque meter, pedal and centrifuge RPM indicators, and a goniometry system. Foot forces and EMG data were collected on a separate, ground-based computer via telemetry (cf. following sections). All data from the on-board instrumentation were acquired at 500 Hz by the DAQ modules (KUSB-3102, Keithley Instruments, Cleveland, OH) that were connected to the on-board computer (VAIO VGN-T250P, Sony, New York, NY) and controlled by Labview software (v7.1, National Instruments, Austin, TX). These data were synchronized with the foot force and EMG data by a synchronization pulse from the foot force measurement system. Acceleration was measured using a triaxial accelerometer (CXL04LF3, Crossbow Technology, San Jose, CA) that was centrally located on the base plate of the gondola. The accelerometer was calibrated in the x-, y-, and z-axes before each test. The torque required to power the centrifuge at any given G was measured using a torque transducer (model 1312, VibraC, Amherst, NH) that was in-line with the pedal crank set. The torque transducer was also calibrated before each test.

**Foot force measurement.** Left and right foot forces were measured at 100 Hz using a Pedar-X Telemetry System (Novel, St. Paul, MN). This system employs insoles that each consist of 99 individual pressure sensors of known areas that allow local foot forces to be measured. The total foot forces were determined by summing the left and right foot forces. Average and peak foot forces were determined for both the eccentric and concentric phases of each repetition.

**Goniometry.** Right hip, knee, and ankle angles (Fig. 1) were measured using electrogoniometers (XM180, Biometrics, Ladysmith, VA). The mean start angle (at standing position) and ROM were identified for each joint and each repetition. The ROM is the difference between the maximum joint angle and start angle. We identified the start and end of each repetition using goniometry and foot forces. The transition from eccentric to concentric phase was determined by the occurrence of maximum knee angle/flexion.

**Electromyography.** During each squat, surface EMG activities of the left and right ES at ~5 cm lateral to the L3–L4 spinous processes level with the iliac crest, and midbellies of the BF, RF, and Gast muscles were recorded. To enhance electrode adherence and conductance of EMG signals, each electrode placement site was cleaned with isopropyl alcohol, shaved, and abraded with gauze (to remove dead skin cells). Disposable bipolar silver-silver chloride electrodes with a 25-mm interelectrode distance (2DT2, Multi Bio Sensors, El Paso, TX) were then placed over the sites in parallel with the underlying muscle fibers. A reference electrode was placed over the tibial bone. All sites were identified by the same researcher.

Raw EMG signals were amplified ×1,000, band pass filtered between 10 and 1,000 Hz (T42AL-10TX1, Konigsberg Instruments, Pasadena, CA), sampled at 1,000 Hz/channel, and processed by a Konigsberg base station (T42 1x1). Data were stored on a computer and analyzed with a software package (Datapac 2K2 Version 3.16, Run Technologies, Mission Viejo, CA). The average amplitude of the root mean square (RMS) of each full wave-rectified EMG signal was evaluated over the duration of the eccentric and concentric phases of each repetition. There was no need to normalize the EMG signals collected during the 10RM and HG squats given that all measurements for a given subject were collected in one session.

**Statistical analysis.** Data from the four HG repetitions were averaged for each set of squats. The total duration of each set of squats was also calculated. The foot force hypothesis was assessed by comparing the average and peak total foot forces obtained during 10RM and HG squats. The differences in average duration per repetition, total duration per set, and start angles and ROM of the right hip, knee, and ankle (kinematic hypothesis), and RPE between 10RM and HG squats were analyzed using paired t-tests. The effect of side (left vs. right) × phase (eccentric vs. concentric) × squat type (10RM vs. HG squats) on foot forces (cf. results for rationale) and EMG activities (**EMG hypothesis**) was analyzed using three-way, within-subject, repeated-measures ANOVA. Assumptions for paired t-tests and ANOVA were assessed. There were some deviations from normality (Shapiro-Wilk Normality test, boxplots, skewness/SE and/or kurtosis/SE) in the EMG activities of the four muscles. However, ANOVA is robust to the violation of normality, and such a violation is not likely to increase type I or II error (30).

Significant two-way and three-way interactions were followed up with simple main effects and simple, simple main effects analyses, respectively, with Bonferroni correction for multiple comparisons. Significance was set at α = 0.05 for all analyses. Statistical analyses were performed using SPSS 10.0 for Windows software package. Data in Table 1 are presented as means and SD to provide an index of the variability of the data, while data in figures are presented as means with 95% confidence intervals to characterize the uncertainty about the estimated value of the population mean.

**RESULTS**

**Foot force hypothesis.** The mean 10RM for all subjects is shown in Table 1. All subjects were able to achieve similar or higher (≥95% 10RM) average total foot forces during HG squats. The G required to most closely match the average total foot forces produced during the 10RM squats was 3.25 G, (range 3.00–3.75 G); and 2.58 G, (range 2.25–3.0 G) for the men and women, respectively. These G conditions produced 104% and 105% of the 10RM average total foot forces for the men and women, respectively. Peak total foot forces were 99% 10RM for the men and 103% 10RM for the women. The men reported similar RPEs for both types of squats, while women reported a lower RPE for the HG squats (P = 0.004). This was because all women were able to complete 10 repetitions of HG squats at 3.0 G, which was of equivalent or higher intensity than their 10RM, during the second session of this study. Given that 1) both men and women were able to achieve their 10RM total foot forces during HG squats, and 2) there is no reason to...
believe that the sex of the subject influences the repeated measures within the same subject, subsequent analyses were analyzed with both men and women combined as a group. Differences in left and right foot forces. While the average and peak total foot forces were similar between the two types of squats, we noticed differences in the left and right foot forces between the 10RM and HG squats. The transition from eccentric to concentric phase for each repetition was determined by the occurrence of maximum right knee angle/flexion (dashed lines).

To investigate differences between right and left foot forces, we performed a three-way, within-subject (side × phase × squat type) repeated-measures ANOVA of the foot forces. There was a significant three-way interaction between side, phase, and squat type $[F(1, 13) = 21.02, P = 0.001]$ (Fig. 3). For the HG squats, during both eccentric and concentric phases, the left foot force was lower than the right foot force. In addition, the left eccentric foot force was lower than the left concentric foot force. For the 10RM squats, there were no differences in the left and right foot forces during both eccentric and concentric phases. The left eccentric and concentric, and right concentric foot forces were different between the two types of squats [all significant $P$ values $<0.001 \times 12$ (12 total post hoc comparisons)].

Kinematics hypothesis: duration of repetitions and sets. The average duration of each repetition and total duration of each set were similar between the 10RM (2.48 and 29.10 s, respectively) and HG squats (2.51 and 28.05 s, respectively). We further investigated if there were differences in the eccentric and concentric durations of the two types of squats with a two-way, within-subject (phase × squat type) repeated-measures ANOVA. There was a significant two-way interaction $[F(1, 13) = 8.62, P = 0.012]$ (Fig. 4). There were no differences in the eccentric and concentric durations between the two types of squats. For the 10RM squats, there was no difference between the eccentric and concentric durations. However, for the HG squats, the eccentric duration was 0.188 s shorter than the concentric duration ($P = 0.003 \times 4$ for 4 comparisons).

Kinematic hypothesis: goniometry. There were no differences in the start angles of the hip, knee, and ankle, and ROM of the hip and ankle between the 10RM and HG squats (Fig. 5). After controlling for the familywise error rate, there was no difference in the ROM of the knee between the two types of squats ($P = 0.37 \times 2$).

EMG hypothesis. For the ES EMG activity, there was a significant three-way interaction between side, phase, and squat type $[F(1, 12) = 19.34, P = 0.001]$ (Fig. 6). There were
no differences in ES EMG activity between the two types of squats within each combination of side and phase. For both squats, the ES EMG activity was greater in the concentric phase than eccentric phase in both left and right sides (all \( P < 0.001 \times 12 \)). For the HG squats, the left concentric ES EMG activity was greater than the right side (\( P = 0.002 \times 12 \)).

For the BF EMG activity, there was a significant two-way interaction between phase and squat type \( F(1, 13) = 5.39, P = 0.037 \). There were no differences in the eccentric and concentric BF EMG activities between the two types of squats. For both 10RM and HG squats, concentric EMG activity was greater than eccentric activity in both legs (with a greater difference in the 10RM squats, explaining the significant interaction) (\( P = 0.001 \times 4 \)).

For the RF and Gast EMG activities, there were no differences between sides, phases, and squat types, although there was a trend for the RF EMG activity to be greater during HG squats (\( P = 0.055 \)).

**DISCUSSION**

While a number of countermeasures have been developed to prevent/blunt the deconditioning effects of microgravity on the musculoskeletal and cardiovascular systems, more effective and integrated countermeasures are needed. Herein lies the potential advantage of artificial gravity/HG because 1) it represents a single countermeasure (i.e., centrifuge) that could be used to load/challenge muscle, bone, and the cardiovascular and vestibular systems; and 2) various applications of HG might effectively shorten the amount of time dedicated to exercise as a countermeasure.

Given this background, we developed a unique human-powered centrifuge that can be configured to optimize the stress placed on a given physiological system. Using a configuration that employed a gondola, the major findings of this study were 1) all subjects were able to achieve similar or higher average total foot forces during HG squats than during 10RM squats, and 2) under similar total foot forces, there were no differences in duration (total duration per set, average duration per repetition, eccentric and concentric durations), goniometry (start angles and ROM) of all the selected joints (hip, knee, and ankle), and mean EMG activities of all the selected muscles (ES, BF, RF, and Gast) for the same side and phase between 10RM and HG squats. These findings substantiate all of our hypotheses and suggest that HG squats are comparable to conventional squats performed under normal 1-G \( z \) condition.
and that HG can be used as a loading modality to potentially prevent the loss of muscle mass that occurs in microgravity.

**Intensity of HG loading.** While the use of resistance exercise (5) or artificial gravity (11) as a countermeasure to microgravity is not new, we are the first to combine both of them and examine the use of HG resistance exercise as a loading modality for the muscles. In our previous study (37), we demonstrated that subjects were able to complete 10 HG squats at high loading of 2.5–3.0 G\(_z\), without experiencing motion sickness or illusory motion. In this study, we quantified the intensity of the loading by comparing the foot forces obtained under HG conditions to those during 10RM squats. All subjects were able to achieve similar or higher (≥95% 10RM) average total foot forces during HG squats compared with those obtained during 10RM squats. In fact, all the subjects would have been able to perform HG squats at >100% 10RM had we not limited the intensity of the HG squats as we were interested in having the subjects perform HG squats at G\(_z\)s that most closely matched the intensity of the 10RM squats. As in the case of the women, they were able to complete 10 HG squats at 3.0 G\(_z\) during the second session, which corresponded to >100% of their 10RM. The ability to perform HG squats at higher intensity may be due to differences in the distribution of loading forces. With conventional squats, subjects experience intense loading of the shoulders and spine, and they must balance the weights. The transmission of loading onto the muscles of the legs is much different with HG, and results in a more comfortable experience, allowing untrained subjects to achieve higher loading conditions while performing HG squats. This may result in greater training volume (combination of sets, repetitions, and load/intensity) and maximize both increases in muscle strength and size (24), representing an advantage over other types of resistance-based countermeasures.

**Potential of HG resistance exercise as countermeasure to microgravity.** One of the key concerns of using artificial gravity as a countermeasure, especially with a short-arm centrifuge, is the potential negative side effects that result from head movement in a rotating environment, including motion sickness, dizziness, illusory motion, and nausea (15, 27, 40). However, researchers from different laboratories have consistently found that high short-arm centrifugation either passively under both ground-based (8, 19) and simulated microgravity [bed rest, (21, 34)] conditions, or in conjunction with cycle exercise under ground-based (9) and bed rest (20, 22) conditions, was well tolerated. Similarly, our previous (37) and present studies have clearly demonstrated that the above potential side effects can be minimized, even at high rates of rotation (≥40 rpm; ≥3 G\(_z\)), by limiting the lateral movement of the head and focusing on a visual cue located on the front of the base plate while performing HG squats on the SC.
performing HG resistance exercise on the SC is safe, tolerable, and feasible even at high $G_z \geq 3.0$.

This then gives rise to an important question: is HG resistance exercise effective in inducing strength gain and muscle hypertrophy in ground-based or simulated microgravity studies? While the purpose of this study was not to answer this question directly, the results from this study set the stage for future studies addressing the above question. The lack of differences in the kinematics (durations and goniometry) of the hip, knee, and ankle between 10RM and HG squats under conditions of similar total foot forces suggests similar technique between the two types of squats. There were also no differences in the EMG activities of ES, BF, RF, and Gast between the two types of squats of the same side and phase. Hence, we speculate that given similar technique and muscle activation between 10RM and HG squats, the muscular adaptation to HG resistance training should be similar to that of conventional squats under conditions of similar total foot forces (indicator of load). No systematic study has been conducted to investigate the efficacy of artificial gravity on human skeletal muscles. However, it is well-established that conventional resistance training using weights can increase both muscle strength and size at 1 G, although it will not work in a microgravity environment. Thus, taken together, HG resistance exercise represents an important potential countermeasure to microgravity for the muscles.

The problem of overcoming muscle atrophy and weakness with exposure to microgravity is not a simple one. There is a differential response between muscle groups and fiber types to the same stimulus. Flywheel (FW) resistance training effectively maintained whole muscle volume, force, power, and EMG activities of the knee extensors (quadriceps) following 29 (4) and 90 (5) days of bed rest. However, the plantar flexors appear to be more affected by muscle unloading and less protected by resistance training in maintaining muscle size and function. Muscle atrophy was greater in the plantar flexors than knee extensors (16% vs. 10% (4), and 29% vs. 18% (5)) in the same studies. FW resistance training only partially attenuated (~50%) the decrease in plantar flexor muscle volume in these same studies (4, 5). Maximum voluntary contraction force of the plantar flexors decreased similarly despite FW resistance training after 90 days of bed rest (5). This reduction in whole muscle function may be in part due to functional changes at the single-fiber level. The soleus, a plantar flexor, consists of predominantly slow-twitch (myosin heavy chain, MHC I) fibers. Although FW resistance training prevented the slow-to-fast MHC isofrom shift in the soleus with 84 days of bed rest (16), evidence from the vastus lateralis (mixed muscle) suggests that the resistance training did not maintain the function (absolute and normalized peak force and power) of MHC I fibers against unloading (36).

This differential response between muscle groups and fiber types clearly indicates a need for different training paradigms to target different muscle groups. Single sessions of four sets of seven repetitions of intense FW supine squats performed every 3rd day was sufficient to maintain knee extensor muscle volume and function during bed rest (5). On the other hand, a much larger training volume of twice a day, five sets of 10 repetitions at 70% maximal isometric force of supine calf raises, performed almost daily, seemed to be needed to maintain plantar flexor muscle volume and function with bed rest (3). Much work is still required to investigate the optimum combination of intensity, duration, or number of sets and repetitions per session, and frequency of training to protect not just the muscles but other organ systems affected by microgravity as well. Such diverse differences in training requirements can be handled by the flexibility of artificial gravity. Artificial gravity offers a continuous and wide spectrum of load ($G_z\text{s}$) to modulate the training volume and, more importantly, an integrative approach to counteract the ill effects of microgravity by being able to target various organ systems affected by microgravity and the flexibility to perform various exercises in one integrated system similar to a multiexercise gym equipment.

One can perform cardiovascular training for long duration if desired (9, 21, 34). Intense interval training may be performed too (2). As shown previously (37) and in this study, high-intensity resistance training targeting the musculoskeletal system can be performed as well. Short-arm centrifugation may also be used to improve vestibular responses and orthostatic tolerance to microgravity (10, 12, 13, 39, 40). A variety of exercises can be performed on the SC. In addition to the cycling and squat resistance exercises, one can perform running exercise if fitted with a treadmill on the gondola or pull ups to target the upper body with a pull up bar attached to the top of the gondola. Calf raises can also be performed on the gondola to specifically target the plantar flexors.

Certainly the space available in a spacecraft is a premium constraint even for short-arm centrifuges. The radius of the SC with the gondola is ~1.9 m, and this configuration was chosen because it was compatible with the dimensions of the Shuttle cargo bay and the International Space Station. Given that studies are currently in a proof-of-principle stage, no attempts have been made to optimize the design (e.g., dimensions, mass) of the SC. Clearly, the effectiveness of HG as countermeasure will determine whether and how such countermeasures will be employed. If a single countermeasure device like the SC is highly effective across a spectrum of key physiological systems, then it may require less total volume than a suite of multiple countermeasure systems such as a treadmill, cycle ergometer, and resistance training device.

Other considerations and limitations. We noticed differences in the left and right foot forces while HG squats were performed on the SC (Figs. 3 and 4). We believe that these differences in foot forces are due to a moment about the center of mass. However, this phenomenon will not occur in microgravity due to the negligible vertical component of gravity.

The reduced EMG activities of the ES and BF during eccentric phase (compared with concentric phase) in both types of squats is in agreement with other studies (6, 23). Interestingly, EMG activity of the ES during the concentric phase was greater on the left than right side during HG squats. This could be the ES compensating for the moment gradient experienced while performing HG squats in their role as trunk stabilizers. The similar muscle activation of RF during both eccentric and concentric phases probably reflects its biarticular actions, working both as a hip flexor (active during eccentric phase) and a knee extensor (active during concentric phase) (18). The low
activation of the Gastrocnemius during squats was also consistent with the literature (18).

One limitation of this study is the possible effect of fatigue by having subjects perform 10RM followed by HG squats in one session. This was done to minimize confounding effects of fluctuations in 10RM strength and normalization of EMG signals if the two types of squats were performed on separate days. To reduce the possibility of fatigue, we allowed subjects to rest between the two types of squats. Given that subjects were able to achieve similar or higher force forces during HG squats, we felt that fatigue was not a major issue. We also recognize that given the aims of the study, we did not randomize the order of exercise.

Conclusions. Collectively, the results of our previous (37) and present studies have demonstrated that performing HG squats on the SC, even at high loading, is safe, tolerable, and feasible. Analyses of foot forces, and kinematics and EMG activities of the select joints and muscles, respectively, in this present study also indicate that HG squats are comparable to conventional squats performed under normal 1-G condition. Hence, the findings of this study provide the basis for further investigations of using HG resistance exercise as a countermeasure to microgravity.

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