



Combining ergometer exercise and artificial gravity in a compact-radius centrifuge[☆]



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ABSTRACT

Humans experience physiological deconditioning during space missions, primarily attributable to weightlessness. Some of these adverse consequences include bone loss, muscle atrophy, sensory-motor deconditioning, and cardiovascular alteration, which may lead to orthostatic intolerance when astronauts return to Earth. Artificial gravity could provide a comprehensive countermeasure capable of challenging all the physiological systems at once, particularly if combined with exercise, thereby maintaining overall health during extended exposure to weightlessness. A new Compact Radius Centrifuge (CRC) platform was designed and built on the existing Short Radius Centrifuge (SRC) at the Massachusetts Institute of Technology (MIT). The centrifuge has been constrained to a radius of 1.4 m, the upper radial limit for a centrifuge to fit within an International Space Station (ISS) module without extensive structural alterations. In addition, a cycle ergometer has been added for exercise during centrifugation. The CRC now includes sensors of foot forces, cardiovascular parameters, and leg muscle electromyography. An initial human experiment was conducted on 12 subjects to analyze the effects of different artificial gravity levels (0 g, 1 g, and 1.4 g, measured at the feet) and ergometer exercise intensities (25 W warm-up, 50 W moderate and 100 W vigorous) on the musculoskeletal function as well as motion sickness and comfort. Foot forces were measured during the centrifuge runs, and subjective comfort and motion sickness data were gathered after each session. Preliminary results indicate that ergometer exercise on a centrifuge may be effective in improving musculoskeletal function. The combination is well tolerated and motion sickness is minimal. The MIT CRC is a novel platform for future studies of exercise combined with artificial gravity. This combination may be effective as a countermeasure to space physiological deconditioning.

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1. Introduction

Intermittent exposure to artificial gravity (AG) on a short radius centrifuge (SRC) combined with exercise is a promising, comprehensive countermeasure to the cardiovascular and musculoskeletal deconditioning that occurs as a result of prolonged exposure to microgravity [1–5]. To date, the study of artificial gravity has been done using SRC's that are 1.8–

3.0 m in radius and position subjects supine with the head at the center of rotation. This is an ideal configuration for terrestrial AG exposure as the body's +Gz axis is aligned with the centrifugal acceleration.

In 2011, the “Artificial Gravity with Ergometric Exercise as the Countermeasure for Space Deconditioning in Humans” (AGREE) project proposed a short radius centrifuge on-board the International Space Station (ISS) in order to study the effectiveness of intermittent AG exposure in microgravity [6]. The AGREE centrifuge was to have been located in the Permanent Multipurpose Module (PMM), as seen in Fig. 1. Placement within the PMM limited the maximum allowable radius of the AGREE centrifuge to 1.4 m. This compact radius

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requirement necessitated that the subject be in a seated position, with the interaural axis parallel to the axis of rotation and the head slightly off-center. The AGREE centrifuge also included a cycle ergometer, as exercise during centrifugation decreases the chances of presyncope by increasing venous return via muscle contractions and an elevated heart rate.

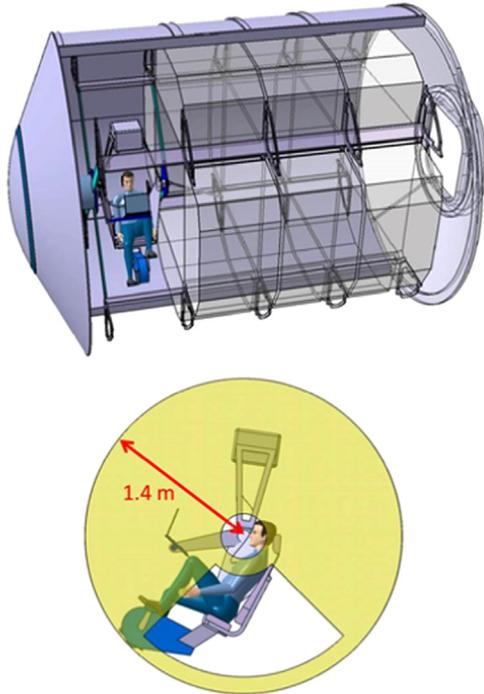


Fig. 1. AGREE centrifuge profile (bottom) and as seen placed in the PPM (top) [6].

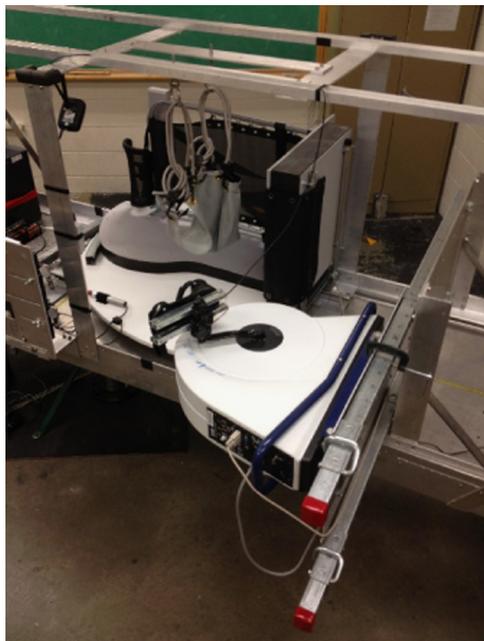


Fig. 2. MIT Compact Radius Centrifuge.

Exercise further enhances the overall conditioning resulting from AG exposure.

Although no longer in development, the AGREE proposal highlighted the reality that future inflight centrifuges will likely be constrained to volumes and radii significantly smaller than has been used on terrestrial SRC's. We define a compact radius centrifuge (CRC) as a centrifuge with a radius of less than 1.95 m, the height of the 99th percentile male astronaut as defined by NASA anthropometry standards [7]. Based on this definition, CRC's represent a class of centrifuges that cannot accommodate all subjects in a supine, radial position as is typically done in existing SRC's. A CRC platform was designed and built on the centrifuge at the Massachusetts Institute of Technology (MIT). The MIT CRC platform is constrained to a 1.4 m radius, such as was proposed for the ISS, and positions subjects in an analogous orientation to how they would be positioned on the proposed inflight centrifuge. This includes facing "into the wind", which both reduces motion sickness and minimizes potentially harmful lateral Coriolis forces on the legs while exercising by aligning the direction of knee flexion/extension when cycling with the direction of Coriolis forces [8].

2. MIT Compact Radius Centrifuge design

The CRC was built on the existing SRC arm at MIT. Originally constructed as the Artificial Gravity Sleeper with a 2.13 m radius [9], the MIT centrifuge has undergone a number of modifications over the years to accommodate various experiments [9]. In all configurations however, subjects were positioned radially with the head near the center of rotation. While still using this arm, all equipment for the CRC, including the cycle ergometer, was constrained to a maximum radius of 1.4 m. To the best extent possible, design and operational requirements were taken directly from the Experiment Science Requirements for AGREE as developed by the European Space Agency's European Space Research and Technology Centre (ESA ESTEC), with supplemental anthropometric requirements from the NASA Human Integration and Design Handbook [6], [7]. These requirements included specifications for anthropometry and hardware adjustability, G-load range, and instrumentation. Fig. 2 shows the MIT CRC in its final configuration.

The CRC consists of three primary components: the chair assembly, the cycle ergometer, and the sensor suite. The chair assembly comfortably accommodates subjects on their side, and can be repositioned radially so as to control the distance from the center of rotation to the subjects' heads. The limiting design factor in previous centrifuges that positioned subjects on their side was a lack of leg support, causing discomfort to the point of being unoperational [10]. On the MIT CRC, the subject dons a low-friction leg pad on the lower leg, which is supported by a Teflon-covered baseplate over which the lower leg glides while cycling. The upper leg is supported by two suspended leg cuffs, one above and one below the knee. The cuffs are on adjustable bungee cords for height adjustment, and rotate with the subject's leg as he or she cycles.

The exercise device on the CRC is a Lode Angio cycle ergometer (Lode BV, Groningen, Netherlands). The ergometer provides workloads up to 700 W and allows for exercise protocols to be preprogrammed in down to 1 W increments.

The base on which the cycle ergometer is mounted has two possible adjustments, radial and tangential, to meet anthropomorphic differences. The ergometer can be exchanged with another exercise device, such as a stepper, or removed completely for exercise control runs.

The final component of the CRC platform is the instrumentation suite. Instrumentation includes both physiological and mechanical sensors, based on the requirements specified in AGREE, cost, and interface requirements. Fig. 3 shows the location of most of the instrumentation that could be used during centrifugation runs. With the exception of the IR camera (Foscam Digital Technologies LLC), all sensors are manufactured by Lode BV (ergometer, blood pressure cuff) or Vernier Software & Technology (heart rate belt, respiration belt, EMG electrodes, foot force sensors, and 3-Axis Accelerometer). These sensors are hardwired to the on-board desktop computer and managed through one of two programs: Logger Lite (Vernier Software & Technology, LLC) and Lode Ergometry Manager (Lode BV, Groningen, Netherlands).

3. Experimental design

An initial human experiment was conducted on the MIT CRC to explore the physiological effects of ergometer exercise combined with artificial gravity. Several ground studies using short-radius centrifugation, in conjunction with head down bed-rest, have shown that exposure to intermittent artificial gravity combined with ergometer exercise is effective in preventing deconditioning [4,11,12,13]. However, the numerous confounding factors between the studies (including centrifuge configuration, gravity level, and use/intensity of exercise) make it very difficult to draw clear conclusions about the parameters needed to maintain physiological conditioning in space [14]. The objective of this research effort is to experimentally determine the effects of different artificial gravity levels (0 g, 1 g, and 1.4 g at the feet) and exercise workload intensities (25 W warm-up, 50 W moderate, and

100 W vigorous) on musculoskeletal and cardiovascular functions, as well as motion sickness and comfort.

3.1. Methods

Twelve subjects (6 males and 6 females) participated in the experiment. It consisted of three sessions scheduled in the morning of different days within the same week. During the sessions, subjects were positioned sidewise, with the head located at the center of rotation and the feet strapped on the ergometer device. The upper leg was suspended by adjustable leg cuffs to facilitate the exercise activity in a sideways position. Fig. 4 shows the subject positioning during the experiment runs.

In each of the sessions, the subject performed the same 25-min exercise protocol under one of the three different artificial gravity levels: 0 g (no rotation), 1 g, and 1.4 g measured at the feet. Angular velocities were approximately 0 RPM (0 g condition), 28.6 RPM (1 g condition), and 33.9 RPM (1.4 g condition). These values varied slightly between subjects, since they depended on the centrifuge adjustments based on each subject's anthropometry, particularly on the location of the feet with respect to the center of rotation. All subjects experienced all three conditions and assignments were randomized across all subjects.

3.2. Exercise protocol

The protocol consisted principally of 15 min of ergometer exercise at three different workload levels:

- The first workload level was set to 25 W. This is a low intensity exercise and was included to serve as a warm-up phase. Its duration was 3 min.
- The second workload level was set to 50 W. It corresponds to a moderate exercise intensity, and its duration was 5 min.
- The third and last workload level was set to 100 W. This is considered as vigorous and high intensity exercise. Its duration was 5 min.

Workload changes between the workload levels were implemented gradually and smoothly. In addition, extra

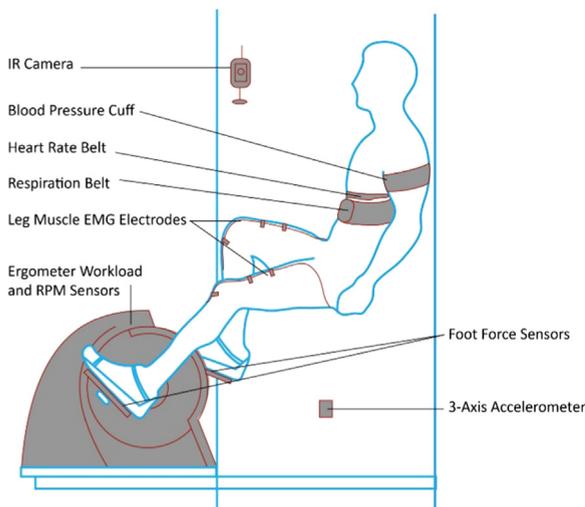


Fig. 3. MIT CRC instrumentation suite (side view).

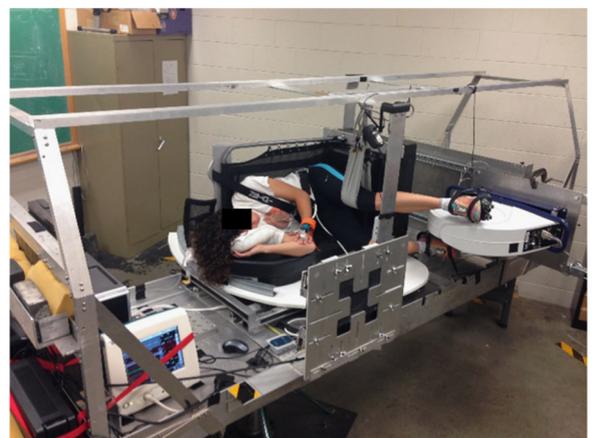


Fig. 4. Subject position during centrifuge experiments at MIT.

time at the beginning and at the end was allotted to the spin-up and spin-down processes to the desired level of artificial gravity. The entire protocol lasted 25 min, and is summarized in Fig. 5. It was created using the Lode Ergometry Manager (LEM) software package and it was run automatically during the experiments. In addition, subjects were instructed to pedal at 60 RPM to get more homogeneous measurements across subjects and avoid additional confounding factors. This particular rhythm was maintained using a metronome.

3.3. Subjects

Participants were healthy subjects, between 23 and 29 years old (25.1 ± 2.1 years old; all values are presented as the average \pm standard deviation), having a good fitness level. Those selected exercised regularly and were able to perform aerobic exercise comfortably for an hour. Due to centrifuge structural limitations, maximum weight was restricted to 200 lb (90.7 kg). Average weight and standard deviation were: 69.3 ± 11.6 kg. Screening for recent injuries, recurrent pain or back problems, and severe motion sickness was also performed. Before participating, each subject provided written informed consent previously approved by the MIT Committee on the Use of Humans as Experimental Subjects.

3.4. Data collection and analysis

Foot force data were collected during the experiment using force plates mounted on the pedals (force range: -200 N to $+850$ N, where a positive value is a compression force; resolution: 0.3 N; Vernier Software & Technology). Average peak forces values for the left and right foot were calculated for each exercise workload level at each AG condition. For two subjects, the right foot force data were

not available and therefore, these two subjects have been excluded from the right foot data analysis. In addition, cardiovascular data were collected using a ccNexfin monitor, a non-invasive advanced hemodynamic monitoring system that provides beat-to-beat continuous cardiovascular measurements (this data will be presented separately). Finally, subjective data concerning motion sickness and comfort were also collected via an exit-survey. The questionnaire included 5-point Likert scales to get subjective data about comfort and difficulty of the exercise. Subjects also rated their overall motion sickness experience on a 0–10 scale (0 – no symptoms, 10 – vomiting). Finally, subjects also reported on their body soreness and their perception of the Coriolis forces.

Statistical tests were performed using SYSTAT 13 Version 13.00.05 (SYSTAT Software Inc.2009). Peak forces were tested for homoscedasticity using Levene's test, and for normality using the Kolmogorov-Smirnov test. A two-factor repeated measures analysis of variance (ANOVA) was used to compare peak forces, where workload intensity and AG level were fixed factors. In addition, pairwise comparisons were calculated using the Bonferroni post-hoc procedure. Furthermore, a hierarchical multiple regression was used to model the effects of the independent variables (AG level and workload intensity) on peak forces. The variable “subject” was considered as the identifier to account for the within-subject design. Force values are presented as the average \pm standard deviation. A non-parametric Friedman test was used to compare subjective data in the different AG conditions. In all cases, significance was taken at the $\alpha=0.05$ level.

4. Results

Foot forces changed accordingly to the exercise workload level, as can be seen in Fig. 6. In addition, the increase in foot forces due to the increase in artificial gravity during

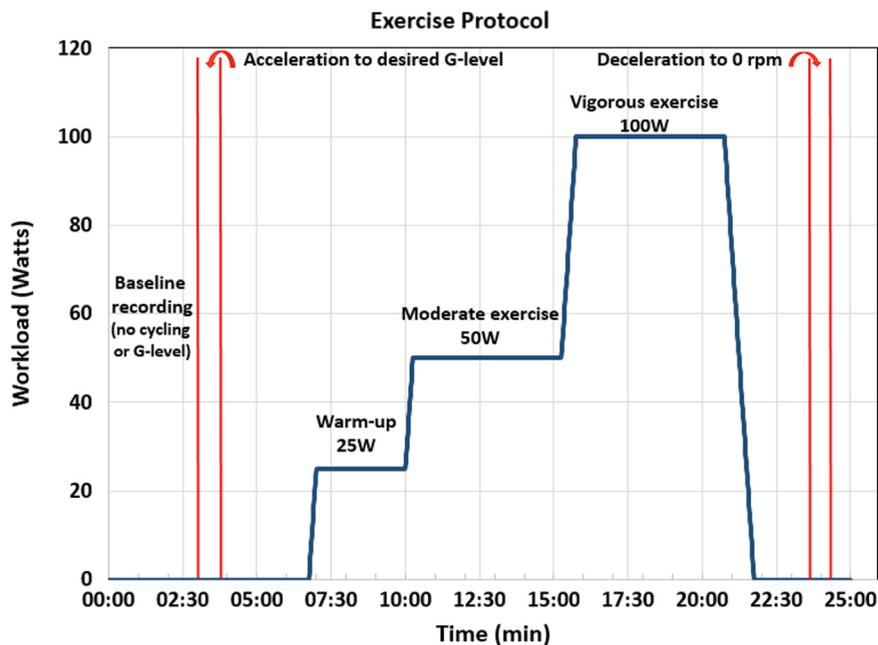


Fig. 5. Exercise protocol used during the centrifuge sessions.

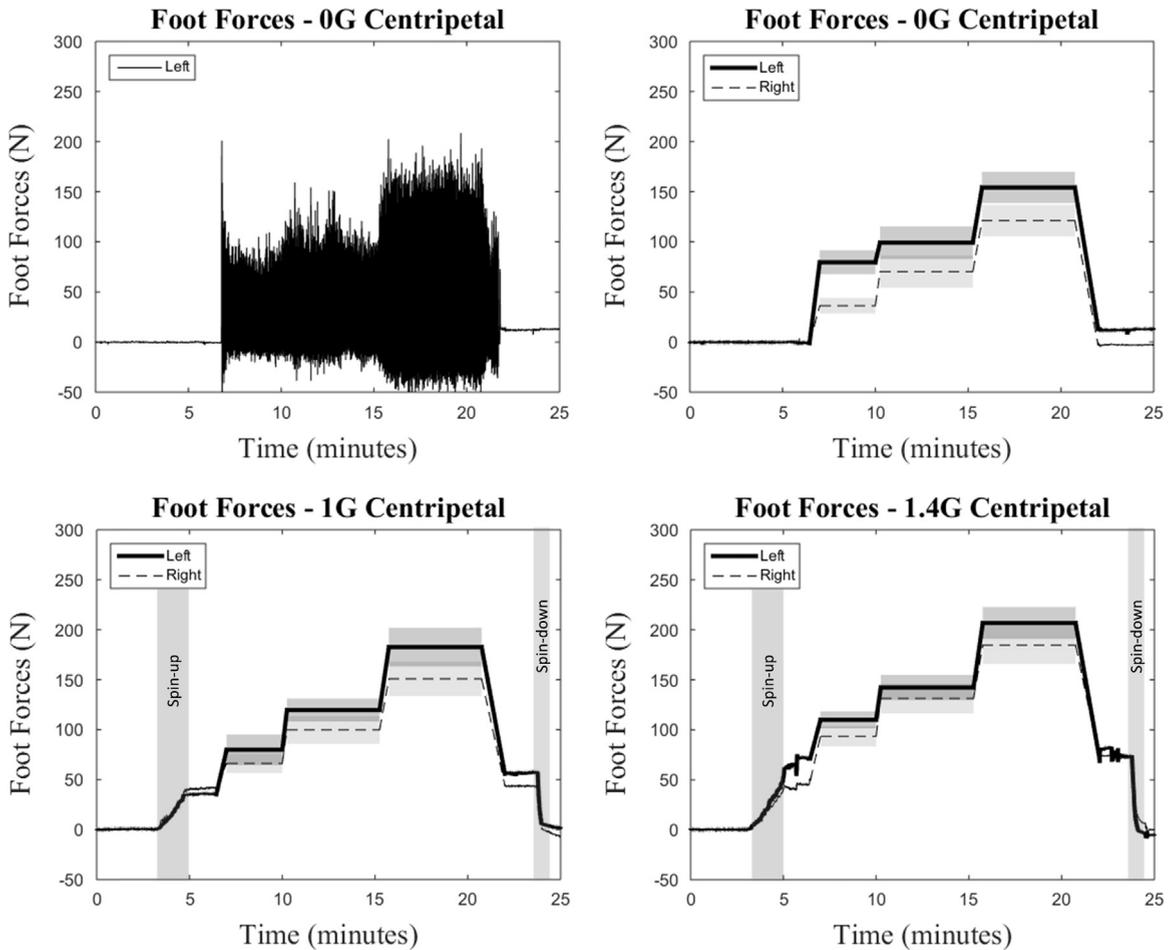


Fig. 6. The top left figure represents an example of the left foot force from one subject recorded during the 25-min protocol at the 0 g condition. Based on these data, peak forces were averaged at each exercise period and are represented by horizontal lines (average \pm standard deviation) in the top right figure, which also include right foot forces. The bottom figures show left and right foot forces in the 1 g condition (bottom left) and the 1.4 g condition (bottom right).

Table 1

Left foot forces (N) average and standard deviation of the 12 subjects for each workload intensity and AG condition.

AG level (g)	Workload intensity		
	25 W	50 W	100 W
0	65.6 \pm 12.4	90.9 \pm 15.6	154.8 \pm 22.1
1	89.9 \pm 14.5	127.0 \pm 17.4	189.6 \pm 13.1
1.4	108.0 \pm 10.4	150.5 \pm 14.8	211.4 \pm 14.9

Table 2

Right foot forces (N) average and standard deviation of 10 subjects for each workload intensity and AG condition.

AG level (g)	Workload intensity		
	25 W	50 W	100 W
0	46.0 \pm 5.8	74.3 \pm 6.6	122.3 \pm 15.8
1	71.6 \pm 10.5	100.6 \pm 9.0	157.8 \pm 11.8
1.4	88.1 \pm 11.5	130.9 \pm 10.7	181.6 \pm 14.5

the spin-up process was highly noticeable, both in the 1 g and 1.4 g condition. It was larger at higher spin-up rates. Likewise, the decrease in foot forces due to the spin-down process at the end of the protocol was also observed.

Average peak force values for the left and right foot for all subjects are summarized in Table 1 (left foot forces) and Table 2 (right foot forces). During each workload period, these values were calculated including all the peak forces generated during that period (excluding the transitions between periods).

A two-way repeated measures ANOVA showed that there was a significant effect of workload intensity on average left peak forces ($F(2,22)=1176.2$, $p < 0.0005$). Pairwise comparisons showed significant differences between the three workload conditions: “25 W” and “50 W” ($p < 0.0005$); “25 W” and “100 W” ($p < 0.0005$); and “50 W” and “100 W” ($p < 0.0005$).

More interestingly, results also indicate that an increase in AG level significantly increased the left foot average peak forces ($F(2,22)=97.0$, $p < 0.0005$). Pairwise comparisons showed a significant increase in peak forces between

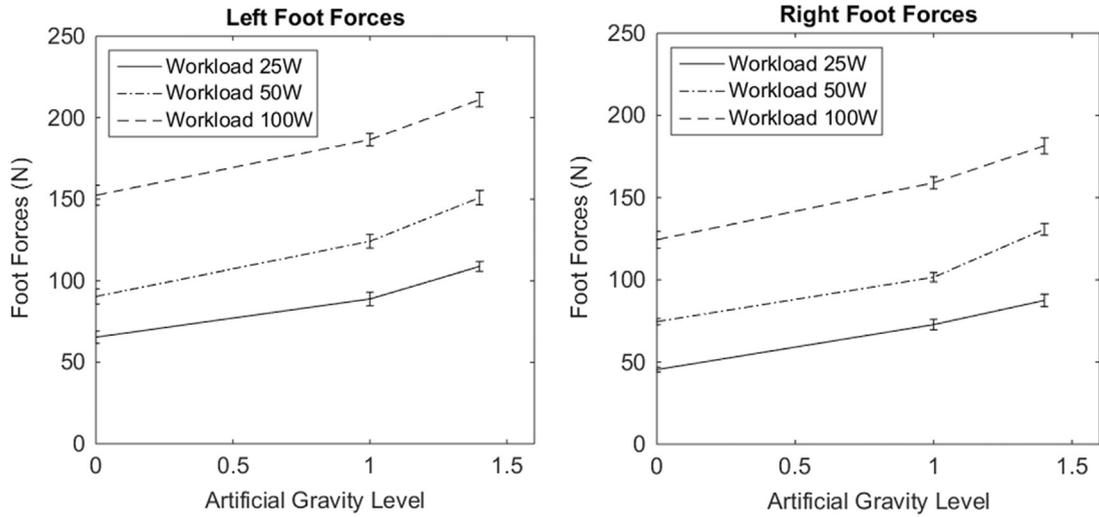


Fig. 7. Left and right foot forces across all conditions (error bars correspond to standard error).

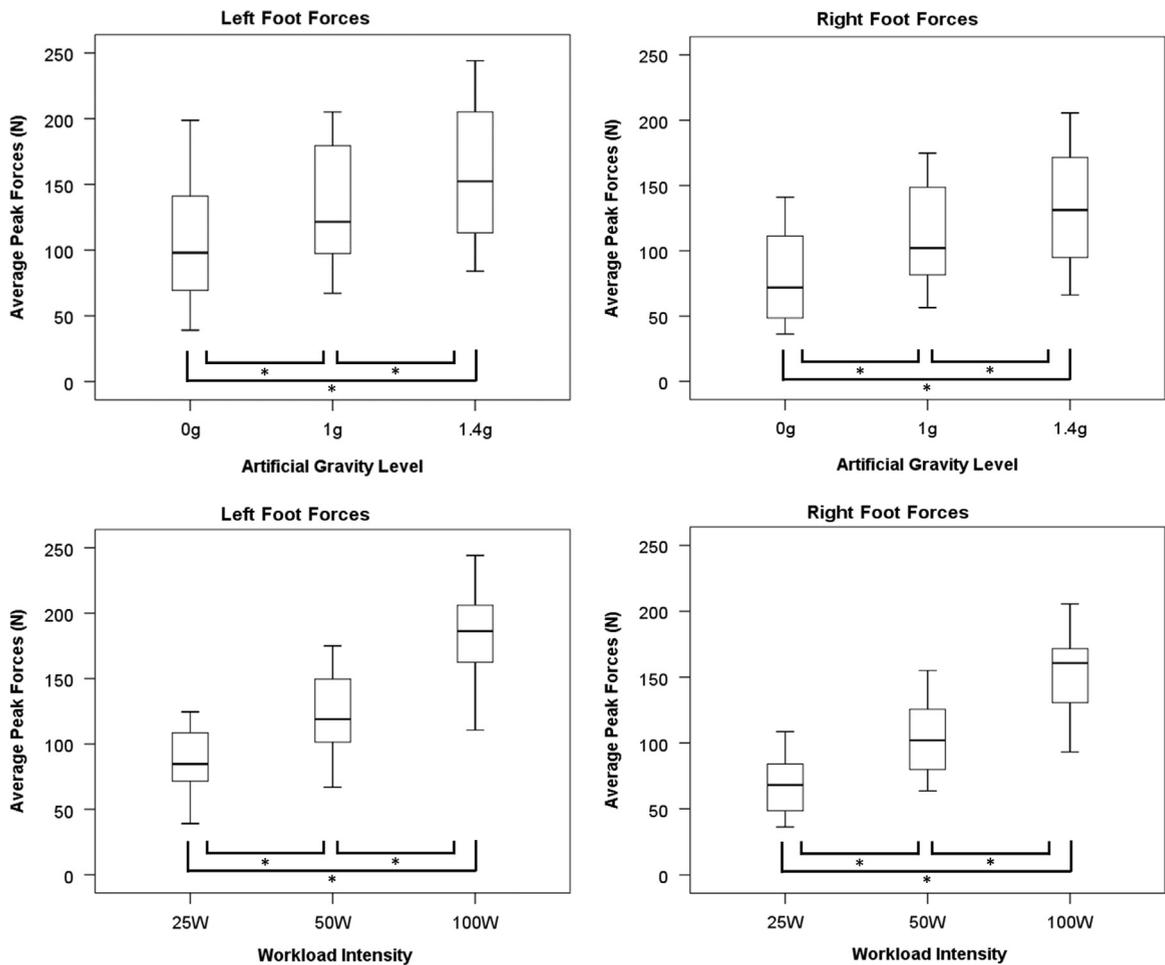


Fig. 8. Pairwise comparisons of left (left) and right (right) foot forces with respect to the AG level (top) and workload intensity (bottom). Only 10 of the 12 subjects were included in the right foot force analysis (* $p < 0.05$).

“0 g” and “1 g” ($p < 0.0005$), “0 g” and “1.4 g” ($p < 0.0005$), “1 g” and “1.4 g” ($p < 0.0005$). Experimental data and box plots are shown in Figs. 7 and 8.

Finally, a hierarchical regression model was fit with subject as the identifier, the average left foot forces as the dependent variable, and AG level and workload intensity as the independent variables.

$$(LFF)_{ij} = \rho_i + \beta_1(AG) + \beta_2(\text{workload}) + \epsilon_{ij} \quad (1)$$

The left foot forces (LFF, in Newtons) from the j th measurements in the i th subject are a function of the AG term (0 g, 1 g, or 1.4 g), and the workload intensity in Watts (25 W, 50 W, and 100 W). The model also includes subject-dependent intercepts (ρ_i , where $i=1-12$ subjects). AG level was statistically significant ($\beta_1=24.9$, $Z(94)=18.2$, $p < 0.0005$) as well as workload intensity ($\beta_2=0.8$, $Z(94)=31.6$, $p < 0.0005$). The interaction term was non-significant. The positive β coefficients support the hypothesis that higher AG and workload levels result in higher foot forces. The coefficients from the model fit are summarized in Table 3.

The analysis of the average right foot peak forces yielded similar results. Statistical analysis revealed a significant effect of workload intensity ($F(2,18)=677.2$, $p < 0.001$) and artificial gravity level ($F(2,18)=87.8$, $p < 0.001$). In the same way as in the case of left foot forces, pairwise comparisons showed significant differences among the three workload conditions: “25 W” and “50 W” ($p < 0.001$); “25 W” and “100 W” ($p < 0.001$); and “50 W” and “100 W” ($p < 0.001$). Similarly, pairwise comparisons showed a significant increase in right foot peak forces between “0 g” and “1 g” ($p < 0.001$), “0 g” and “1.4 g” ($p < 0.001$), and “1 g” and “1.4 g” ($p = 0.001$). Experimental data and box plots are shown in Figs. 7 and 8.

As in the left foot forces analysis, a hierarchical regression model was fit with subject as the identifier, the average right foot forces as the dependent variable, and AG level and workload intensity as the independent variables. In the same manner, AG level was statistically significant ($\gamma_1=35.5$, $Z(84)=17.3$, $p < 0.0005$) as well as the workload intensity ($\gamma_2=1.1$, $Z(84)=28.7$, $p < 0.0005$). The interaction term was non-significant. Table 4 summarizes the results of the model fit.

$$(RFF)_{ij} = \rho_i + \gamma_1(AG) + \gamma_2(\text{workload}) + \epsilon_{ij} \quad (2)$$

Another interesting observation is that right foot forces were generally smaller than left foot forces. On average, the difference between left and right foot forces was 21.5 ± 3.5 N. A paired t -test showed that this difference was statistically significant ($t(95)=12.140$, $p < 0.0005$). This result could be explained by the sideway position of the subjects during the ergometer exercise. The right leg was partially supporting the body weight, and therefore its movement was more restricted. In addition, the larger surface area of contact likely resulted in higher friction. The left leg was supported by leg cuffs, having a better range of motion. This effect was unnoticeable to subjects and none of the subjects reported any difference in pedaling between legs, either intentional or unintentional.

Subjects were generally comfortable and were able to complete the three-session experiment. Subjects reported no soreness other than normal exercise fatigue on the

spinning centrifuge. None of the subjects reported an overall motion sickness rating higher than 1 in a 0–10 scale (see Table 5). Those subjects who had slight symptoms (motion sickness rating=1) reported that they voluntarily moved their head, mostly to position themselves more comfortably on the chair. The spin-down process was also reported as a potential source of motion sickness. Finally, subjects did not notice the Coriolis forces on their knees acting in the lateral direction. These results were expected due to the sideways positioning of the subjects while cycling.

Subjective data concerning the perceived “comfort” and “strenuousness” (or difficulty of exercise) during the experiment are summarized in Table 6. Data were collected using 5–point Likert scales, both for “comfort” (1 – very comfortable/natural, 5 – very uncomfortable/unnatural), and “strenuousness” (1 – easy, 5 – very strenuous). The Friedman test showed no significant effect of AG level on comfort ($\chi^2(2)=4.941$, $p=0.085$). Similarly, the Friedman test showed

Table 3
Results for the left foot forces hierarchical regression model.

Coefficients	Units	Estimate	SE	Z value	P-Value
ρ_i	N	−13.1	2.7	−4.9	< 0.0005
β_1	N/g	24.9	1.4	18.2	< 0.0005
β_2	s/m	0.8	0.03	31.6	< 0.0005

Table 4
Results for the right foot forces hierarchical regression model.

Coefficients	Units	Estimate	SE	Z value	P-Value
ρ_i	N	14.3	3.1	4.7	< 0.0005
γ_1	N/g	35.5	2.0	17.3	< 0.0005
γ_2	s/m	1.1	0.03	28.7	< 0.0005

Table 5
Motion sickness symptom scale.

Rating	Motion sickness symptoms
0	No symptoms
1	Any symptom no matter how slight
2	Minimal warmth, fatigue
5	Stomach awareness
7	Moderate nausea
9	Incipient vomiting
10	Vomiting

Table 6
Comfort and strenuousness subjective data average and standard deviation. Data collected using a 5–point Likert scale. (Comfort: 1 – very comfortable/natural, 5 – very uncomfortable / unnatural. Strenuousness: 1 – easy, 5 – very strenuous).

AG level (g)	Comfort	Strenuousness
0	3.0 ± 0.7	3.1 ± 0.9
1	2.2 ± 0.8	2.5 ± 1.0
1.4	2.7 ± 1.0	2.8 ± 1.0

Table 7
Foot forces (% body weight) average and standard deviation for each workload intensity and AG condition.

AG level (g)	Workload intensity					
	25 W		50 W		100 W	
	Mean \pm SD	Range	Mean \pm SD	Range	Mean \pm SD	Range
0	8.7 \pm 2.7	5.2–13.8	12.7 \pm 2.7	8.6–17.5	21.3 \pm 4.9	14.2–30.6
1	12.3 \pm 2.3	8.9–18.4	17.4 \pm 3.3	11.7–25.4	26.5 \pm 5.2	18.3–42.5
1.4	14.9 \pm 2.3	10.7–19.0	21.5 \pm 3.4	14.8–29.1	30.1 \pm 5.3	20.1–42.0

no significant effects of AG level on difficulty of exercise ($\chi^2(2)=5.214$, $p=0.074$).

5. Discussion

The new CRC at MIT is a unique AG platform capable of performing a wide range of human experiments. In particular, subjects have the capability to exercise while being rotated, which is a promising countermeasure against human deconditioning in space. Currently, the MIT CRC has an ergometer in place, but it could be replaced by other exercise devices in the future.

A first experiment validated both the mechanical aspects of the centrifuge and the capability of gathering physiological data during centrifugation and exercise. Subjects successfully completed the exercise protocol and they tolerated the centrifugation well, including the spin-up and spin-down processes.

Recorded peak forces attained up to 42.5% body weight. Workload intensity and AG level both had a significant effect on peak foot forces. Therefore, these forces could be increased by using higher centrifuge rates, or increasing the ergometer resistance following the hierarchical regression models developed in this work. However, ergometer exercise does not produce foot forces as high as other types of exercise, such as stair-steppers. These are able to produce higher foot forces similar to treadmill running in space (up to 124% body weight [5]).

Previous studies using the Cycle Ergometer with Vibration Isolation System (CEVIS) onboard the ISS showed that foot forces on astronauts ranged from 7.0% to 19.0% of body weight, depending on the workload, which varied from 75 to 210 W [15]. For the subjects in our study, peak forces ranged from 5.2–30.6% of body weight for AG level 0 g, 8.9–42.5% of body weight for AG level 1 g, and 10.7–42.0% of body weight for AG level 1.4 g. Average and standard deviation peak forces values (in % body weight) are summarized in Table 7. Peak forces measured at AG level 0 g were within the same range as those measured in actual microgravity. Moreover, the increase in foot forces (% body weight) due to increase in AG level is also observed in the data.

The ergometer was set to generate a particular workload profile during the exercise protocol (see Fig. 5). Thus, the ergometer automatically adjusted its resistance based on the desired workload output, but also on the subject's pedaling speed: the faster the cycling RPM, the lower the ergometer resistance, in order to maintain a constant workload. Peak forces values obtained in this experiment

correspond to a cycling rhythm of 60 RPM, which was maintained using a metronome. Different pedaling speeds would produce slightly different peak forces.

Subjects were positioned in a right-side down lateral decubitus position. This configuration offers two advantages over a left-side down, or more traditional supine position. First, it faces “into the wind”, given the centrifuge's clockwise direction of rotation. Left-side down lateral decubitus position would be equivalent if the direction of rotation of the centrifuge were counterclockwise. Second, it minimizes the effects of Coriolis acceleration during knee flexion/extension in a rotating environment. Previous studies have shown that Coriolis forces can induce mediolateral knee deflections during centrifuge supine squats [8]. The proposed lateral orientation of subjects minimizes (or eliminates) these deflections, and the subjective reports from participants in our study support this statement.

Subjective data show that subjects did not feel soreness or cycling difficulties other than normal discomfort due to the sideways positioning. Subjects reported that exercising in the 0 g condition was more difficult and unnatural (see Table 6). This is probably due to the fact that, in this condition, there was no acceleration in the +Gz axis (or artificial gravity) to facilitate body positioning against the chair. In addition, none of the subjects noticed the Coriolis acceleration, or reported severe motion sickness.

These results indicate that the new and more realistic MIT CRC configuration is a viable platform for continued and future AG ground research. An initial human experiment has been successfully performed showing that there is a significant effect of AG level and workload intensity on peak forces generated during ergometer exercise. Quantitative values of these forces at different AG levels and workload intensities have also been provided. These preliminary results show that centrifugation combined with exercise may have a positive impact on musculoskeletal function.

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