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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.

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.

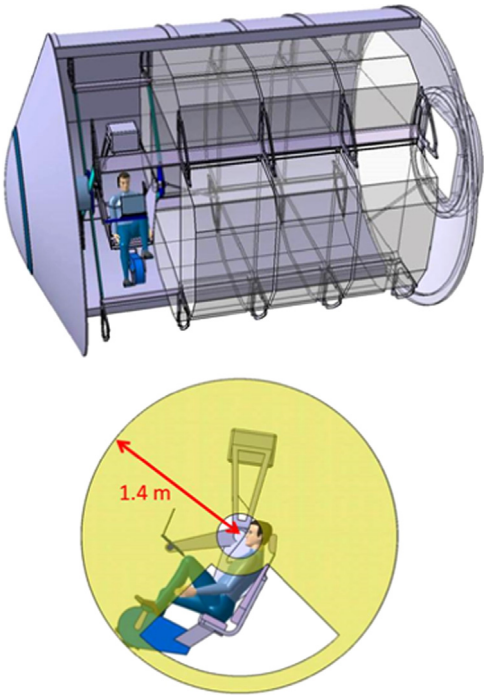

Fig. 1. AGREE centrifuge profile (bottom) and as seen placed in the PPM (top) [6].

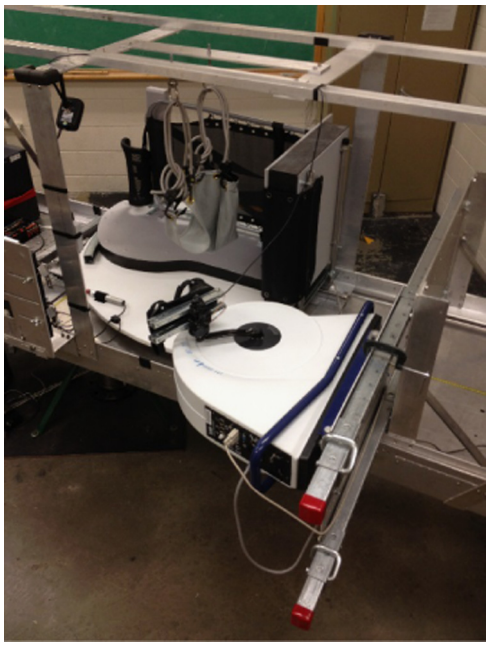

Fig. 2. MIT Compact Radius Centrifuge.

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.