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EXERCISE COUNTERMEASURE TO WEIGHTLESSNESS DURING MANNED SPACEFLIGHT

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Abstract

The purpose of this Brief Commentary is to review some of the problems inherent in past and current exercise machines that were designed as attempted countermeasures to weightlessness during manned spaceflight. A countermeasure is a procedure or device that prevents or minimizes the adverse health effects of prolonged weightlessness. This commentary also will show that there is a way to effectively perform exercises in a weightless environment that will counteract or at least reduce the loss of muscular size and strength, bone mineral density, and cardiovascular function during prolonged spaceflight.

Key words: strength training, aerobic capacity, bone density, weightlessness

Long duration human space flight results in a significant loss of muscular strength and size, cardiovascular function, and bone mineral density because of prolonged weightlessness. Medical doctors and physiologists often describe the environment in an orbiting space craft approximately 400 km above the Earth's surface as *zero gravity* or *microgravity*. However, the gravitational forces attracting the space craft and astronauts actually are similar to the gravitational effect when standing on Earth (~10% difference). The inertia of a high speed (~28,160 $km \cdot h^{-1}$) orbiting space craft creates a centrifugal force that counteracts the centripetal force of gravity. This balance of forces results in a *weightless* environment [1].

In an attempt to develop countermeasures to the effects of prolonged weightlessness, the National Aeronautics and Space Administration (NASA) is currently using resistance and cardiovascular exercise machines that are extremely massive and produce significant vibration and noise. The Dynamic Exercise Countermeasure device (DECD), Flywheel Exercise Device (FWED), Combined Operational Load Bearing External Resistance Treadmill (COLBERT), Interim Resistance Exercise device (iRED), and an Advanced Resistance Exercise device (ARED) with a mass of approximately 300 kg, are all voluminous exercise machines. These exercise devices were designed to function on the International Space Station (ISS) and are not practicable for long term manned interplanetary space flight.

NASA's iRED has been shown to be as effective as free weights for increasing muscular strength and muscle volume but failed to stimulate changes in bone mineral density [2]. Unfortunately, there were several injuries (~20% of the trainees) in their healthy young male subjects because of overtraining or equipment failure (e.g., two fractured cervical spinous processes). Loehr and colleagues [3] reported that training with the ARED produced results similar to resistance training with free weights. However, it is important to note that neither the iRED nor the ARED has ever been used for training in a bedrest or weightless condition such as on the ISS.

By using a ship's thrusters, it is technically possible to generate a force that would rotate a space ship at a constant angular velocity around its eccentric axis to create some level of artificial gravity [4]. Artificial gravity, which hypothetically could reduce deconditioning during long term space flight, can be achieved by centrifugation. It was brilliantly demonstrated by an astronaut jogging on the inside wall of a space craft in the 1968 science fiction movie *2001: A Space Odyssey*. However, the fictional space ship was ~50 m in diameter and would present serious design, financial and operational challenges for an actual maneuvering space station. It becomes even more problematic and perhaps prohibitive for a smaller interplanetary space craft [4] and a short-arm centrifuge (~1.5-2.0 m) would produce significant lateral strains on the exercising joints [5]. This centrifugation-produced artificial gravity hypothesis has not been tested on a manned space craft and Allen and colleagues [6] speculated that long term exposure to sustained continuous centrifugation may negatively affect how astronauts readapt to Earth or Mars gravity.

Yang and colleagues devised and tested a human powered Space Cycle [7]. An astronaut pedals a cycle on one side of its axis to generate the rotating centrifuge and another astronaut performs resistance exercises against a force platform in a gondola on the other side of the rotating Space Cycle. Yang and colleagues [8] reported that males and females could generate similar forces at their feet when performing either 10 repetition maximum barbell squats or squatting on the centrifuge platform. The so-called *hypergravity* effect produced approximately three times the acceleration of Earth's gravity when the Space Cycle unit rotated at ~40 rpm. The forces recorded at the feet were equivalent to approximately 2.5 times body weight or performing barbell squats with ~90 kg and 125 kg, females and males, respectively. However, the diameter of the Space Cycle is almost four meters and it occupies even greater area during centrifugation when the gondola is swinging at a 70 degree angle to the vertical axis. Therefore, it is unlikely that any interplanetary mission space craft currently being constructed could accommodate this type of voluminous device. Allen and colleagues [6] noted that in addition to the potential significant discomfort to crew members from intermittent centrifugation and artificial gravity, the relatively rapid transitions from the desired level of gravity to the ambient gravity of the space craft may result in a host of adverse cardiovascular effects. Moreover, the minimal gravitational level and its duration, length of the short-arm centrifuge radius, and rotation rate for optimal physiological adaptations in a weightless environment are unknown [9]. None of these proposed artificial gravity countermeasures has ever been tested on humans in a weightless environment.

To counteract the deconditioning during long term space flight, the exercise device must be small and lightweight (minimizing the size and number of moving parts), simple and reliable, require relatively brief durations of exercise, should not affect surrounding environment with noise and vibration or require external power, and must produce benefits in the muscles, bones and cardiovascular system that are similar to the adaptations from exercising in a gravitational environment [9-10]. Hardware with a high failure rate is a significant liability in the inherently risky and hostile environment of interplanetary space and the surfaces of the Moon and Mars [9]. The size and mass of the equipment are major issues when space for food and medical supplies, which cannot be replenished on a mission to another planet, are of critical importance [10]. There will be no short term easy access to Earth on a journey to Mars. Communication delays will range from 8-56 minutes and an emergency flight back to Earth would require several months compared with 24-36 hours from the ISS and 4-7 days from a Lunar base [9].

Tito and colleagues [11] reported an estimated total mass of 347 kg for human accommodations on a proposed 2018 manned space flight to Mars, which included clothing, medical supplies, radiation shelter, personal provisions, hygiene, waste collection, and exercise equipment. They clearly noted that the deconditioning from long term space flight must be counteracted with vigorous resistance exercise that should provide full range of motion exercise for all the major muscle groups [11]. Loenneke and colleagues [12] recently noted that current exercise interventions have been ineffective in preventing muscle atrophy and bone loss. They concluded that the success of a long duration space flight, such as a manned mission to Mars, is dependent on the development and implementation of more effective exercise countermeasures. Likewise, Hargens and colleagues [5] stated that the ineffectiveness of current exercise countermeasures to prevent muscle atrophy or bone loss is primarily because of inadequate exercise hardware and that moderate intensity aerobic exercise in a weightless environment is not sufficient for maintaining cardiovascular fitness. Unfortunately, Tito and colleagues did not specify in the aforementioned feasibility analysis [11] how they would accomplish these goals or what type of exercise equipment would be used on their proposed 501-day manned mission to Mars.

There is a way to exercise in a weightless environment using a device (CONRED) that will provide a stimulus to increase muscular strength, power and endurance in all the major upper and lower body muscle groups, as well as enhance aerobic capacity and bone mineral density. It would provide full range dynamic instantaneously variable or constant resistance for shortening (aka *concentric*), lengthening (aka *eccentric*), and so-called *isometric* muscle actions at any desired speed of movement. The resistance could be instantaneously increased or decreased at any point in the range of motion. The ability to increase the resistance at the beginning of the concentric muscle action would simulate the force required to overcome the inertia of a mass encountered in a gravitational environment (e.g., a future Mars landing) and generate forces similar to the impact loading that would stimulate bone mineral density. As with most gravity dependent exercise modalities, eccentric loads would be equal to but not exceed concentric loads. The research strongly suggests that training with an eccentric resistance greater than the concentric resistance does not produce superior results in females or males [13-16].

Trainees can exercise at any desired level of effort and the external muscular output and heart rate would be recorded for each exercise session. Contrary to the extensive time devoted to current exercise countermeasures, which astronauts claim is much too long [4], the stimulus for physiological adaptations can be attained more efficiently in several minutes a day [17-21]. Muscular strength could be instantaneously tested at any point in each astronaut's range of motion. The new device (CONRED) could accommodate astronauts with considerably different body mass, strength levels and aerobic capacity. All the aforementioned benefits would eliminate the need for the massive aerobic and resistance exercise devices that NASA has attempted to develop over the last half century.

A computerized prototype, which would be powered by a small rechargeable battery (recharged as the trainee performs aerobic exercise) or linked to a laptop computer, would have a mass of only several kilograms. CONRED's mass is miniscule compared with the estimated 10,000 kg payload for a manned Mars mission [11] and would generate very little friction and no vibration or noise. This would eliminate any disturbance to other equipment or payload. CONRED does not have to be assembled or disassembled on the space craft. A computer could display and save a report on the quality of each exercise session. Even with an unlikely mid-mission computer failure, the astronauts could continue indefinitely to perform their exercises. CONRED would eliminate the potential equipment failures inherent with artificial gravity centrifuges, pneumatic and hydraulic resistance, motors, canisters, vacuum cylinders and pistons, flywheels, elastic bands (bungee cords), rope, or recoil springs [10], and the time required for maintenance of the equipment that is currently used by NASA. The projected lifespan for NASA's ARED is approximately 15 years [22]. The expected lifespan of CONRED is greater than an astronaut's lifespan.

Computer programmers and mechanical engineers could build a prototype of CONRED that would be functioning within the next several months. Using the prototype, the first priority is to conduct a training study (~4-6 months duration) to compare adaptations such as muscular strength, power, endurance, bone mineral density, aerobic capacity, and body composition to those produced by gravity dependent modalities such as free weights, weight stack machines, and standard treadmills. Astronauts could begin training with CONRED within the next year and researchers could then begin to evaluate the responses from training in a bed rest environment and on the ISS.

With a privately funded manned flyby mission (no landing and a free-return trajectory) to Mars proposed for 2018 [11], there is an urgent need to produce and demonstrate the effectiveness of CONRED.

Author disclosures

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