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Review Article

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Exercise and Ergonomics on the International Space Station and Orion Spacecraft

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Abstract

It is widely accepted that astronauts living in space undergo many physical and psychological challenges as a consequence of being in microgravity. The ergonomics of living in microgravity demands countermeasures and mitigation strategies which today and in part, are delivered by undergoing defined, rigorous exercise regimes. On the International Space Station, it is common for astronauts to spend many months working and living in microgravity and to sustain a healthy crew, it is essential to implement a 'design-make-test-refine' cycle of exercise which can be accommodated in the surroundings, is optimized both in terms of intensity and duration and is enjoyable for the astronaut. This review focuses on the current exercise equipment and regimes used on board the International Space station and presents a forward-looking vision which may support future long duration missions in space craft where exercise is adapted to the size of the habitat such as Orion.

Keywords: Cardiovascular fitness; Astronauts; Spacecraft

Introduction

Ever since Yuri Gagarin completed a single orbit of the Earth on April 12th 1961, his 89 min flight in which he experienced microgravity (μG) demanded an understanding of the effects of μG on the human body which has and will be essential for the development of future space missions. The ergonomic challenges facing manned spaceflight for both human physiological and psychological adaptation to microgravity are well understood and countermeasures for and mitigation of the effects of μG are being developed [1]. Both physiological and psychological affects experienced by astronauts have been extensively reviewed together with an exhaustive set of actual and potential countermeasures, which include both exercise regimes and pharmaceutical intervention [2-10]. The International Space Station (ISS) is a huge feat of technical engineering. The first module was launched in 1998 and having flown 55 missions to date it has hosted over 230 astronauts who spend on average 180 days living and working in space [11-13]. Typically accommodating up to 7 crew members and mainly 3 at any one time, with a pressurized habitable volume of approximately 388 cubic meters, there is ample space to be able to work and live [14]. Part of the original conception for building the ISS was to explore the effects of μG on both astronauts, animal and cellular physiology. Today in 2018, we have a wealth of scientific data to draw on and develop as we prepare for deeper and longer missions throughout our Solar system and in spacecraft for which habitation volume is reduced which in turn, will demand the development of miniaturized exercise devices. In this review, I will first describe the current exercise countermeasures that have been deployed for habitation on the ISS, briefly describe a study aimed at further optimization of current exercise countermeasures which will be reporting in 2018 and lastly, describe 2 devices under development to be deployed on smaller spacecraft for future long duration missions (LDMs).

Current Countermeasures

To reduce the physiological effects of living and working in μG, the ISS has been equipped with exercise equipment specifically adapted to work in the space environment. Developed by the National Aeronautics and Space Administration (NASA), exercise machines comprise a treadmill (Combined Operational Load Bearing External Resistance Treadmill; COLBERT), a stationary bicycle (Cycle Ergometer with Vibrational Isolation System; CEVIS) and a resistance device that simulates weightlifting (Advance Resistance Exercise Device; ARED), A description of these devices is shown in Table 1 and their use has been previously described [15]. Images for the devices are shown in Figure 1 and lessons learned from the first decade on the ISS have been comprehensively reviewed [16]. In 2009, a study on the effect of LDMs on skeletal muscle after 180 days on the ISS was published, representing an early assessment of the exercise regimes deployed at the time [17]. A combination of aerobic and resistance exercise in the regime used showed a decrease in calf muscle volume of approximately 13%, a 32% reduction in peak power and a slow to fast fibre transition in the gastrocnemius and soleus muscles, indicative of unloading in humans. This early study, which utilized the best knowledge available at the time, clearly signaled that improvements in exercise regimes and equipment were necessary to maintain astronaut health and well-being.

ARED was introduced in 2009 and the European Space Agency's (ESA) regime was altered to understand whether an increased component on ARED would reflect better astronaut conditioning. ARED comprised 46% of exercise with the remainder from COLBERT (33%) and CEVIS (20%), representing an overall increase in the use of ARED and a decrease in COLBERT and CEVIS [18]. Findings from the study, which included 8 (ESA) astronauts on LDMs, concluded that there were contradictory associations with post-flight reductions in muscle mass, strength and cardiovascular capacity which may have reflected adaptation to exercise and personal comfort issues with the hardware. The study may have identified potential confounders as a limitation of working with small data sets in the environment. However, it serves to highlight the need to acquire a larger data repository which has now accumulated over the years.

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Acronym	Full name and purpose	Exercise type	Exercise method and regime	Citation
ARED	• Advance Resistance Exercise Device • Built for the ISS • Device uses vacuum cylinders which exert up to 272 kilos of resistance on a bar or cable which imitates free weights used on Earth	• Maintains muscle strength and bone density by targeting the major muscle groups	• Grasp the exercise bar and adjust resistance to desired level • Perform heel lifts, squats, and deadlifts according to muscles to be targeted	[15,22, 30,33]
COLBERT	• Combined Operational Load Bearing External Resistance Treadmill • Built for the ISS • Bungee and harness apply a load to the shoulders and hips based on the astronaut's bodyweight	• Cardiovascular, muscular and skeletal	• Attach harness system and adjust load of harness to the desired workout intensity • Complete run period • At the start of a mission, the load is set at 60% of the astronaut's body weight and increased throughout the mission until it is at 85% to 100% of the weight	[15,22, 31,33]
CEVIS	• Cycle Ergometer with Vibrational Isolation System • Built for the ISS	• Cardiovascular	• Place feet on clip pedals and put on back harness to secure astronaut in machine • Grasp hand holds to maintain balance • Complete cycling period	[15,22, 32,33]

Table 1: Description of exercise equipment and regimes used on the ISS for long duration missions (LDMs).

All astronauts spend up two-and-a-half hours a day for 6 days per week using exercise regimes designed using all three devices and despite deployment of the exercise countermeasure, astronauts on LDMs return to Earth with muscular atrophy, cardiovascular deconditioning and bone loss that may take many months to fully reverse. Despite this exercise regime, astronauts experience a decline in a number of physiological parameters. Data obtained from 24 ISS missions from astronauts who typically spent 180 days in space and followed their exercise regime, experienced a 10-19% decrease in muscular strength, an 8-10% decrease in muscular endurance, a decrease in maximal aerobic capacity of 14% and a decrease in bone mineral density of between 2-7% on return to Earth [19]. A study published in 2011, investigating the cardiovascular health of 6 male astronauts living and working for between 60-180 days on board the ISS, showed that the currently adopted exercise countermeasures provided adequate maintenance of cardiovascular stability under resting conditions. In another more recent case study, a 38 year old male ESA crew member, underwent pre and post-flight (at days 6 and 21 after landing) physical performance assessments after a 180 day ISS mission [20,21]. Assessments included squat and bench press as a proxy for muscle strength, vertical jump as a measure of power and sit and reach and Thomas test as an assessment of core muscle endurance. Surprisingly and despite excellent compliance with the 2 hour daily exercise programme, the study showed impaired post-flight performance at day 6 after landing all of which recovered by day 21 with the exception of muscular power. Widely accepted as the best measure of cardiovascular fitness, VO_{2peak} is a measure of peak oxygen uptake and is the greatest amount of oxygen the body can use to produce energy during exercise. It is measured using CEVIS, with astronauts starting at low intensity and gradually increasing pedaling resistance over a short period of time until exhaustion. The tests were performed three months before launch to the space station; after approximately 15 days in space; every 30 days throughout flight; and one, 10 and 30 days following return to Earth. According to results published in 2014 from 9 male and 5 female astronauts, VO_{2peak} decreased by an average of 17% by day 15 in space, but then gradually increased during flight [22].

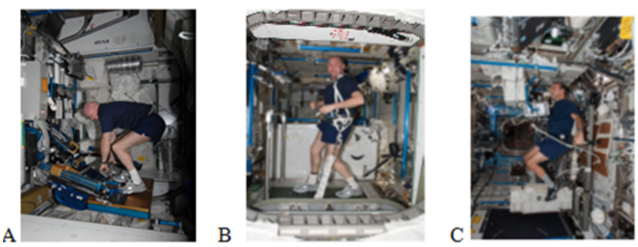

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Figure 1: Images of exercise equipment and regimes used on the ISS for long duration missions (LDMs). (A) Advanced Resistance Exercise Device (ARED; 3o), B) Combined Operational Load Bearing External Resistance Treadmill (COLBERT; 31), C) Cycle Ergometer with Vibrational Isolation System (CEVIS; 32). All sources of images are cited and acknowledged.

Most astronauts never recovered their pre-flight $V0_{2peak}$ levels during the mission, however, several astronauts were able to maintain or even improve VO_{2peak} during flight with frequent episodes of high intensity exercise. The study suggests that although VO_{2peak} may be difficult to maintain during LDMs on board ISS, aerobic deconditioning, at least in some astronauts is not an inevitable consequence of LDMs. In addition, the study may have some predictive power at the level of the individual. The data may help predict what activities an astronaut could be able to tolerate after an LDM, which may help in planning future missions. Astronauts with higher VO_{2peak} levels may be better able to work in heavy spacesuits or on prolonged extra vehicular activities carrying out maintenance, or walking on the Moon or Mars.

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The sprint study

Sprint (Integrated Resistance and Aerobic Training Study) was introduced by NASA in 2011, specifically to design, test and develop a fitness regime using ARED and COLBERT equipment installed on the ISS [19]. The Sprint study evaluates a high-intensity, low-volume exercise protocol to counteract the effects of microgravity integrating both aerobic and resistance training of between 15-35 min and 30-60 min respectively over 6 days per week and used a cohort of 20 active and 20 control subjects [23]. As a consequence of regime optimization, Sprint aims to save up to 3 h per week of exercise when compared with the standard exercise protocol. The Sprint protocol includes regular measurements of VO_{2peak}, heart rate response to submaximal exercise and respiratory ventilator threshold. Monthly ultrasound measurements of the thigh and calf are used to evaluate spaceflight-induced changes in muscle volume. Post-flight data on muscle and bone mass is compared with pre-flight measurements and with data from control subjects that use the regular exercise protocol. On completion and publication of the findings, expected in 2018, investigators will be able to provide and integrated resistance and aerobic exercise training regime which will maintain muscle and bone integrity and cardiovascular condition while reducing time spent performing exercise routines throughout the duration of a 180 day LDM. Not only will this study be able to support the longer-term goals of maintenance of astronaut health in smaller spacecraft such as Orion, it should also be able to help optimize exercise practice for human beings on Earth, in order to maintain soft and hard tissue and cardiovascular health particularly in patients who are confined to bed, or have disabilities which limit movement and in the ability to exercise regularly.

Exercise regimes for future LDMs

Having established he need for defined exercise regimes which must be met with rigorous compliance and monitoring procedures for and by the crew, it is now appropriate to think forward to the likelihood of LDMs where the luxury of ISS size habitats will not be feasible. NASA is currently preparing a new generation of space craft for LDMs, of which Orion will serve in two missions, an unmanned Exploration Mission (EM)-1 and a manned EM-2 [24]. With a habitable volume of just 9 cubic metres, space is clearly at a premium and this has led to the development and further planning of prototype exercise devices [25]. Table 2 describes 2 systems which combine ultra-compactness and light weight with the need to provide both aerobic and resistance training. It is anticipated that both systems will be deployed and tested in the early 2020s.

Acronym	Full name and purpose	Exercise type	Exercise method and regime	Citation
MED-2	• Miniature Exercise Device. • Devised for LDMs where space is at a premium (eg ORION Mars mission) • • All-in-one motion and resistance device that is an order of magnitude lighter and smaller than existing systems. • Can be mounted on the ARED platform	• Cardiovascular, muscular and skeletal.	• 3×1 h sessions separated by 1 w to allow for data interpretation • A variety of constant, progressive and non-linear resistance loads	[34-36]
ROCKY	• Resistive Overload Combined with Kinetic Yo-Yo. • Devised for LDMs where space is at a premium (eg ORION Mars mission). • Ultra-compact device which accommodates both aerobic activity and strength training.	• Cardiovascular, muscular and skeletal.	• Uses loads that simulate up to 180 kg of resistance, astronauts can perform squats, deadlifts, heel raises, bicep curls and upright rows. • To be tested for the first time on Exploration Mission-2 (EM-2), the first mission where the spacecraft will be launched with a crew aboard; planned launch date 2021	[37,39]

Table 2: Description of exercise equipment and regimes under further development for long duration missions (LDMs).

Summary

Since the deployment of the ISS 20 years ago, over 230 astronauts have visited the ISS from all over the world from different space agencies and organizations. This has provided excellent opportunities to test multiple exercise regimes, record data and make improvements on both exercise intensity and duration. As expected, the conclusion is very clear, which is that it is vital to the health of the astronaut and the success of the mission that countermeasures to living in this environment are put in place and adhered to and that continuous improvements are made. The challenges are considerable given the goals of deeper space travel on space craft who are constrained by the size of environment to accommodate equipment installed on the ISS. Nevertheless, the development of miniaturized equipment together with an optimized exercise regime such that will report from the Sprint study, offers the potential to understand limitations of space ergonomics on astronaut health and to provide an environment conducive to minimizing the risk to long term health, particularly on return to Earth from LDMs. One potential solution which would permit sustained human travel in space for many years is the development of systems capable of providing simulated or artificial gravity, in either a continuous or defined intermittent regime. The publication of an International Roadmap for Artificial Gravity Research sets out the ambition for multiple space agencies around the globe to safely develop or adapt a spacecraft to provide a habitat in which astronauts may experience artificial gravity (AG) and it is estimated that a system will be deployed in space in the mid-2020s [26]. Indeed, the first step towards demonstrating a positive effect of a AG in animals has also recently been published and reviewed [27,28]. Irrespective of whether astronauts will experience AG or not in future, the need for exercise to counteract the effects of μG will be with us for

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many years to come. As we refine our understanding of the effects of space ergonomics and develop our technology to meet the challenges ahead, it promises to be a very exciting voyage of discovery for space ergonomics over the next decade as we continue to develop our thinking and goals towards ultra-long duration missions [29].

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