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The Impact of Exercise in Spaceflight and Microgravity Environments

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THE IMPACT OF EXERCISE IN SPACEFLIGHT AND MICROGRAVITY ENVIRONMENTS

A Capstone Project Presented in Partial Fulfillment
of the Requirements for the Degree Bachelor of Science
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Western Kentucky University

By

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ABSTRACT

Since mankind's first spaceflight, a significant barricade in reaching distant planets has been the damaging effects of microgravity upon the human body. Effects range from loss in bone mineral density and severe muscle atrophy to autoimmune disorders. The most effective countermeasure of these effects to date is exercise. Implementation of exercise in microgravity is not an easy task, so various specialized equipment must be utilized to effectively administer it. Even with this equipment, exercise as it is currently used does not entirely prevent body systems from undergoing detrimental changes. New modalities and implementations are currently being investigated that may significantly improve the ability of exercise to prevent major losses during long-distance spaceflight and allow for space agencies to put humans on another planet within the next few decades.

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CONTENTS

Introduction

Just sixty years ago, every human that had ever lived had functioned within the confines of Earth's atmosphere. This changed in 1961 when Russian cosmonaut Yuri Gagarin completed one entire orbit of the Earth and became the first human to ever reach space. While there, he was exposed to a near-zero gravitational force known as microgravity. Exposure to microgravity will result in deleterious acute physiological changes, which will affect a person's ability to perform in space, as well as making daily living much more challenging following return to Earth. Spending enough time in microgravity can result in devastating effects such as bone loss, muscular atrophy, and cardiovascular changes (Jones et al., 2019). The longer the time spent in space, the greater the level of disability experienced when returning to Earth (Hides et al., 2016). The predominant method used to counter these effects is exercise. Exercise in microgravity is vital because of the rapid degeneration of muscles that occurs when the body no longer needs to support its full weight as it does in Earth's full gravity. For this reason, it is crucial for astronauts to exercise every single day for up to three hours. However, exercise in near-zero gravity is not an easy task, and special machines need to be developed to allow for astronauts to experience resistance when weight training and to stay attached to the treadmill when running. These machines are both expensive and heavy and are not entirely effective in retaining muscle mass on the astronauts. Studies have shown muscles can begin to atrophy within 24 hours of leaving Earth's gravity, and this atrophy continues at a rate of 2% per month (Keller et al.,1992). This is acceptable when considering the average space station mission lasts six months, but future trips to

Mars can take up to ten months in one direction. Arriving on another planet with a hostile environment carrying 20% less muscle mass than what one is used to is not an ideal scenario. Before long-term spaceflight can be attempted, proper exercise technique and equipment need to be understood.

Exercise in space is seeing many new ideas and research come out that completely change the landscape of current theories. For this scenario, a literature review is fitting as it provides a general foundation of where research currently stands, as well as gaps where there is not enough information or ideas have not been explored. These gaps can then be used to generate new ideas or perspectives on the topic which would have been overlooked without all the information presented together. This review examines what is currently being done in the labs regarding exercise and microgravity, and then using that data to discuss how it is being applied, as well as what role exercise could play in future space endeavors.

The Origins of Exercise in Space

The idea of using exercise to counter the effects of microgravity can be traced back to the early National Aeronautics and Space Administration (NASA) Project Mercury and Gemini missions, as well as being a significant focus of research on the Soviet space station, Mir. However, this review will focus more on American advances up to the formation of the International Space Station (ISS). For NASA, Project Mercury served as the foundation to demonstrate that humans could survive the harsh elements of spaceflight for short bursts of up to 34 hours. There were a few abnormalities when astronauts returned to Earth, which included increased heart rate as well as decreased blood pressure for a period of several hours (Johnston et al., 1975). Project Gemini allowed for improved study opportunities on its multi-day missions, and at the end of its nearly 2,000 hours of microgravity exposure, three key conclusions were observed: 1) postflight orthostatic hypotension persisted around 50 hours after returning back to Earth; 2) there was a decrease in red blood cell count of five to twenty percent; and 3) bones began to demineralize in space (Johnston et al., 1975). The culmination of these two projects resulted in Project Apollo, which transported the first humans to the surface of the Moon. Unfortunately, as a direct result of the Apollo 1 spacecraft fire, planned in-flight exercise tests during the Apollo mission were eliminated. Pre- and post-flight tests were done instead using a bicycle ergometer and a graded exercise test. The results of these tests show that pre-flight cardiac output was 20-25% greater than that of post-flight levels after just a few weeks in a microgravity environment (Johnston et al., 1975). In addition, bone mineral studies were conducted onboard several Apollo flights and while no significant bone loss was reported, NASA scientists concluded that if allowed to continue unabated for a prolonged period of time, the consequences would be more severe (Johnston et al., 1975). Following these tests, it became obvious that a solution would need to be found to prevent the effects of microgravity upon the human body if long-term spaceflight was to become a reality. One proposed solution to combat these effects was exercise. The findings of the Mercury, Gemini, and Apollo missions were to serve as the basis for NASA's new project, Skylab, and exercise testing would be at the forefront of research testing done there. Skylab was the United States' first long-term space station and provided opportunities for research and testing that had never before been possible. Exercise equipment was introduced in Skylab's first manned mission, known as "Skylab 2" and was improved and evolved throughout Skylab 3 and 4. Skylab

2 used only a bicycle ergometer for its 28-day span and despite it being the shortest Skylab mission, it displayed the worst muscular atrophy rate with the deficit in leg extensor strength approaching 25% (Johnston et al., 1977). For this reason, NASA scientists concluded that although it was a useful machine for aerobic exercise, a bicycle ergometer was not advanced enough for maintaining strength in microgravity environments. Skylab 3 marked the debut of a specially designed low-gravity gym known as the MK-II, which consisted of handles attached to tension springs allowing for large forces to be developed (Johnston et al., 1977). This allowed for a slight improvement compared to Skylab 2 but still saw a rather significant reduction in muscle strength overall, which can largely be attributed to the lack of leg exercises performed with the MK-II. Skylab 4 again saw the use of a bicycle ergometer and the MK-II; however, the addition of a treadmill resulted in the smallest deficit in muscular strength yet in post-flight testing. The Skylab 4 crew was standing and walking without difficulty the day after landing, and after eleven days, leg volume had returned to pre-flight levels while the Skylab 2 and 3 crews had been nowhere near that level (Johnston et al., 1977). Despite Skylab 4 more than doubling the length of Skylab 2's mission (84 days vs. 28 days), it lost only one-half the leg volume (Johnston et al., 1977). The reason the treadmill is such an important addition is because the astronauts use their arms frequently during the day, whether to pull themselves around the station or to perform simple tasks like eating. This is in contrast to the legs, which see almost no use and can severely atrophy in the short time spent in low-gravity environments. Still, the arms still need to be exercised in which case each exercise machine can be seen as a piece of the entire solution, and all are needed together to provide a complete treatment. In the summation of Skylab's findings

written by NASA, it was said “daily in-flight personal exercise regimens … essential for maintaining crew health and well-being” as well as “remedial or preventive measures may be required for mission durations in excess of 9-12 months” (Johnston et al., 1977). Exercise in its current implementation was vital in keeping the crew in the proper physical condition needed to survive in a space station, but if humans ever wanted to leave Earth’s orbit, NASA was going to have to improve its capabilities.

Current Implementations of Exercise in Space and the International Space Station

Since 1998, the ISS has been orbiting the Earth and serving as the main microgravity research facility for the United States and several other nations. It has been continuously inhabited by humans since November 2000, and astronauts spend an average of six months on board during each expedition. Spending six months exposed to microgravity can cause a myriad of deficiencies to the human body, many of which can be slowed or countered by exercise. For this reason, astronauts exercise an average of two hours each day using a variety of complex equipment, five days per week of aerobic and 3-6 days per week of resistance training (Jones et al., 2019). The intention behind having multiple exercise machines is to target different systems of the body. Resistance training is necessary to sustain strength, which is important for returning to Earth’s gravity and needed in the event of emergency egress (Jones et al., 2019). Aerobic training is required to sustain functional capacities and conduct activities such as prolonged space walks (Jones et al., 2019). By using separate machines, each system is able to be targeted more effectively. The nature of microgravity means that you cannot simply transport a regular treadmill or barbell to space as the astronaut would float away while running and be able to move large amounts of weight with ease. During the first ISS expeditions, NASA developed a specialized treadmill and resistive exercise device to meet the minimum standards of crew fitness (Korth, 2015). The treadmill with vibration isolation and stabilization (TVIS) was in use from the inception of the ISS until 2013 and included bungee cord straps that attached to the astronaut's waist and shoulders to hold them in place on the device (Korth, 2015).These straps allow for static loading up to 100% of crewmembers body weight, although most astronauts use loads in the 70-80% range as 100% is too uncomfortable (Petersen et al., 2016). Despite these straps, TVIS functioned very similarly to a conventional treadmill and allowed astronauts to continue aerobic training while aboard the station and was even used by astronaut Sunita Williams to run the equivalent of a marathon while aboard the station. The key to designing a zero-gravity treadmill is that each crewmember must be restrained in a way that mimics Earth's ground reaction forces, but also allows for the natural rise and fall of the body's center of mass during the gait cycle (Petersen et al., 2016). The interim resistive exercise device, or iRED, was developed to meet the need of counteracting bone and muscle loss brought about by microgravity but was never intended to serve as a long-term solution. iRED used an innovative stack of elastomer discs called "Flexpacks" to increase or decrease the desired load (Korth, 2015). iRED included a number of significant shortcomings, chief among them the low peak load of 136 kg. In space, body mass does not apply to peak load, so a 90 kg astronaut would only be subjecting themselves to a 46 kg mass, or about 50% of their bodyweight (English et al., 2019). This is obviously not ideal for long-term usage, so NASA set about designing a new set of exercise equipment for the ISS. Currently, the ISS exercise equipment consists of T2, CEVIS, and ARED (Korth, 2015). T2 is the second generation of TVIS and allows for higher speeds to support NASA's shift in exercise philosophy away from low to moderate intensity and towards vigorous, high-intensity exercise (Korth, 2015). ARED was designed to replace iRED and also comes with a slew of upgrades, most notably an increase in peak load of 272 kg as well as increasing range of motion to allow for squats to be performed (Korth, 2015). ARED was shown to be approximately 5% more effective than iRED when used for a full-term ISS mission (Tanaka et al., 2017). After 16 weeks of training, ARED was demonstrated to have similar physiological when compared to free weights (English et al., 2019). The final machine, a cycle ergometer with vibration isolation and stabilization (CEVIS) operates similarly to a traditional cycle ergometer with slight modifications such as clips on the pedals and a belt to keep the crewmember from floating away (English et al., 2019). These machines are currently in use on the ISS and are a part of an ongoing study involving the efficacy of a high-intensity, lower volume training, known as SPRINT, that may be more effective during long duration spaceflight (English et al., 2019).

The skeletal system typically has two functions: 1) to provide a rigid structure to support, move, and protect the body; and 2) to serve as a reservoir of calcium in the body (Tanaka et al., 2017). Within just a few days of exposure to microgravity urinary calcium excretion increases by 60-70%, resulting in increased bone mineral loss at rates of -7.4% after just 2 months of spaceflight (Tanaka et al., 2017). Another effect of microgravity upon the body is significant bone loss due to decreased loading of the skeleton. In space, the lack of any significant load on the musculoskeletal system causes significant losses of bone mass and bone mineral density (BMD) in weight-bearing bones, mainly in the spine and lower limbs (Grimm et al., 2016). Using dual X-ray absorptiometry (DXA) techniques, it was discovered regional losses during spaceflight of 1.0-1.5% per month in the spine, pelvis, and proximal femur (Tian et al., 2016). Part of this bone loss is a result of bone migrating from the legs to the skull (P. Bishop, Personal Interview, April 6, 2020). The rest can be attributed to gravitational unloading in a microgravity environment and impaired osteoblast function (Grimm et al., 2016). This results in a condition similar to osteoporosis and has been a major concern to manned spaceflight since its inception. The effects of decreased BMD can have serious consequences both onboard the ISS and back on Earth. In elderly adults, a 10% loss in BMD will represent a 2-3x increase in risk of fracture. In space, BMD decreases at a loss of 2.5-2.7% a month, presenting a serious risk of skeletal fracture after a six-month mission (Wang et al., 2018). Even after returning to Earth and living for a year in its gravity, astronauts' bone structure and density as well as hip strength had still not returned to pre-flight levels (Roy, 2007). In order to counteract this, astronauts must exercise for up to three hours a day using ARED, T2, and CEVIS. Bedrest studies have shown that resistance training is an effective countermeasure against disuse-induced bone loss, and ARED is categorically much more effective than iRED at mitigating bone loss, although not enough to fully halt the effects of microgravity (Grimm et al., 2016; Smith et al., 2014). Recent studies with the SPRINT protocol have shown promising improvements, but for now a combination of ARED resistance training as well as pharmacological and nutritional treatments are needed to fully counter bone loss (Cappellesso et al., 2015). Before space flights longer than one year can be seriously attempted, a more efficient way to combat bone loss must be found.

The muscular system is often described as the musculoskeletal system because they are essentially inseparable. When bone and muscle are properly stressed and nourished, they will thrive. When the pull of Earth's gravity is removed there is no longer a need for these muscles to remain at that size, so they will shrink. For example, dramatic losses of up to 24% have been demonstrated in the lower limbs after six months on the ISS (Hackney et al., 2015). In the quadriceps and triceps surae, losses of -6.0% and -6.3%, respectively, after eight days have been recorded and after 16 days losses of -15.4% and -15.9%, respectively (Tanaka et al., 2017). Additionally, the slow-twitch soleus shows greater atrophy than the fast-twitch gastrocnemius at first, yet over longer spaceflight durations the gastrocnemius will see larger decreases (-24%) when compared to the soleus (-20%) (Tanaka et al., 2017). The main reason for this decay is that the muscles, designed for use in Earth's, gravity are simply not being stressed. In order to move about the station astronauts use their hands instead of their lower body, so therefore lower extremity muscles will see the largest decrease in strength and mass. The soleus and gastrocnemius are often the most affected with peak force values decreasing by up to 21% (Widrick et al., 1999). The reason for this is the soleus is more susceptible to unloading due to its oxidative nature (Jones et al., 2019). In all cases, type II fibers will see more atrophy than type I, specifically type IIb (Tanaka et al., 2017). The main machine capable of combatting these losses is T2 and CEVIS. Astronauts go under extreme physical preparation leading up to their mission into space, and therefore the effects microgravity has upon their musculoskeletal system can be comparable to detraining. As with most deficiencies, the best way to combat microgravity is with a combination of cardiovascular and resistance training. Resistance training has a lower

VO_2 cost (and therefore uses less valuable oxygen) and has been shown to be the most effective for upper body, hip, and trunk musculature (Steele et al., 2019). Cardiovascular training is more effective at preserving the lower limb musculature. By running on a treadmill, the downward force of the foot can restore absent neuromuscular activation throughout the entire limb (English et al., 2019). Even still, after landing atrophy of the plantar flexor will progress for four days and can induce muscle damage while weight bearing after returning to Earth (Tanaka et al., 2017). These exercises in their current state are not effective for prevention of reduction of calf muscle mass, performance, and the slow-to-fast transition of fiber type in the gastrocnemius and soleus muscles (Takashi et al. 2015). The most promising new hardware currently being tested to solve these issues is the flywheel. Flywheels can be used for multiple exercises and their small size, low energy requirements, and ability to produce higher eccentric loads than concentric loads (eccentric overload) can be very valuable in a small space like the ISS (English et al., 2019). In a 70-day trial, a flywheel was shown to be as effective as the entire suite of ISS exercise machines to attenuate or prevent unloading-induced changes in muscle function (English et al., 2019). Discoveries like these show promise for use in long-term space travel.

Although not affected to the same degree as the musculoskeletal system, the cardiovascular system does not remain unaltered during exposure to microgravity. During long-term spaceflight, an increase in cardiac output of 10% as well as a moderate decrease in systolic and mean arterial pressure were recorded (Garrett-Bakelman et al., 2019). This can be attributed to the way microgravity affects fluids and pressure in the cardiovascular system. On Earth, the body naturally increases heart rate and total peripheral resistance when the body is supine but will lower it when sitting or standing. Microgravity causes the body to act as if it is always in the supine position, resulting in increased heart size and stroke volume (Tanaka et al., 2017). The weightlessness experienced by the astronauts also causes the blood volume in the lower limbs to decrease by 10% and redistribute towards the head, giving an appearance of facial fullness and puffiness (Williams et al., 2009; P. Bishop, Personal Interview, April 6, 2020). Additionally, large contractility of the heart is no longer required to send blood to the head against gravity, therefore the cardiac muscle of the heart will atrophy by -8 to -10% after just 10 days of spaceflight (Tanaka et al., 2017). The lack of any downward pull also results in decreased arterial mean pressure acting to pull blood into distal capillaries and muscle. This in combination with the extreme sedentary lifestyle that comes from living in space (due to the muscles not having to work the majority of the day) can lead to cardiac deconditioning and increased risk of cardiovascular disease, or CVD (Hughson et al., 2017). After two weeks of flight, maximal oxygen consumption (VO_2 max) decreases by 17% and then gradually increases, although it will never return to preflight levels while the astronaut is still in space (Wang et al., 2018). Finally, the increased levels of radiation experienced outside of Earth's atmosphere means there is a much higher risk for an astronaut to develop cancer and CVD later in life (Hughson et al., 2017). Exercising for two hours per day on a treadmill cannot overcome spending the other 22 hours in a day essentially sedentary, and certainly cannot defend against cancer. Solutions other than exercise will be needed to solve the problem of cardiovascular challenges in microgravity.

As described in previous sections, the musculoskeletal system is extremely sensitive to changes in the environment, including the cartilage that holds it all together. However, it is generally unknown if microgravity has an effect on this tissue. Bone and tissue have been shown to be restored over time, but cartilage can be damaged to the point where it is no longer feasible to repair it (Fitzgerald, 2017). Upon returning to Earth, the reloading of joints, tendons, and ligaments may cause damage and joint degradation (Strollo et al., 2018). None of this has been seriously tested, however, only hypothesized. This is an area that would certainly need more research before any long-term flights could be conducted.

One of the major concerns of landing a man on the moon was that he would get an uncurable “moon disease” and spread it once he got back to Earth. For this reason, all three astronauts of the Apollo 11 mission were kept in isolation for three weeks. While there turned out to be no disease to infect them on the moon, space does have an altering effect upon the immune system. Observations of astronauts’ immune status immediately post-flight show changes such as altered cytokine production, altered virus immunity, and altered neuroendocrine responses, as well as many others (Williams et al., 2009). Fortunately, recent tests have shown the immune response to vaccines is the same in space as it is on Earth (Garrett-Bakelman et al., 2019). Daily exposure to gravity has also been shown to protect against immune dysfunction and may be used in the future to reduce the risk to astronauts in space (Williams et al., 2009).

The psychological impact of making a trip into space is often one that goes unnoticed. Astronauts often report inconsistent sleep schedules, overworking, discomfort, and injury risk as being among the top stressors impacting them in flight (McKay &

Standage, 2016). Despite this, there are not many studies or monitoring of astronauts' behavioral health at any phase of their missions. As exercise has been shown many times to be effective in assisting with depression and other mental health issues it is likely it could be implemented to a greater extent in the future.

Although countermeasures have greatly improved since man first went to space, upon return to Earth space crews still often experience difficulty in walking and maintaining an upright posture, and occasionally need to be carried from the vehicle after long stays (Hawkey, 2003). NASA and other space agencies lessen this as much as possible by performing three stages of training: 1) preflight training; 2) inflight training; and 3) postflight rehabilitation. Inflight training has already been covered thoroughly by the preceding sections. Preflight training is extremely thorough in order to get the astronaut in peak physical condition at the time of their spaceflight as well as practicing the movement patterns they will perform on the ISS (Lambrecht et al. 2016). The main objective of preflight training is to support astronauts in maintaining an overall fitness level that is above average for their age, therefore decreasing the risk of them being critically unfit when returning to Earth (Petersen et al., 2016). The goal of postflight conditioning is to return the astronaut to preflight physical condition. Starting the day after return to Earth (R+1), a 21-day exercise program begins that is individualized to each astronaut (Peterson et al., 2016). Each session is generally two hours, with the first hour being dedicated to physical therapy (PT) rehabilitation and the second hour consisting of physical training. At first, the majority of the PT and exercise takes place in a pool as the decreased gravity is similar to that in space. Gradually, more time is spent in the gym performing resistance exercises than in the pool (Peterson et al., 2016). By the end of the 21-day period sessions should be at or near preflight intensity. Throughout this entire three-week period the astronaut is receiving constant treatment by the physical therapist, who slowly introduces exercises designed to restore balance and improved motor control (Lambrecht et al., 2016). At the end of the 21-day period, the physical therapist can decide to require more rehabilitation or release the astronaut to continue training on their own. Physical therapy makes up an essential part of the post-flight rehabilitation and will continue to increase in importance as missions become longer.

Future Implementations of Exercise in Space: Interplanetary Travel

Exercise countermeasures have come a long way since the Apollo flights in the late 1960s. Improvements such as hardware reliability, more tailor-made exercise programs for crewmembers, and utilization of supplements such as nutrition and pharmaceuticals have all aided microgravity countermeasures in becoming more effective (Loerch, 2015). Despite these advances, space agencies have not quite reached the threshold necessary for long-distance, interplanetary spaceflight. Several experimental solutions are currently being explored, and at the forefront is the SPRINT program and the flywheel-based exercise machine. The SPRINT program consists of alternating days of continuous cycling exercise for 30 minutes at 75% of VO_2peak three days per week with treadmill sessions of 30 seconds, two minutes, and four-minute intervals at near max intensity for another three days per week (Ploutz-Snyder et al., 2018). The treadmill sessions are comparable to current high intensity interval training (HIIT) workouts while the cycle exercise resembles long-distance aerobic training. There are several reasons for the program layout: 1) to provide diverse loading stimuli to the bone and muscle; 2) to reduce training plateaus and staleness; 3) to allow for attaining higher training intensities;

and 4) to attempt to minimize overuse injury by optimizing exercise duration and repetitions (Ploutz-Snyder et al., 2018). The results of SPRINT testing show it is effective in reducing or completely preventing losses in muscle mass, strength, and function (English et al., 2019). In a 70-day bedrest study, SPRINT mitigated muscle and cardiac deconditioning regardless of what exercise device was used, and peak aerobic capacity was maintained from pre- to post-bedrest condition (Ploutz-Snyder et al., 2018). There are, however, several limitations to be considered. For instance, the SPRINT protocol did not have any significant effect on bone loss or BMD (Ploutz-Snyder et al., 2018). Ground-based studies are not entirely accurate when concerning bone, as the presence of gravity even in the supine position will mitigate some of the bone loss observed during complete unloading, such as spaceflight. Despite this, NASA is continuing testing with SPRINT and is suggesting it may be used on future exploration missions. The other upcoming breakthrough for long-term spaceflight is flywheel-based exercise devices. These go hand-in-hand with SPRINT as they can be used to perform the SPRINT protocol in small, volume-constrained vehicles. Resistance training using a flywheel and aerobic training via continuous and intermittent rowing was able to preserve several key muscle characteristics using the same compact machine (Jones et al., 2019). Removing the treadmill and using solely the cycle ergometer to save space is also being considered, as it would be more conductive to maintain strength than treadmill running (Jones et al., 2019). Flywheel devices as well as the SPRINT protocol are seen as the leading countermeasures for attempting a flight to Mars.

The goal of NASA has always been to visit another planet in our solar system. However, if we are ever going to walk on another planet’s surface, current exercise countermeasures are going to need to be improved. With bone losses approaching 2% a month and muscles atrophying up to 24% in just six months, a ten-month, one-way journey to Mars is not feasible (Hackney et al., 2015; Cappellesso et al., 2015). In order to keep astronauts in the best condition possible during such a long journey, NASA will need to continue to improve its approach to exercise countermeasures. A key component will be developing a more efficient, compact countermeasure system than what is being used currently (Tanaka et al., 2017). In future missions, it is possible that restrictions will be placed on available exercise time. Therefore, it is imperative that the nature of exercise training is streamlined to allow for similar benefits in a shorter amount of time (Jones et al., 2019). In this regard, developments in utilizing the SPRINT protocol in conjunction with flywheels to reduce muscular atrophy and cardiovascular loss will be greatly important, in addition to using pharmacological supplements to reduce the rate of BMD decay (English et al., 2019; Smith et al. 2014). Before an interplanetary space flight is attempted, more research needs to be conducted in this area.

Conclusion

The goal of this literature review was to look at current exercise countermeasures and how they are being applied, and then use that data to discuss how the use of exercise has improved and where it may go in the future. Current exercise implementations, such as ARED and T2 are well studied and the information on them is endless, while newer implementations such as SPRINT are less pervasive. Some areas of research, such as the impact of microgravity on cartilage or how space and exercise affect the psychology of astronauts have next to no research on them and warrant some investigation. NASA plans on setting foot on Mars in the 2030s. Before that can happen, I believe the gaps shown in this literature review will need to be methodically researched and filled. While some exercise applications can be researched on the ISS, in my opinion it is nearing the end of its effectiveness. Before Mars, NASA has plans to return to the moon and establish a base which I believe will result in much more accurate findings about long-term space travel than the ISS will produce. Private companies such as SpaceX have more ambitious timelines for reaching Mars, and data produced on those journeys will be beneficial to NASA’s astronauts as well. The most important areas worth examining currently are the SPRINT program and flywheels. Both have key components needed to make interplanetary travel a reality such as improved efficiency and the decreased need for equipment. In combination with pharmaceutical supplements to combat bone loss, these implementations have the greatest chance to see us on another planet within the next 20 years.

REFERENCES

Bishop, P. (2020, April 6). Phone Interview.

Cappellesso R, Nicole L, Guido A, Pizzol D. Spaceflight osteoporosis: current state and future perspective. *Endocr Regul*. 2015;49(4):231–239. doi:10.4149/endo_2015_04_231

English KL, Bloomberg JJ, Mulavara AP, Ploutz-Snyder LL. Exercise Countermeasures to Neuromuscular Deconditioning in Spaceflight. *Compr Physiol*. 2019;10(1):171–196. Published 2019 Dec 18. doi:10.1002/cphy.c190005

Fitzgerald, Jamie. “Cartilage Breakdown in Microgravity—a Problem for Long-Term Spaceflight?” NPJ Regenerative Medicine 2.1 (2017): 1–2. Web.

Grimm, Daniela, Grosse, Jirka, Wehland, Markus, Mann, Vivek, Reseland, Janne Elin, Sundaresan, Alamelu, and Corydon, Thomas Juhl. "The Impact of Microgravity on Bone in Humans." *Bone : Official Journal of the International and Mineral Society* 87 (2016): 44-56. Web.

Hackney KJ, Scott JM, Hanson AM, English KL, Downs ME, Ploutz-Snyder LL. The Astronaut-Athlete: Optimizing Human Performance in Space. *J Strength Cond Res*.2015 Dec;29(12):3531-45. doi: 10.1519/JSC.0000000000001191. Review. PubMed PMID: 26595138.

Hawkey A. The physical price of a ticket into space. *J Br Interplanet Soc*. 2003;56(5-6):152–159. Cardiovascular

Hayes J. The First Decade of ISS Exercise: Lessons Learned on Expeditions 1-25. *Aerosp Med Hum Perform*. 2015;86(12 Suppl):A1–A6. doi:10.3357/AMHP.EC01.2015

Hides J, Lambrecht G, Ramdharry G, Cusack R, Bloomberg J, Stokes M. Parallels between astronauts and terrestrial patients - Taking physiotherapy rehabilitation "To infinity and beyond". *Musculoskelet Sci Pract*. 2017;27 Suppl 1:S32–S37. doi:10.1016/j.msksp.2016.12.008

Hughson RL, Helm A, Durante M. Heart in space: effect of the extraterrestrial environment on the cardiovascular system. *Nat Rev Cardiol*. 2018;15(3):167–180. doi:10.1038/nrcardio.2017.157

Johnston, R.S. "Biomedical Results of Apollo." NASA Johnson Space Center (1975). Web.

Johnston, R.S. "Biomedical Results from Skylab." NASA Johnson Space Center (1977). Web.

Jones TW, Petersen N, Howatson G. Introduction to the Frontiers Research Topic: Optimization of Exercise Countermeasures for Human Space Flight - Operational Considerations for Concurrent Strength and Aerobic Training. *Front Physiol*. 2019;10:173. Published 2019 May 16. doi:10.3389/fphys.2019.00584

Jones TW, Petersen N, Howatson G. Optimization of Exercise Countermeasures for Human Space Flight: Operational Considerations for Concurrent Strength and Aerobic Training. *Front Physiol*. 2019;10:584. Published 2019 May 16. doi:10.3389/fphys.2019.00584

Keller TS, Strauss AM, Szpalski M. Prevention of bone loss and muscle atrophy during manned space flight. *Microgravity Q*. 1992;2(2):89–102.

Korth DW. Exercise Countermeasure Hardware Evolution on ISS: The First Decade. *Aerosp Med Hum Perform*. 2015;86(12 Suppl):A7–A13. doi:10.3357/AMHP.EC02.2015

Lambrecht G, Petersen N, Weerts G, et al. The role of physiotherapy in the European Space Agency strategy for preparation and reconditioning of astronauts before and after long duration space flight. *Musculoskelet Sci Pract*. 2017;27 Suppl 1:S15–S22. doi:10.1016/j.math.2016.10.009

Loerch LH. Exercise Countermeasures on ISS: Summary and Future Directions. *Aerosp Med Hum Perform*. 2015;86(12 Suppl):A92–A94. doi:10.3357/AMHP.EC12.2015

McKay CD, Standage M. Astronaut adherence to exercise-based reconditioning: Psychological considerations and future directions. *Musculoskelet Sci Pract*. 2017;27 Suppl 1:S38–S41. doi:10.1016/j.msksp.2016.12.011

Petersen, Nora et al. “Exercise in Space: The European Space Agency Approach to in-Flight Exercise Countermeasures for Long-Duration Missions on ISS. (Report).” *Extreme Physiology & Medicine* 5.1 (2016): 9. Web.

Petersen N, Lambrecht G, Scott J, Hirsch N, Stokes M, Mester J. Postflight reconditioning for European Astronauts - A case report of recovery after six months in space. *Musculoskelet Sci Pract*. 2017;27 Suppl 1:S23–S31. doi:10.1016/j.msksp.2016.12.010

Ploutz-Snyder LL, Downs M, Goetchius E, et al. Exercise Training Mitigates Multisystem Deconditioning during Bed Rest. *Med Sci Sports Exerc*. 2018;50(9):1920–1928. doi:10.1249/MSS.0000000000001618

Roy, S. (2007, February 26). How long does it take to rebuild bone lost during space flight? Retrieved April 7, 2020, from https://www.nasa.gov/mission_pages/station/research/subregional_bone.html

Smith SM, Abrams SA, Davis-Street JE, et al. Fifty years of human space travel: implications for bone and calcium research. *Annu Rev Nutr*. 2014;34:377–400. doi:10.1146/annurev-nutr-071813-105440

Steele J, Androulakis-Korakakis P, Perrin C, et al. Comparisons of Resistance Training and "Cardio" Exercise Modalities as Countermeasures to Microgravity-Induced Physical Deconditioning: New Perspectives and Lessons Learned From Terrestrial Studies. *Front Physiol*. 2019;10:1150. Published 2019 Sep 10. doi:10.3389/fphys.2019.01150

Strollo F, Gentile S, Strollo G, Mambro A, Vernikos J. Recent Progress in Space Physiology and Aging. *Front Physiol*. 2018;9:1551. Published 2018 Nov 12. doi:10.3389/fphys.2018.01551

Tanaka K, Nishimura N, Kawai Y. Adaptation to microgravity, deconditioning, and countermeasures. *J Physiol Sci*. 2017;67(2):271–281. doi:10.1007/s12576-016-0514-8

Tian, Ye et al. “The Impact of Oxidative Stress on the Bone System in Response to the Space Special Environment.” International Journal of Molecular Sciences 18.10 (2017): n. pag. Web.

Wang, Linjie et al. “Physiological Effects of Weightlessness: Countermeasure System Development for a Long-Term Chinese Manned Spaceflight.” Frontiers of Medicine 13.2 (2019): 1–11. Web.

Widrick, J. J., Knuth, S. T., Norenberg, K. M., Romatowski, J. G., Bain, J. L., Riley, D. A., Karhanek, M., Trappe, S. W., Trappe, T. A., Costill, D. L., & Fitts, R. H. (1999). Effect of a 17 day spaceflight on contractile properties of human soleus muscle fibres. *The Journal of physiology*, *516 (Pt 3)*(Pt 3), 915–930. https://doi.org/10.1111/j.1469-7793.1999.0915u.x

Williams, D., Kuipers, A., Mukai, C., & Thirsk, R. (2009). Acclimation during space flight: Effects on human physiology. *Canadian Medical Association Journal,180*(13), 1317-1323. doi:10.1503/cmaj.090628