KMANPUB | Health Nexus Vol. 2 No. 2 (2024): 30-40

Article history:
Received 20 February 2024
Revised 13 March 2024
Accepted 22 March 2024
Published online 01 April 2024

Brief Review: Virtual Reality and Physical Exercise as Countermeasures of Coping the Space Missions

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Article Info

Article type:
Review Article

How to cite this article:
Russomano, T., Vinagre, N. A. C., Gessinger, R. P., Castro, J. de C., Herbert, J. da S., Oliveira, A., Oliveira, E., Costa, K. L., Xavier, A. P., Ruiz, R., Dihl, Y., Knechtle, B., Weiss, K., Andrade, M. S., de Lira, C. A. B., & Vancini, R. (2024). Virtual Reality and Physical Exercise as Countermeasures of Coping the Space Missions. *Health Nexus, 2*(2), 30-40.
https://doi.org/10.61838/kman.hn.2.2.4

ABSTRACT

Microgravity is an environment incompatible with human physiology that induces unique physiological changes to the body. Exposure to microgravity environment can cause some possible physiological hazards, such as impairment of immune function, bone mass and skeletal muscle mass, in addition to possible negative psycological alterations (depression, anxiety, apathy, and personality changes). These pysico-physiological changes negatively impact health status and quality of life and result in operational difficulties on a space mission for the astronauts. Countermeasures designed to lessen the effect of microgravity on the human body include daily physical exercise and rehabilitation, psychotherapy, specific diets, pharmaceutical treatments, and the use of technologies. Virtual reality (VR) added to physical exercise programs, in the training and preparation of the astronauts for the space missions, could have more exuberant effects. Therefore, the aim of this perspective article is to present the application of VR and physical exercise as countermeasures for training and preparation before, during and after a space missions.

Keywords: *Virtual reality, Physical exercise, Microgravity, Physical rehabilitation, Space sience.*

1. Introduction

Earth's gravity has had an integral effect on the development of life, shaping the anatomy and physiology of human beings. Exposure to microgravity has been shown to affect the body, causing numerous changes, such as a reduction in heart size and circulatory blood volume, disturbances of the neurological system, impairment of the immune function and functional capacity, and decrease in bone density and skeletal muscle mass (1, 2). The space and microgravity environment predisposes astronauts to extreme physical conditions that require mental resilience, which can affect their physical and mental performance in activities of daily living and space routine, creating a constant tension regarding the possible dangers and damage that may threaten life and health of crew members, as well as fatal accidents (3).

National Aeronautics and Space Administration (NASA) describes the microgravity environment on its website: *"In the microgravity environment aboard the orbiting International Space Station (ISS), bones and muscles don't have to support the body's mass (weight on Earth). Without Earth-like exercise, astronauts would experience bone and muscle loss or atrophy during their stays in space"* (4). This puts astronauts at risk of musculoskeletal injuries during spaceflight and upon normal gravitational reloading (5). Moreover, the loss of muscle mass can also negative influence general metabolism, once skeletal muscle is an important regulator of glucose and lipd homeostasis (6). These physiological changes could lead to undesirable health consequences and operational difficulties, especially in medical emergencies (7).

Imagine a medical emergency associated with an open bone fracture on a space mission in a microgravity environment. What if a crew member sustains a fracture while outside of the spacecraft? Although the risk of fracture in microgravity is believed to be low due to the lack of impact, the risk of fracture increases upon re-entering a gravity environment (7).

To mitigate the loss of bone mineral density and the risk of bone fractures on the ISS, physical exercise is essential, once it is considered an effective way to stimulate bone mass acquisition (8). The Advanced Resistance Exercise Device (ARED), T2 treadmill (Combined Operational Load Bearing External Resistance Treadmill), and cycle ergometer with isolation and vibration (CEVIS) are part of the long-term space treatment and physical conditioning and rehabilitation (7).

Furthermore, drugs characterized as inhibitors of bone resorption (bisphosphonates) are used for its effect in preventing bone loss (9). For fractures, treatments that would improve bone healing in space include traditional treatments, such as splints, as well as the use of low-intensity pulsed ultrasound, electromagnetic field therapy, and intermittent subcutaneous injections of parathyroid hormone (7).

However, the best scenario is to proactively consider health prevention and risk prediction. Namely, it is important to have in place emergency plans to mitigate traumatic and musculoskeletal injuries on deep space missions (10). This involves a combination of strategies to reduce the loss of bone mineral density and muscle mass, and improve risk management protocols for medical emergencies (7, 8), as being extremely far from Earth could increase the risk of serious complication and death. This undoubtedly nowadays involves the use of technology (3) and the physical exercise practice (6, 10-12).

A series of physical rehabilitation and countermeasures procedures are used pre-, in-, and post-flight to improve the wellbeing and health of space travelers (2). These include daily physical exercise, meditation, psychology therapy, a tailored diet, and pharmaceutical treatments (2). We can now also include technologies, such as virtual reality (VR), which can be used in conjunction as a form of mental and physical training and preparation (3).

In this sense, a recent investigation delved into a cutting-edge, bespoke adaptive training regimen aimed at preempting stress in environments characterized by high stress, such as those encountered by astronauts during space missions. This study unveiled a VR system engineered to dynamically adjust stressors in alignment with real-time stress indicators, ensuring the maintenance of optimal stress levels throughout the training. The research incorporated sixty-five healthy subjects, segmented into three distinct groups, each subjected to varying training modalities: skill acquisition devoid of stressors, consistent stressor adjustments, and adaptive stressor modifications. The outcomes demonstrated that the adaptive training with VR markedly decreased heart rate and exhibited promising trends towards improved heart rate variability, signifying a

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E-ISSN: 2981-2569

reduction in stress. Furthermore, this regimen notably increased task engagement and reduced distress more effectively compared to the other training scenarios. The study underscores the unparalleled efficacy of the adaptive program with VR in mitigating stress and posits its capability to more adeptly equip individuals for high-stress scenarios by customizing stressor levels to an individual's present state, thus bolstering resilience against impending stressors. This tailored approach within a VR framework means a profound leap forward in stress management training, particularly pertinent for astronauts and other professionals operating in comparably high-stress domains (13).

In general lines, training with immersive VR holds the potential for a significantly positive impact on the mental and physical health of astronauts, primarily due to its ability to simulate space environments and scenarios with high fidelity, thus preparing astronauts not only technically but also psychologically for the challenges of space missions. Scientific research in the field suggests that immersive VR training can enhance cognitive functions, reduce stress and anxiety levels by allowing astronauts to practice mindfulness and relaxation techniques in a controlled, yet realistic, virtual space environment. Furthermore, physical training in VR can be tailored to individual needs, promoting physical fitness and preventing the muscle atrophy and bone density loss associated with long-duration spaceflight. However, the literature points to gaps such as a limited understanding of the long-term effects of immersive VR on cognitive functions and mental health, the need for more personalized and adaptive VR training programs that can adjust to the evolving psychological and physical needs of astronauts during missions, and the challenge of creating fully immersive environments that accurately replicate the sensory and physical experiences of space. These gaps underscore the need for continued research to optimize VR training for space exploration, ensuring it fully addresses the complex demands of space travel on human health and performance. Thus, this is a current and relevant topic because of the growing demand for manned spaceflight and the rapid advance of companies focused on the commercialization of spaceflight (5).

2. Methods and Materials

The methodology employed for this study is a comprehensive literature review combined with an analytical perspective on existing research findings. This approach involved an extensive examination of the relationships between physical activity and microgravity, virtual/immersive reality and microgravity, virtual/immersive reality and physical activity, microgravity and emergency situations, and the physiological effects of microgravity on the human body. To ensure the credibility and relevance of the information, the research focused on content from entities renowned for their expertise and contributions to space exploration and health sciences, notably NASA. Sources were primarily drawn from publications available on PubMed, a respected database in the field of medical and scientific research. This methodology facilitated a deep dive into the vast possibilities and current limitations within the field, highlighting the challenges of accurately simulating microgravity environments on Earth. The difficulty in creating such simulations underscores the value of virtual reality (VR) technology as a tool for investigating the multifaceted aspects of space exploration. Through this analytical lens, the article discusses the significant impact of microgravity on astronauts' health and proposes the integration of digital technologies, especially VR, as effective countermeasures. These technologies are presented as beneficial for acquainting space travelers with equipment and protocols, supporting physical exercise routines, facilitating pre-flight and in-flight simulations, and aiding in post-flight rehabilitation. Additionally, the article emphasizes the importance of VR in establishing safety measures and emergency prevention practices, showcasing the potential of digital solutions in enhancing the preparation and resilience of astronauts for the challenges of space missions

3. Findings and Results

Table 1 elucidates some important concepts of aerospace medicine, including that associated with the daily practice of physical exercises by the crew members, and the technology that can be used as an alternative strategy in space missions.

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Table 1

Concepts to be elucidated regarding aerospace medicine and the use of technology in the space missions.

Concept	Definition*
Gravity	The force by which a body attracts objects towards its center. Everything that has mass is affected by gravity. In addition, objects with more mass are more affected by the gravity (14). Biological effects of gravity and their magnitude depend on scale of mass and difference in density (15).
Microgravity	The condition in which people/objects appear to be weightless. Its effects can be seen when astronauts/objects float in space (heavy objects move easily) (16). Physical exercise countermeasures are employed during spaceflight to combat the deleterious physiologic effects of long duration microgravity exposure(17).
International Space Station (ISS)	A research laboratory that has the purpose to expand the knowledge of human space exploration. Astronauts aboard the ISS do not feel the effects of gravity as they do on Earth. As the ISS orbits Earth, the spacecraft and crew members are in a constant state of "free fall". As a result, astronauts experience a constant feeling of lightness. In the state of reduced gravity, it is easier to carry out physical efforts and activities of daily living because the muscles and bones are less demanded. As minimal/no physical exertion would result in muscle deterioration and loss of bone density, astronauts must undertake physical exercise routines (18).
Advanced Resistive Exercise Device (ARED)	The ARED allows astronauts to do resistance training exercises that simulate the use of free weights and is used to maintain/improve muscle strength, bone strength, and endurance. The resistive force is generated by pistons/cylinders with adjustable load. For physical exercises done on the barbell, the load can be adjusted from 0 to approximately 2670 Newtons (0 to 600 pounds in the terrestrial environment/1g environment). For physical exercises done on the cable, there can be an imposed load of up to approximately 670 Newtons (150 pounds in a 1g environment). Astronauts can perform physical exercises of different types: deadlift, squat, heel raise, hip abduction and adduction, bench press, biceps curl, triceps extension, and upright row (18).
Augmented reality (AR)	Enhances the user's perception of the environment by superimposing graphics and media on what people see in the real world. By showing information in the right context and place in the physical environment, AR reduces the cognitive effort to relate the information to the physical environment; reduces the number of errors, through visual guidance; and reduces the time needed to find information (19). AR associated with physical exercise practice can be used as an effective alternative for improving physical fitness and motivation (20).
Virtual reality (VR)	A technology that allows the user to explore/manipulate computer-generated real/artificial three-dimensional multimedia sensory environments in real time (21). In addition, it is as immersive experience that help isolate users from the real world, usually through a specific headset device (with headphones) (22). One of the goals of virtual reality is that it provides an immersive experience. In this regard, immersive reality (IR) is the presentation of an artificial environment that replaces the real-world surroundings of the users, so convincingly, so that the users can believe in the created digital reality and fully engage. The aim of IR reality is to fully immerse the user in a computer-generated world, giving the impression that they have immersed themselves in an alternate reality (23). VR added to the practice of physical exercise in a traditional way has the potential to positively impact the individual's physiological, psychological and physical rehabilitation gains (24).

* In this case, we opted to keep the text, almost entirely, according to its original source, in order to avoid interpretation distortions.

3.1. An addendum on VR

Spaceflight has negative effects on the human body, imposing significant risks on crew members due to exposure to unique and occasional physical and psychological stressors associated with limited capabilities to provide medical assistance (25). Technologies, such as VR, have been used to advance the ability to support and develop medical care procedures for astronauts and to mitigate the psychological risks and preservate physical and mental health (26). The space sector is working to establish human settlements on the Moon and Mars. Space agencies and companies are developing new technologies and improving existing ones to allow humans to remotely explore our solar system through simulation and guided human thought and senses, i.e., training and mental coping (26). The ability to simulate an extraterrestrial settlement, for example, will dramatically improve the design considerations for future space missions and, as a consequence, may make them safer (3).

VR has enabled the creation of high-fidelity simulations of space environments, with the addition of physical modeling, making it possible to obtain more information about how future astronauts will experience the various spaces of a spacecraft. For example, using a 3D motion capture tracking system, humans, spacecraft, and other structures can interact in a physical workspace and simulate situations that could happen on a space mission. This includes the practice of physical exercise, the simulation of eating and resting in a confined and restricted space, and training in different medical emergency scenarios (3, 26, 27). The integration of this information in a VR environment provides more sensory help and, consequently, possibilities of simulations of real scenarios to support more assertive and faster decision-making (3).

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3.2. About the general aim and article

For this article, the following relationships were researched: physical activity and microgravity, virtual/immersive reality and microgravity, virtual/immersive reality and physical activity, microgravity and emergency, and physiological effects and microgravity. Content from entities recognized for their excellence in their sectors of activity, such as the NASA, were also researched. After reading and studying the material, which has been published over the years on Pubmed, the impression is that this is a field of vast possibilities and still requires further research, given the difficulty of simulating the microgravity environment. These difficulties legitimize the use of VR simulation studies to investigate the entire domain of space exploration. This perspective article addresses the impact of the microgravity environment on the human body, as well as the countermeasures that can be used. We point out how the application of digital technologies, such as VR, can be useful for familiarizing with equipment and protocols, carrying out physical exercises and pre- and in-flight simulations, and post-flight rehabilitation procedures for preparing space travelers, as well as for establishing safety and emergency prevention practices.

In general lines, VR can simulate space environments and provide realistic and immersive training experiences. Astronaut-focused VR training protocols can recreate challenging or dangerous scenarios that are difficult to replicate. In this regard, it could be applications of VR in the context of space missions: environment familiarization, extravehicular activities, emergency procedures, psychological and physical well-being, and team training and collaboration (3, 26, 27).

3.3. Microgravity vs. Physical exercise

An important point to highlight is that exposure to microgravity can lead to physical deconditioning (28). Physical deconditioning refers to the decline in physical fitness, strength, endurance, and overall functional capacity that occurs because of prolonged inactivity or reduced physical activity levels. It is commonly observed when individuals are immobilized, such as during bed rest studies, prolonged hospital stays, or periods of reduced physical activity due to injury or illness (28) and can be classified into mild, moderate, and severe physical deconditioning (29). During periods of deconditioning, various physiological systems in the body undergo negative adaptations. Muscles may weaken and lose mass (atrophy), cardiovascular fitness decreases, and flexibility and joint mobility may be compromised (30). It is worth noting that physical deconditioning can be reversible with appropriate exercise and rehabilitation programs (31, 32). Undoubtedly, everything mentioned above can happen to astronauts, especially on long-term space missions.

It has been shown that physical deconditioning associated with prolonged exposure to the microgravity environment leads to a loss of muscle strength and cardiorespiratory fitness. Muscle overload/stress (which produces a piezoelectric effect - *when certain anisotropic crystals are mechanically loaded, a charge is generated on the surface*) plays a vital physiological role in musculoskeletal health because it produces mechanical tension with the resultant mechanotransduction (*processes through which cells sense and respond to mechanical stimuli by converting them to biochemical signals that elicit specific cellular responses*) initiating molecular signaling that stimulates muscle adaptations (1, 28, 30, 32). The practice of physical exercise by astronauts can reverse the physical deconditioning, resulting from the phases of physical detraining and lack of musculoskeletal overload/prolonged immobilization (32).

In this context, to evaluate the effectiveness of physical training, the crew of the ISS performed the following model of physical training: either the high intensity/lower volume integrated sprint resistance (3 days/week) and an aerobic (interval and continuous workouts, every 3 days/week in alternating fashion) physical exercise program or the standard/traditional ISS countermeasure consisting of daily resistance and aerobic exercise during long-duration spaceflight (control group). Post-flight bone mineral density at the femoral neck (dual-energy X-ray absorptiometry, -1.7%), peak torque of the knee extensors (isokinetic dynamometry, -5.8%), muscle function (cone agility test, +7.4%) and cardiorespiratory fitness (peak oxygen uptake - $\dot{V}O_2$peak, -6.1%) decreased in both groups. To save time and adequately prepare crew members to perform physically demanding mission tasks, high-intensity and low-volume physical training can be an alternative prescription for physical exercise countermeasures during spaceflight (17).

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Reinforcing previous findings regarding cardiorespiratory fitness, it was demonstrated that a long-duration spaceflight mission on the ISS (~6 months) resulted in a significant decrease in maximal oxygen uptake ($\dot{V}O_2max$). This decrease was associated with a significant decrease in maximal cardiac output and convective/diffusive oxygen transport (33).

Long-duration spaceflight results in a loss of muscle strength that poses operational and medical risks, particularly during emergency exit, return to Earth, and surface exploration. The isokinetic dynamometry test can help to quantify changes related to muscle strength and the installed muscle imbalances from movements of different joints (34), which may predispose to injuries before and after space missions. Therefore, this provides useful information on musculoskeletal health for future development of effective and safe countermeasures that consider the practice of physical exercise for minimizing physical deconditioning and assisting in the physical rehabilitation of astronauts (35). Changes in the isokinetic strength of crew members on missions to the ISS of approximately 163 spaceflight days (Expeditions 1-25) were evaluated, retrospectively. The authors observed that mean isokinetic strength was decreased between 8-17% after space missions. However, even though isokinetic strength increased a month after returning to Earth, deficits of 1-9% still persisted among astronauts. Interestingly, isokinetic strength losses induced by space missions were not different between men and women. It should be noted that the average losses of isokinetic strength were up to 7% lower in crew members who carried out space missions after use of the ARED. Additionally, the ARED program did not prevent the decrease in isokinetic strength after long-duration spaceflight, but its use helped in recovery and in the process of physical and muscular rehabilitation. After returning to Earth, with physical reconditioning, isokinetic strength is largely recovered within 30 days (35).

3.4. VR applications: focusing on physical activity

VR can be a new approach to promoting health and physical activity and promoting good behaviors and life habits. In addition, it can be an alternative for improving the psychological benefits of physical activity and increase the likelihood of adherence to its practice. VR is defined as a digital technology, in which sensory experiences (visual, auditory, tactile, and olfactory stimuli) are artificially created, leading users to manipulate objects within a virtual environment (36). The use of VR during the practice of physical activity through its integration with traditional physical exercise equipment has been applied in the fields of kinesiology and public health (37). As a therapeutic tool, VR offers the opportunity to intensify repetitive tasks and increase visual and auditory feedback, making the use of VR more interesting than traditional physical therapy and without causing physical discomfort and threatening the integrity of users (24). In addition, VR and the practice of physical activity have been widely used in the field of physical and mental rehabilitation (26, 27). VR rehabilitation training promotes cognitive function rehabilitation and recovery of activities of daily living in patients with poststroke cognitive impairment and may be a good complementary approach to conventional cognitive interventions (37).

3.5. VR in space missions

VR has already been successfully applied in different physiological and psychological scenarios, especially involving motion sickness and mental health (26, 27, 38). The use of VR for physical exercise practice, training, and simulations, however, is a step further and could play an important role in optimization of the efficacy of countermeasures against both in- and post-flight muscle atrophy (3).

Space tourists and crew members must maintain a balanced diet, good hydration, adequate hygiene, and undergo periodic medical assessments during a space mission (2). Although physical exercise protocols have not yet been defined for space tourists, astronauts are required to perform 2h30min of high-intensity physical exercise 6 times a week, with a combination of devices (ARED, treadmill, and cyclo ergometer) that are adapted for use in microgravity (2, 39). Several rehabilitation equipment and protocols are also available to improve the physical condition of space travelers after short- and long-term space missions. VR could be applied to demonstrate how the physical exercise and rehabilitation equipment operate, especially considering the challenge of performing movements in a microgravity environment (11).

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The use of VR with these aims needs further investigation to assess its impact on physical exercise performance and to evaluate other physiological variables. This includes measurement and analysis in healthy adults (men and women) of the influence of VR on muscle, cardiopulmonary and neurovestibular physiology.

Table 2 below shows the space mission coping strategy through the use of VR at different stages of preparation and training.

Table 2

Space mission coping strategy using VR at different stages of preparation and training.

Stage	Strategy	Reference
Pre-Mission	Astronauts can practice various procedures, such as spacewalks, spacecraft operations, and emergency scenarios, in a controlled virtual environment. This training helps them develop necessary skills, muscle memory, and decision-making abilities, enhancing their preparedness.	(3, 36, 40, 41)
In-Mission	VR can assist astronauts by providing them with additional training and support. As unforeseen situations may arise in space, VR can be used to simulate and practice emergency procedures or handle critical equipment failures. Astronauts can access VR training modules and simulations on-demand to refresh their knowledge, ensuring they can respond effectively to challenging circumstances.	(3, 36, 40-42)
Post-Mission	Astronauts undergo a period of physical and psychological rehabilitation. VR can play a role in this phase by assisting in the rehabilitation process. For instance, VR-based exercises can aid in retraining balance, coordination, and motor skills that might have been affected by extended periods in microgravity. Additionally, virtual environments can serve as a transitional tool, allowing astronauts to gradually readjust to Earth's conditions and cope with the challenges of reintegration.	(3, 26, 36, 40-42)

4. Discussion and Conclusion

Acute changes in normal physiology in response to unusual and abnormal environments are called acclimatization, which can involve either short-term (hours-days) or long-term (days-months) exposure (43). This applies to both physiological and psychological responses and adaptations to, in this case, a space mission environment. Adapting acclimatization strategies can enhance human adaptation to an extreme conditions such as heat/solar radiation and microgravity environments (43, 44). Thus, traditional strategies (psychological therapy, meditation, special physical exercises, breathing techniques, and proper nutrition) used in conjunction with alternative strategies, using modern technologies and VR, can optimize these processes. Microgravity has a detrimental effect on both human physiology, with all systems and organs being affected to some degree, and human psychology, whereby isolation and social confinement can take a non-negligable toll on the wellbeing of astronauts (44).

VR is increasingly being used as a treatment strategy in predictive and preventive health, and offers future possibilities in the context of clinical and applied research. VR used for continuous mental training can help patients with psychiatric disorders better cope with the disease and change harmful habits. This can improve overall health and quality of life, since it can momentarily take the focus away from negative situations that cause acute and chronic emotional suffering, while training the brain to think positively and acquire more healthy habits (3, 26, 27, 37). Therefore, its use can have an important application in a situation of isolation and social distancing, as drastic and extreme as that which occurs on a space mission.

It is possible that immersive exposure, through VR, can present a person with a different scenario to that in which they find themselves through use of the technique of vision and guided thinking. In addition to traditional treatments, such as physical exercise, VR exposure could improve motivation (45), quality of life, and emotional health and help improve lifestyle, mental hygiene, and self-care in an extreme situation like a space mission (1, 3, 26, 27).

Astronauts are exposed to an environment that is not compatible with human physiology, namely, microgravity. This environment causes unique physiological alterations that require the attention of researchers; in addition to understanding the physiological changes that take place in astronauts, it can also help in understanding the aging process, as it mimics some changes (44).

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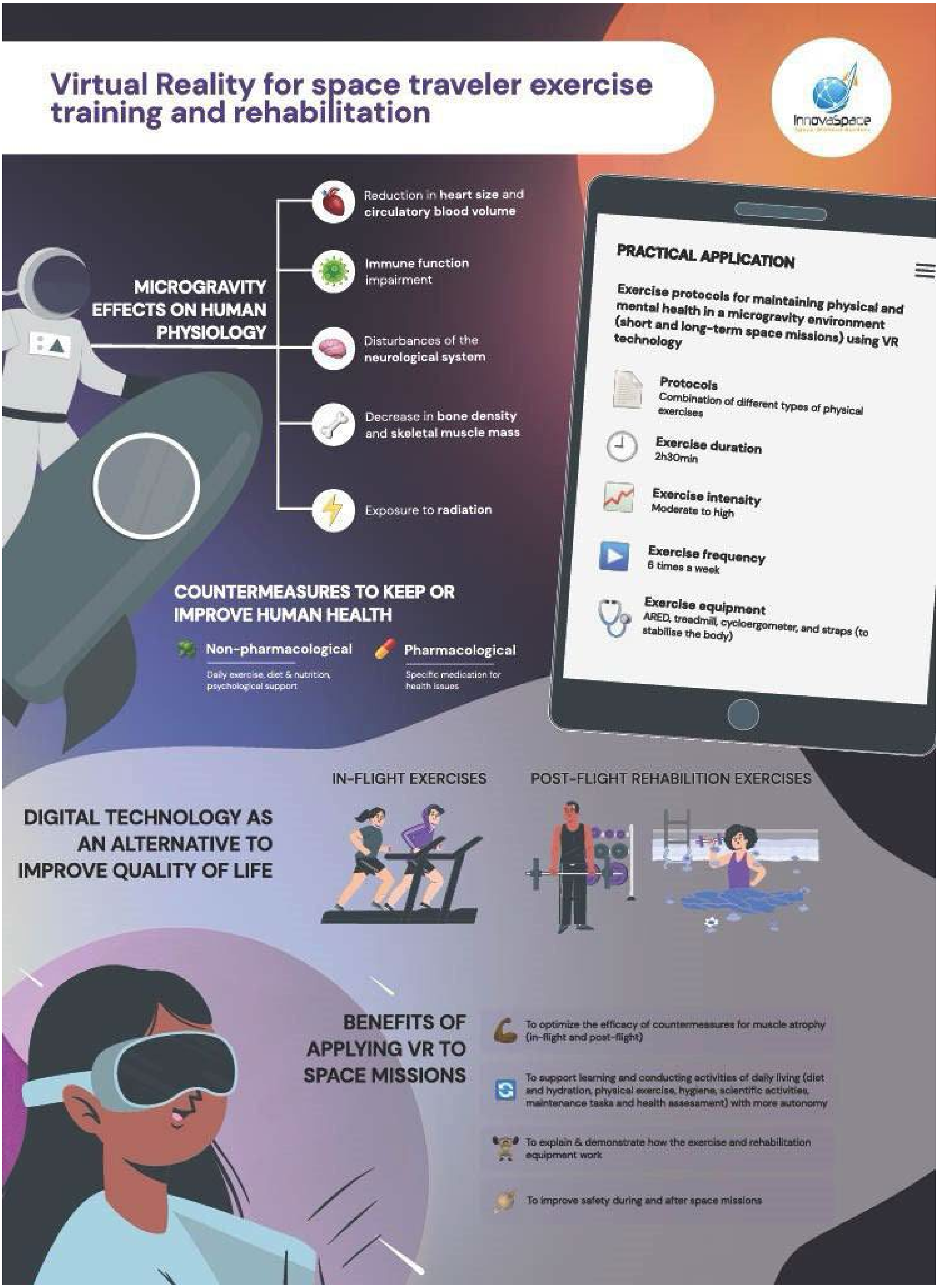
Figure 1

Negative microgravity effects in the physiology of space travelers: How virtual reality and physical exercise can help to minimize it?



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The microgravity effects on human physiology include impairment of cardiovascular function, immunosuppression, disturbances of the neurological system (for example, motion sickness), increased possibility of sarcopenia, greater exposure to radiation. This last factor, in particular, increases the chance of genetic mutations that may predispose to cancer. It should be noted that astronauts are probabilistically more vulnerable to cancer due to exposure to space radiation during missions (46).

The countermeasures to maintain or improve human health in the microgravity environment are both non-pharmacological (daily physical exercise, diet and nutrition, psychological support) and pharmacological (specific medication for health issues) (1, 3, 9-11, 26-28, 30, 47-49).

Considering the practice of physical exercise in the microgravity environment, we suggest combining different types of physical exercises with digital technology. For example, the use of VR combined with physical exercise could optimize physical and mental benefits by helping to explain and demonstrate how exercise and rehabilitation equipment work and momentarily disconnecting the space traveler from the sensation of the spacecraft's confined environment.

Applying VR in space missions could optimize the efficacy of countermeasures against physiological changes, especially muscle atrophy (in-flight and post-flight), as well as contributing as a learning tool (diet and hydration, hygiene, scientific experiments, maintenance tasks, and health assessments) to achieve a more efficient, accurate and autonomous operation. In addition, VR could improve mental health during space missions through enabling a more immersive contact with the terrestrial environment.

To summarize, Figure 1 illustrates the benefits of VR and physical exercise to improve physical and mental health and quality of life during space missions and upon return to Earth.

Authors' Contributions

All authors made substantial contributions to the drafting and revising of the work and gave final approval of the version published. The authors agree to be accountable for all aspects of the work.

Declaration

In order to correct and improve the academic writing of our paper, we have used the language model ChatGPT.

Transparency Statement

Data are available for research purposes upon reasonable request to the corresponding author.

Acknowledgments

We would like to express our gratitude to all individuals helped us to do the project.

Declaration of Interest

The authors report no conflict of interest.

Funding

According to the authors, this article has no financial support.

Ethics Considerations

Not applicable.

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E-ISSN: 2981-2569

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