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ORIGINAL ARTICLE

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Design and construction of a microgravity simulation treadmill for exercise in varying gravity conditions

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ABSTRACT

Background and Objective: Microgravity simulators, which provide both static and dynamic environments closely resembling real weightlessness, are of significant interest to space medicine, sports medicine, rehabilitation specialists, occupational therapists, and sports science experts. The primary aim of this study was to introduce a designed microgravity simulation treadmill for training in variable gravity conditions.

Methods: To build this device, the following components were used: a horizontal restraining surface that supports the user in a horizontal position, a supporting chassis that holds both the vertical treadmill belt and the horizontal supporter, six elastic straps for lower limb restraints (thigh and leg), a protractor that indicates the angle of the user's horizontal position relative to the ground and the exact amount of weight reduction due to applied gravity, and a rotating vertical treadmill belt, which is vertically oriented in this device, unlike traditional treadmills.

Results: After designing the device, it was compared with similar devices based on the relevant physical laws, and its reliability and validity were assessed.

Conclusions: The results of this research, considering the specific feature of the microgravity simulation treadmill designed for training in variable gravity conditions, which allows for the creation of environments with varying weights, recommend its use for walking and running on a treadmill in weightless and microgravity environments. Additionally, this device can be utilized for research in the fields of rehabilitation, space medicine, and paramedicine.

KEYWORDS: Simulated microgravity, Weightlessness, Treadmill, Spatial intelligence, Walking

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Introduction

Humans are among the most adaptable creatures on the planet, with the ability to live in diverse environments. One of the most challenging and stressful environments for humans is traveling to and living in microgravity or low-gravity conditions, which present significant challenges. Astronauts, who must navigate and adapt to this hazardous environment, experience entirely new conditions [1]. Although an object's total mass in space remains the same as it does on Earth, the gravitational forces acting on it are nearly zero, resulting in a state of weightlessness [2]. Exposure to a low-gravity environment affects various bodily systems, including the musculoskeletal, nervous, cardiovascular, immune, and hematologic systems. Even short-term space missions can cause profound changes in the human body [3].

Within the inner ear, the vestibular system plays a crucial role in maintaining balance. This system sends information about position and movement to the brain, which, through neural connections, regulates balance, posture, muscle tone, motor coordination, and vision, as well as energy expenditure by muscles [4]. Van Ombergen et al. (2017) reported that microgravity impacts many parts of the brain, including the cerebellum, sensory-motor areas, and the vestibular system [5].

Spatial intelligence—the ability to solve problems through manipulation, create mental images, and think through visualization—is known as visual-spatial intelligence (6). This form of intelligence is linked to one’s level of visual understanding of the surrounding environment and the objects within it [6]. Often referred to as visual intelligence, it allows individuals to learn more effectively through images [6].

In flight missions involving pilots and astronauts, where weight reduction and microgravity are significant factors, the ability to perceive and understand the environment visually becomes crucial. As a result, the use of tools and equipment designed to prepare individuals for weightless and microgravity conditions is essential. Given the features and capabilities of such devices, they appear to be valuable in aerospace organizations.

Since studying astronauts in microgravity is both challenging and expensive, scientists and researchers seek ways to simulate space-like environments for research. This can be achieved by using equipment and methods that replicate microgravity at a lower cost, enabling researchers to conduct studies and gather new information in this field.

Wattenpaugh et al. (2016) created a microgravity simulation environment by restricting movement and limiting overall body motion [7]. Similarly, Cebula et al. (2022) employed a suspension method in which the lower body or entire body was rendered weightless. This was achieved by suspending subjects above the ground using springs and air jets blowing from below, effectively simulating a microgravity environment [8]. In another approach, Haranz et al. (2013) utilized free-fall and parabolic flight methods to provide a more realistic microgravity environment [9].

Bed rest is one of the most common methods used to simulate the physiological effects of low gravity in humans. This approach was notably applied by Northey et al. in 1996 through long-term bed rest studies [10]. In 2012, Tenford et al. utilized an anti-gravity treadmill, developed by NASA, designed to allow individuals to walk or run at a reduced weight. The user is placed inside an airtight chamber, and the desired weight is set by adjusting the air pressure within the chamber.

This enables the user to experience only a fraction of their body weight on their legs [11]. Additionally, in 2015, Feng et al. introduced the use of an inclined bench, positioning the head at a downward angle of 4 to 16 degrees. This method causes fluid shifts and cardiovascular responses similar to those experienced during spaceflight or physical activity in microgravity [12].

Walking, as one of the most fundamental human activities, has been extensively studied, yet many aspects of it remain unclear [13]. In microgravity conditions, treadmill walking has been shown to help maintain physiological functions, providing protection during extended periods in microgravity [14]. To ensure the health and well-being of astronauts, it is essential to train in environments that simulate microgravity, which is a critical aspect of space travel preparation [1]. The purpose of this research was to design and construct a microgravity simulation treadmill that can be used for training in variable gravity conditions. This device aims to simulate the microgravity environment and be applicable in field activities.

Material and Methods

Microgravity simulators, which create environments that closely resemble real weightlessness in both static and dynamic ways, are of great interest to researchers in space medicine, sports medicine, rehabilitation, occupational therapy, and sports science.

In Jazer's study, a treadmill exercise simulator for use in a microgravity environment was developed using the principle of weight reduction on an inclined surface. This innovation has been patented and is registered with the Intellectual Property Center of the National Deeds and Real Estate Registration Organization under the number 139950140003009105 (Fig. 1).

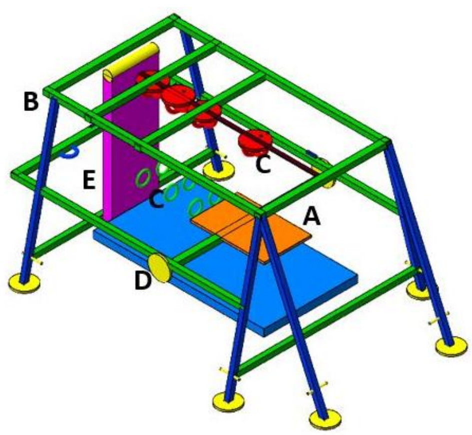

Figure 1: Three-dimensional schematic diagram of the microgravity simulation treadmill for training in variable gravity conditions

To construct this device, a horizontal restraining surface was designed to support the user in a horizontal position. The user is positioned horizontally on this surface. A supporting chassis, which consists of a frame, holds both the vertical treadmill and the horizontal support in place. The user is secured using six elastic bands that restrain the lower limbs (thighs and legs). A protractor is included to measure the angle of the user's horizontal posture relative to the ground and to indicate the precise amount of weight reduction according to the applied gravity. Unlike conventional treadmills, this device uses a vertically oriented treadmill belt. The specifications of the patented device are as follows:

A. Horizontal Restraining Surface (Supporting the User in a Horizontal Position):
This component is made from a combination of fabric, leather, and plastic. It is positioned horizontally in the center of the chassis frame and secured to the frame with straps. The user lies horizontally on this surface, with the lower limbs perpendicular to the treadmill slider. It is important to note that this surface only supports the upper part of the pelvis.

B. Supporting Chassis:
The chassis is constructed from metal profiles and serves as a frame that holds the treadmill belt vertically while supporting the horizontal component. The frame secures the user in place. The supporting chassis has the appearance of an incomplete pyramid, parallel to the base, which enhances the device's stability. The horizontal support for the user is connected to the chassis with straps, while the legs are secured to the chassis using six elastic straps, which act as restraints for the lower limbs.

C. Lower Limb Restraints (Thighs and Legs):
The thighs and legs are secured to the supporting chassis with six elastic vibrating straps, which function as restraints for the lower limbs. These straps allow the user to perform all phases of walking naturally, including stance and swing phases. Each pair of straps is connected to the middle of the thigh, the middle of the leg, and the ankle. According to the spring law in physics, the straps have a specific elasticity coefficient that prevents the legs from dropping down (making it difficult for the user to lift them). The stiffness of the straps also limits the range of motion in the legs during walking cycles. These embedded straps are specifically designed to create an appropriate range of motion for the full execution of the walking cycle.

D. Protractor:
This device is mounted on the chassis and measures the angle of the user’s horizontal position relative to the ground. The protractor allows for precise control of the amount of weight reduction according to the applied gravity.

E. Vertical Treadmill:
This is a standard treadmill belt, but in this device, it is positioned vertically, unlike in conventional treadmills. The treadmill allows for adjustments to the user's movement speed, depending on the purpose and type of exercise.

Figure 2: An alternate view of the treadmill device designed to simulate training in a zero-gravity environment, suitable for training in variable gravity conditions.

Results

The purpose of the device was to simulate a microgravity environment for treadmill training. After designing the device, it was compared with similar devices and evaluated based on relevant physical principles to assess its reliability and validity. The key distinction of this device is its ability to adjust weight by changing the angle of the user relative to the ground. The features of the microgravity simulation treadmill for training in variable gravity conditions are as follows:

- The amount of weight reduction can be adjusted and observed by the user via the protractor component of the device.
- There is no weight limit for users of this device.
- The device is user-friendly for both researchers or trainers and participants.
- This microgravity simulator enables both users and researchers to simulate forces corresponding to specific weights, allowing for rehabilitation and exercise.

When the user is positioned on the horizontal plane, their feet are aligned perpendicularly to the treadmill. The weight index is displayed by the protractor, with weight changes corresponding to angle adjustments. Weight reduction is managed by adjusting the lever to alter the variable angle between the horizontal and vertical planes of the turntable. This adjustment decreases the weight applied to the user's knees and lower body joints, following the law of weight force on an inclined surface (R). Given that gravitational acceleration (g) is constant and the weight force acts at an angle (WcosΘ), the vertical component of the weight force due to the body mass (M) is:

$$R = Mg\cos\theta$$

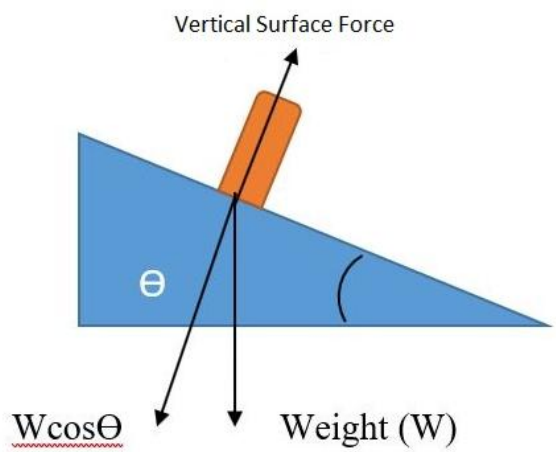

Figure 3: The formula and method for calculating weight force along with the effect of angle

The results indicate that this device is effective for creating a microgravity simulation environment.

Discussion

The aim of this research was to introduce and evaluate a microgravity simulation treadmill designed for training in variable gravity conditions. The results demonstrate that this treadmill effectively creates an

environment with adjustable weights, making it suitable for walking and running in simulated weightless and microgravity conditions. Its use is recommended for training purposes in these environments. Furthermore, the device is valuable for research in rehabilitation, space medicine, and paramedicine.
By utilizing this device, users can adjust the weight force on their legs and joints to varying degrees, catering to specific exercise and training needs. This adaptability makes it an ideal tool for exercise and treadmill training in simulated microgravity. It is particularly beneficial for treating lower limb injuries, supporting elderly individuals, aiding those with neuromuscular degeneration, and assisting people with arthritis in the joints and knees. Additionally, it helps in designing exercises that ensure the optimal health of the neuromuscular system during rehabilitation.

Regarding the innovation of the invented device, it can be said that in microgravity conditions, due to occupational demands (such as for pilots, fighter jet pilots, astronauts), and for athletes (gymnasts, swimmers, motorcyclists, etc.), the implementation of special training programs to enhance performance and improve spatial intelligence in athletes (goalkeepers, etc.), as well as rehabilitation for individuals after prolonged hospitalization to improve functionality, increase efficiency, and prevent (or reduce) related injuries, the use of an appropriate tool becomes essential. In the present invention, a change in weight under microgravity conditions is introduced, which, in addition to preparing individuals for flight missions, can also be used for the aforementioned purposes.

Regarding the innovation highlighted in this invention, it involves the creation of simulated microgravity conditions that closely resemble the real experimental conditions experienced by individuals engaged in flight activities (achieved by adjusting weight according to the slope of an inclined surface). In other words, as the angle between the individual's surface and the horizontal plane changes relative to the ground, a proportional change in the weight and gravitational force exerted on the individual is observed. Typically, in space research and microgravity simulations, the individual's body is placed in a fully horizontal position or with a slight negative tilt of about 6 degrees. The body in this position mimics the condition of a patient who is bedridden for an extended period in a hospital. On Earth (with gravity 9.807 m/s^2), by adjusting the angle appropriately, it is also possible to simulate the gravity of Mars (3.711 m/s^2) and the Moon (1.62 m/s^2), which can be useful for future scientific investigations into space travel.

Regarding the commercial potential of the invented device presented in this study, it can be said that the wide range of activities performed under microgravity conditions creates the possibility for the industrial production and commercialization of the device. In this regard, similar devices were reviewed, and it was found that they lacked the capability to vary the simulated weightlessness or microgravity conditions, typically simulating only a specific degree of microgravity. However, this device, by adjusting the angle of the supporting surface, can simulate various weights based on the physical law of weight force on an inclined plane.

It is important to note that creating microgravity conditions is not simply equivalent to reducing weight. This means that while we can alter a person's weight merely by suspending them vertically, this alone does not replicate all aspects of artificial microgravity environments. Microgravity refers to conditions where not only are gravitational forces along the body’s longitudinal axis minimized, but the vestibular system and inner ear are also affected by disrupting the balance of fluid in the cochlear region, which is the center for receiving sensory input to maintain balance.

Humans can experience short periods of low gravity during free fall on Earth, similar to conditions found in some amusement park rides. There are various methods to simulate microgravity. For example, when subjects are lying in bed, they are placed in a horizontal or head-down position, minimizing the effects of gravity on the body. These subjects are in simulated microgravity conditions, but this is a static state.

In the inner ear, there is a structure called the vestibular system, whose most well-known function is maintaining balance. This system primarily sends information about the position and environment as input to the brain. Based on its neural connections and the role assigned to it, the vestibular system is responsible for balance, postural control, muscle tone, motor coordination, vision, and muscular synergy.
In the field of multiple intelligences theory, there is a concept known as spatial intelligence, which involves spatial reasoning and the ability to visualize with the mind's eye. This type of intelligence, sometimes referred to as visual intelligence, suggests that some individuals learn more effectively through images. When a person's body changes position from vertical to horizontal and remains in this position for an extended period, the human brain responds to the information gathered from the vestibular system. The individual experiences conditions similar to those encountered during space travel and in low-gravity environments. Over time, these conditions lead to the reduction of bone mass, muscle atrophy, and other physical effects.
Focusing on this system is of particular importance in research related to the effects of weight reduction and microgravity, especially in studies concerning flight missions involving pilots and astronauts. This system can also be utilized to enhance individuals' spatial intelligence.

Conclusion

The microgravity simulation treadmill designed for training in variable gravity conditions offers several advantages. Its unique feature of creating adjustable weight environments sets it apart from similar devices. Unlike other devices, it does not exert vertical pressure on the user, thereby preventing the aggravation of joint and knee issues. This makes it highly recommended for walking and jogging. Additionally, the device's potential extends to research in rehabilitation, space medicine, and paramedicine, highlighting its versatility and value in these fields

Ethical Considerations:

Ethical approval was obtained from the Ethics Committee in Biomedical Research at Kinesiology Research Center, Kharazmi University of Tehran (Ethics Code: IR.KHU.KRC.1000.132).

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Conflict of Interest

The authors declare that they have no competing interests in this section.

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«مقاله پژوهشی»

طراحی و ساخت تردمیل شبیه سازی میکروگرانشی برای تمرین در گرانش‌های متغیر

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چکیده

مقدمه و هدف: از آنجایی‌که شبیه‌سازهای میکروگرانشی، محیطی کاملا مشابه با محیط بی‌وزنی واقعی را برای فرد به صورت استاتیک و داینامیک فراهم می کند، مورد توجه پژوهشگران پزشکی-فضایی، پزشکی-ورزشی، توانبخشان، کاردرمان‌گرها و متخصصین علوم ورزشی قرار دارد. هدف از انجام این پژوهش، معرفی دستگاه طراحی شده تردمیل شبیه سازی میکروگرانشی برای تمرین در گرانش‌های متغیر بود.

روش شناسی: جهت ساخت این دستگاه از یک سطح مهار کننده افقی (حمایت کننده از فرد در حالت افقی) که کاربر به حالت افقی روی این سطح قرار می گیرد, یک شاسی نگه دارنده که به‌صورت چهارچوب نگه دارنده نوارگردان تردمیل عمودی و حمایت کننده‌ی افقی، کاربر را در خود جای می دهد, شش بند ارتجاعی مهارکننده‌های اندام تحتانی (اندام ران و ساق پا), یک زاویه سنج که زاویه‌ی حالت افقی کاربر نسبت به زمین و میزان دقیق کاهش وزن با توجه به گرانش اعمال شده را نشان می دهد و یک نوار گردان تردمیل عمودی که در دستگاه حاضر بر خلاف تردمیل‌های رایج به صورت عمود قرار دارد استفاده شد.

نتایج: بعد از طراحی دستگاه فوق با توجه به مقایسه با دستگاه های مشابه و قوانین فیزیک مربوطه مقایسه صورت پذیرفته و پایایی و روایی آن مورد ارزیابی قرار گرفت.

نتیجه گیری: نتایج این تحقیق با توجه به ویژگی خاص دستگاه طراحی شده تردمیل شبیه سازی میکروگرانشی برای تمرین در گرانش‌های متغیر که قابلیت ایجاد محیط با وزن‌های متغیر را دارد, استفاده از آن برای پیاده روی و دویدن روی تردمیل در محیط های بی وزنی و میکروگرانشی مورد نیاز توصیه می‌شود. ضمن اینکه از این دستگاه برای انجام پژوهش‌ها در حوزه توانبخشی و پزشکی-فضایی و پیراپزشکی نیز می‌توان استفاده نمود.

واژه‌های کلیدی: میکروگرانشی شبیه سازی شده, بی وزنی، تردمیل، هوش فضایی، راه رفتن

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