

Technical Solutions Enabling the Physical Training of Astronauts During Long-Term Stays at Space Stations

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ABSTRACT

This article describes problems related to the adaptation of the human body to the state of weightlessness. International studies on changes in the parameters of the musculoskeletal and cardiovascular systems are analysed. The paper also presents technical solutions in the form of numerous devices enabling human functioning in microgravity conditions, without significant decrease in physical capacity, as well as muscle and bone atrophy. The chief purpose of this paper is to propose an innovative piece of equipment that applies two pneumatic actuators for training of lower bodily parts of astronauts in a space station. The equipment recommended in the article is of the authors' own patent. Additionally, the authors put forward a proposition of how to control the patented device in a novel way.

Keywords: microgravity, exercise devices, aerobic capacity, resistive training, whole body vibration, pneumatic

training device.

INTRODUCTION

The state of weightlessness causes a number of adaptive changes in the human body. Since the first flight into the space, biomedical research has been carried out on the human body, to ensure the effective functioning of astronauts, especially during long flights. Weightlessness causes bodily fluids to shift to the upper part of the body, and a loss of calcium in the bones may occur. Osteoporosis and muscle atrophy can lead to the reduction in the mass and strength of skeletal muscles. Articular cartilage also degenerates. As a result of the lack of gravity, physical capacity decreases, which is due to the weakening of the cardiovascular system's functions. Ionizing radiation also

exerts negative effects on the body, damaging the structures and tissues of the human body [1]. The above changes affecting the body are detrimental for the health of astronauts. It is worth noting that the success of a space mission depends on: completing all mission objectives without losing a life. Therefore, certain preventive measures should be implemented effectively as possible, with the use of modern technologies. In order to maintain the appropriate functional fitness of the cardiovascular and musculoskeletal systems, tested training methods are used, such as aerobic and anaerobic, resistance and vibration training. After a long stay in the state of weightlessness and a return to normal gravity of 1 G, astronauts should undergo an intensive rehabilitation process. Their physical capacity is limited, the mass and strength of skeletal muscles as well as bones are reduced, and motor coordination is impaired. Properly planned

and implemented physical activity during space missions is beneficial for the cardiovascular and musculoskeletal systems of astronauts, and also has a positive effect on mental health [2-4]. During a long time spent in space, physical exercises with the use of specialized equipment play an important role in the proper functioning of the human body [5-8].

THE EFFECT OF WEIGHTLESSNESS ON THE BODY OF AN ASTRONAUT

The impact of the lack of gravity on the body has been studied extensively based on the experience gained during space flights in low orbits - LEO (Low-Earth Orbit) and earlier flights to the Moon (Apollo program) [9]. In the early phase of weightlessness, the occurring physiological changes that occur are related to the displacement of bodily fluids towards the chest and head due to the lack of hydrostatic pressure. There are also disorders of the vestibular system (neuro-vestibular disturbances) and symptoms of cosmic motion sickness - SMS (Space Motion Sickness). Astronauts are subject to swelling and reddening of the face and complain of discomfort behind the eyes and in the area of the maxillary and frontal sinuses. These symptoms tend to appear within a few minutes or within several hours of weightlessness [10].

Cardiovascular system

Due to the lack of gravity, the cardiovascular system becomes unstrained and the mass of the heart muscle decreases. However, following long-term space flights lasting over 180 days, the maximum oxygen consumption (VO_{2max}) decreases by approximately 10–15%, owing to aerobic exercises (treadmill, cycle ergometer), and on the surface of the Mars it will be reduced by around 5–6% [11, 12]. These decreases in physical capacity are triggered not only by the reduced physical load and lack of gravity, but also by the reduction in plasma volume and the mass of red blood cells [13].

Changes in the skeletal system

In the research program carried out at the MIR station, from 1986 to 2001, the flights lasted from 4 to 6 months. Measurements of bone

mineral density (BMD) using the DEXA method showed the following mean monthly values of the decrease in spongy bone density: 1.07% of the lumbar spine, 1.16% of the femur neck, 1.58% of the femoral trochanter and 1.35% of the pelvic bones. Simultaneously, large individual differences were shown, with some astronauts losing about 20% of BMD in the femur neck after spending 6 months in space. Similar changes were observed in the control group implementing the long-term lying position program, the so-called bed rest [10]. Also, studies of astronauts carrying out missions at the International Space Station (ISS) showed that they lost 1.0–1.2% of BMD per month. During a 6-month stay in space, they lost about 7% of BMD, and the risk of osteoporotic fractures increased 2–3 times [11]. Undoubtedly, osteoporotic changes resulting from the natural aging processes and postmenopausal changes in women constitute an additional health risk for astronauts participating in long-term space missions and experiencing premature osteoporotic changes caused by a stay in the state of weightlessness. Research conducted on the Earth by American astronauts and astronauts after a long stay at the MIR station showed that the full recovery of the baseline bone density in the majority of subjects took place within the period of 6 months up to 3 years. Bone tissue mass recovery estimates based on flights lasting 126–208 days and double flights from 311 to 489 days are as follows: a 50% recovery of femoral trochanter in 255 days, and a 100% recovery in 1,150 days, a 50% recovery of femur neck within 211 days, and its full recovery in 1300 days, a 50% recovery of lumbar spine in 151 days, with a 100% recovery within 750 days [13].

Articular cartilage is braditrophic and feeds on the principle of diffusion as a result of constant mechanical stresses. In the case of immobilization of healthy people (bed rest), mechanical loads disappear with the lack of adequate activity of skeletal muscles. This leads to malformation of the articular cartilage, especially in the joints of the lower limbs. Changes in the cytoskeleton of chondrocytes and their matrix cause softening of the cartilages and reduction in their thickness. These involution changes seem slower compared to atrophic changes in antigravity muscles and bone demineralization. Currently, we do not possess objective data on the effects of prolonged exposure to microgravity on articular cartilage, due to the lack of non-invasive methods for measuring cartilage

morphology and composition. The described changes are based only on studies of volunteers in bed rest and patients with spinal cord injury. It has also been shown that vibration training alone or combined with resistance training used in the prevention of cartilage health disorders does not counteract disorders of cartilage metabolism [9].

A serious problem for astronauts in space is progressive demineralization and decalcification of bones, resulting from the loss of calcium and phosphorus. During the Skylab mission (1973–1979), an average calcium loss of about 100 mg per day was attested. Decalcification varied linearly and depended on the time spent in microgravity. The highest bone demineralization was observed in a Russian astronaut after a six-month flight on board the first Russian space station SALUT, with the loss of 8% in the calcaneus and up to 10% loss in the lumbar vertebrae. Consequently, a variety of countermeasures have been devised in order to enable astronauts to stay in orbit longer and to recover faster after returning to the Earth. Among other things, the astronauts are recommended to receive enriched food with easily digestible calcium, use pharmacological agents (typical in the treatment of osteoporosis) and perform intense physical exercises with the use of special devices, such as treadmill, ergometer, multifunctional atlas – ARED [14].

Changes in the muscular system

Long-term space flights have led to provided cases of significant decrease in muscle mass, volume and strength. Atrophy of the rectifiers was but in the end, a 30% decrease in the strength of the extensors and flexors of the lower limbs was observed. Larger changes concerning were seen in type II (fast) muscle fibers as compared to slow (type I) fibers. Muscle atrophy was accompanied by increased urinary excretion of deoxyypyridinoline and pyridinoline, which are considered to be markers of muscle collagen. Magnetic resonance imaging (MRI) has shown an approximate 4% decrease in the volume of the lumbar muscle, and an approximate 17% decrease in the volume of the gastrocnemius and soleus muscles. Less radical decreases were seen in concerned the quadriceps muscle of the thigh, hamstrings and deep back muscles. Recovery lasted 30 to 60 days after the completion of a 16 to 28 week space mission. The volume in of muscles of the cervical spine remained unaffected. Recent studies on the causes

of muscle atrophy in astronauts experiencing microgravity have focused on the influence of vestibulo-autonomic regulation of muscle structure. According to the adopted hypothesis, the vestibular system influences the phenotypic structure of antigravity muscles [15]. It has also been shown that after extended missions of more than a month to one year and upon returning to the Earth, the astronauts' bodies adapt to gravity and postural control for many months. After shorter flights, a period of several weeks is required for full control of the body balance [16].

Exercise equipment currently used in space

Effective countermeasures have been developed due to the growing period spent in the state of weightlessness and due to the implementation of advanced scientific research on negative physiological, structural and psychological changes. The countermeasures have been implemented in the period from 1973 to the present [10, 17, 18]. During this time, new devices were designed and older ones were developed to improve physical training to prevent cardiovascular system, osteoporotic bone changes and skeletal muscle atrophy.

The first modern training device introduced on the ISS was the IRED set (The Interin Resistance Exercise Device) [19–21]. This device is designed for strength exercises only using spring force which constituted a significant drawback of the device as the weight simulation required both the inertia and a constant force to simulate a gravity of 1 G. A controlled vacuum versus atmospheric pressure in two large cylinders to keep the force relatively constant. The device could increase the weight of the astronaut's weight to about 272 kg [13].

In 2009–2010, the ISS introduced a new Advanced Resistive Exercise Device (ARED), providing an adjustable load of approximately 272 kg [4, 22]. ARED is more durable than the previous IRED device and has a much higher mechanical resistance. It allows the use of higher absolute loads [8]. The device uses piston-driven vacuum cylinders with adjustable resistance along with a flywheel system to simulate free weight exercises in normal gravity. Additionally, the flywheel assemblies provide variable resistance, mimicking the the inertia forces generated when lifting free weights on Earth. The ARED device can be adapted to each astronaut, regardless of varying anthropometric parameters. The big advantage of this device is the touch screen

on which the astronaut can select personalized exercises. Astronauts perform exercises using a lifting bar or a rope set [4, 22].

To maintain functional fitness on board the ISS, astronauts use a variety of devices. They use ARED (Advanced Resistance Exercise Device) for strength exercises, and for aerobic exercises, treadmills (T2, COLBERT) and bicycle ergometers (CEVIS, velo-ergometer). Using the ARED device, the astronaut can perform resistance exercises activating all muscle groups. Their main goal is to maintain the desired level of muscle strength, mass and bone mass during long stays in space [22, 23]. Typical exercises on the ARED device for anti-gravity muscles include heel lifting, bench press, squats, barbell pulls along the torso, forearms lifting barbells. The T2 treadmill (used for aerobic training) is equipped with a harness and elastic straps that simulate the weight of the body and keep the astronauts on a moving belt. The loads correspond to 70% of the body weight. These exercises combine the elements of workload and high intensity. The CEVIS exercise bike (without a saddle, unnecessary in weightlessness) is mainly used for training the cardiovascular system [13]. Each exercise device requires a different period of adaptation of astronauts to the loads applied and the use of a harness and rubber bands. While running on the treadmill, the exerciser bounces slightly, which is unnatural in typical human locomotion and requires additional effort. However, the lower limbs require less effort than in the environment involving 1 g [9, 24]. Despite strength training, astronauts, especially those of a shorter height, are apt to lose about 15% of their total muscle mass during an extended mission [2, 6]. In 2007, NASA Health Standards: Crew Health's recommendations stated that in long-term space flights, VO₂ max (aerobic capacity) may decrease to the value of 75%, the mass of skeletal muscles may drop to the value of 90%, and the muscle strength to the value of 80% [12]. Such values of physiological parameters ensure the fulfillment of a space mission, but after returning to the Earth, the parameters are expected to return to the average values typical of a given population.

Joint research and physical training of astronauts have been carried out at the MIR station and at the ISS station. The findings and experience contributed to the development of the TVIS treadmill (treadmill with vibration isolation system, T2 – the second generation of treadmills) and two bicycle ergometers. The CEVIS (Cycle

Ergometer with Vibration Isolation and Stabilization System) cycle ergometer and the Russian velo-ergometer (100–250 W, 40–120 rpm) were constructed for aerobic exercise. Initially, as reported by NASA, the TVIS devices (installed in the Russian segment) and CEVIS (in the American segment) did not work due to the failure of the vibration isolation system [25, 26]. CEVIS was installed in 2001, and it can be used with loads from 25 to 350 W, and the pedalling speed range is from 50 to 120 rpm. On the ISS, the bicycle is attached to the ground, while astronauts need to strap their feet to the pedals to move their lower limbs. To maintain the correct position, astronauts are strapped to the device. CEVIS is a computer-controlled device that maintains a constant load selected individually for each crew member. After the completion of exercises, certain parameters are obtained, including heart rate, workload, exercise time, speed, which subsequently are transmitted to the data server [25,28].

COLBERT is a treadmill, a stationary training device used on the ISS (in the American segment). Treadmill exercise helps prevent bone and muscle loss. It also positively influences the functional efficiency of the cardiovascular system [25]. The device has two operating modes: Powered Active Mode, where the treadmill is powered by an electric motor, and Powered Passive Mode, where, while running, a person presses the lower limbs to move the treadmill belt. Treadmill is equipped with data server where the parameters of the exercising person are collected and stored. Based on the obtained monitored parameters, doctors are able to determine the progress of the exercising person. An astronaut on a treadmill can reach speeds of 4.8 to 20 km per hour, while walking and running [18].

Combined resistance training, through systemic vibration (RVE), has a considerably beneficial impact upon the health of an astronaut. This type of training prevents both bone and muscle atrophy [27]. Two vibration platforms have been designed: Galileo for standing exercises and Galileo Space Trainer for lying exercises. For these platforms 60-days long studies were carried out at the Charite Berlin hospital in 2006/2007, involving 23 people, divided into three groups. The first control group was subject only to the BR (bed rest) regime, while the second group additionally performed resistance training. The third group, on the other hand, used resistance training together with vibration training. 25 sessions were performed,

and the research has shown very beneficial effects of resistance training together with systemic vibration. The authors recommend this type of training not only during a stay in weightlessness, but also before a flight into space and after returning to Earth from a space mission. Mechanical and nervous signals obtained with RVE stimulation have a positive effect on the neuromuscular connections. For example, applying a systemic vibration of 25 Hz for 3 minutes has a similar effect on the body as walking 4,500 steps which is half of the recommended distance for sedentary people to maintain physical condition [27].

Before returning to the conditions of the Earth's gravity, astronauts, following a recommendation of the US Johnson Space Center training specialists, increase the physical loads on the training devices. Yet, if the loads are not used carefully, overload changes or muscle damage are likely to occur [24].

A DESIGN FOR A RESISTANCE TRAINING DEVICE FOR ASTRONAUTS' LOWER BODILY PARTS

Pneumatic drives have applications not only in industry but also in exercise equipment, rehabilitation [29–31]. A device designed to reinforce the muscles of the lower part of an astronaut's body (patent No. 233327 [32]) has a simple structure and can be flexibly adjusted to the size of the astronaut, which can optimize therapeutic results. The device includes both shin and hip holders to secure the lower limbs' repetitive position during successive exercises. The device's scheme is presented in Figure 1.

The design of this device provides an alternative to other devices used inside the space station. Its main advantage is its simplicity based on the use of compressible air and its ease of adjustment with correct pneumatic drives. The device is equipped with straps used to fasten it to the thigh and shin of the exercising person, and additional straps are provided to further stiffen and stabilize the foot. This fastening system ensures that the limb will not slip out of the equipment.

The device for training lower parts of astronauts' bodies (as shown in Fig. 1) contains two pneumatic actuators (1) mounted in the case (2), above which two guides (3) are installed on the upper wall of the case. The axes of the guides are parallel to the axes of the actuators (1). Each guide is attached to the hip arm (4), which has a telescopic construction that allows for changing its length. The hip arm (4) is connected to the shin arm (5), which also has a telescopic structure that ends with a bearing (6) located in the groove of the guide. Near its end, the shin arm is positioned within the bracket (7), which is connected to the piston of the pneumatic actuator (1) in its lower part. In the upper part of the bracket, the footrest (8) is mounted at an angle of 100 degrees off the axis of the actuator (1) to ensure ergonomic positioning of the astronaut's foot during exercises. The device is equipped with holders (9) fastened to the hip arm (4) and the shin arm (5) to stabilize the lower limbs of the astronaut. The footrest has stiffening belts (10) that stabilize the foot [32].

Pneumatic drives have many advantages, including small size and light weight, resistance to overloading, contamination, humidity, and temperature, as well as negligible maintenance costs. These important advantages of pneumatic drives make them widely used not only in industry but

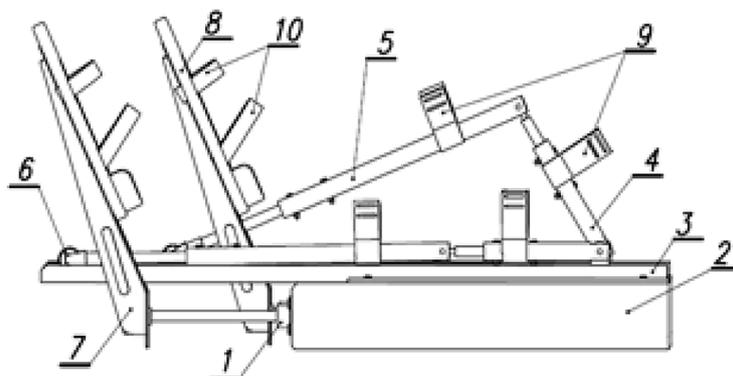


Fig. 1. A scheme of a pneumatic device for training lower bodily parts of astronauts: 1 – pneumatic actuators, 2 – case, 3 – guides, 4 – hip arm, 5 – shin arm, 6 – bearing, 7 – bracket, 8 – footrest, 9 – holders, 10 – stiffening belts [32]

also in various other fields [33]. The use of fluid propulsion elements in the exercise process is beneficial due to their characteristics similar to those of human muscles [34]. The advantage of the device is that the user can exercise both lower limbs simultaneously or alternately. In addition to increasing the strength and muscular endurance of astronauts, using the device depicted in Figure 1 also leads to the following benefits:

- Increased range of motion in joints through active movements.
- Improved joint stabilization through proprioceptive reduction.

During the exercises, the astronaut’s body must be positioned correctly. After settling into the chair and placing their limbs (as shown in Fig. 1) in the hip arm, shin arm, and footrest, the astronaut secures their upper body with belts and fastens

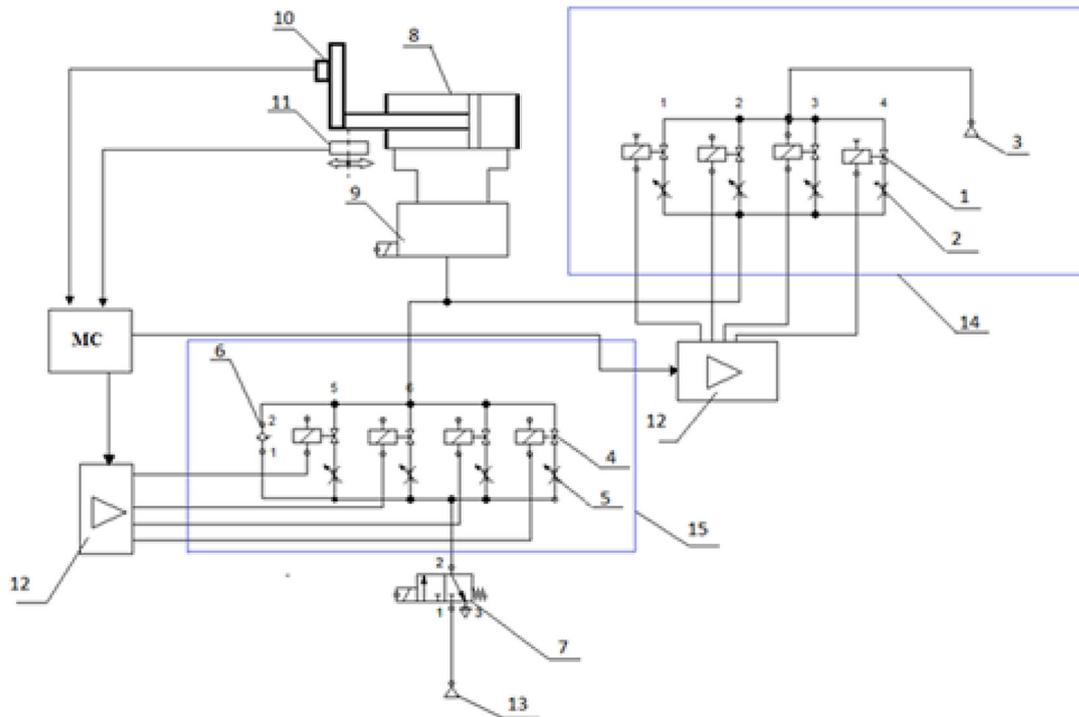


Fig. 2. A scheme of the pneumatic actuator steering system. Numbers refer to the following: 1 – group of solenoid valves of the auxiliary system, 2 – group of throttle valves of the auxiliary system, 3, 13 – power pressure, 4 – group of solenoid valves of the main system (A), 5 – group of throttle valves of the main system, 6 – non-return valve, 7 – solenoid valve (D) 3/2, 8 – double-acting cylinder, 9 – solenoid valve (C) 5/2, 10 – tensometer, 11 – potentiometer converter, 12 – power module, 14 – group of auxiliary solenoid valves (B), 15 – group of main solenoid valves (A)

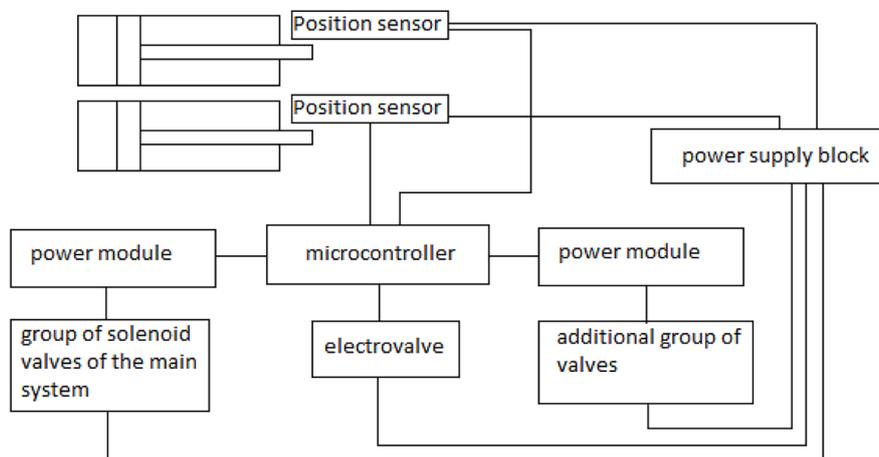


Fig. 3. Mechatronic control of the pneumatic drive

belts on the upper part of their foot. Throughout the training, the torso must remain in a stable position in the chair.

The following training forms on the device for astronauts are suggested:

1. Pushing exercises – both limbs are trained simultaneously as the feet press (push) upon the footrest.
2. Pull exercises – both limbs are trained at the same time as the feet pull the footrest towards the body.
3. Mixed exercises – one foot pushes, the other foot pulls the footrest.

The steering system plays a key role in the device depicted in Figure 1. The scheme of the system steering the pneumatic actuator is shown in Figure 2. The novelty of the circuit shown in Figure 3 is that potentiometric sensors are connected to the microcontroller. Based on the readings of the values from

the sensors during the movement of the piston rods, the microcontroller calculates the speed of the drive movement. The microcontroller implements switching on or off a group of main (A) or auxiliary (B) solenoid valves by feeding a binary combination.

Strength analysis of the developer designs

The designed model was analyzed for strength using Ansys 2021 R1 software [35, 36]. The boundary conditions (shown in Figure 4) adopted for the strength analysis of the devices were selected based on the loads encountered during exercise. For the strength verification of the device, the load for the thigh arm and shin arm was assumed to be 1.2 times the weight of a human weighing 80 kg, according to the human anthropometric atlas [37, 38]. For the analysis of the model, the following



Fig. 4. Boundary conditions

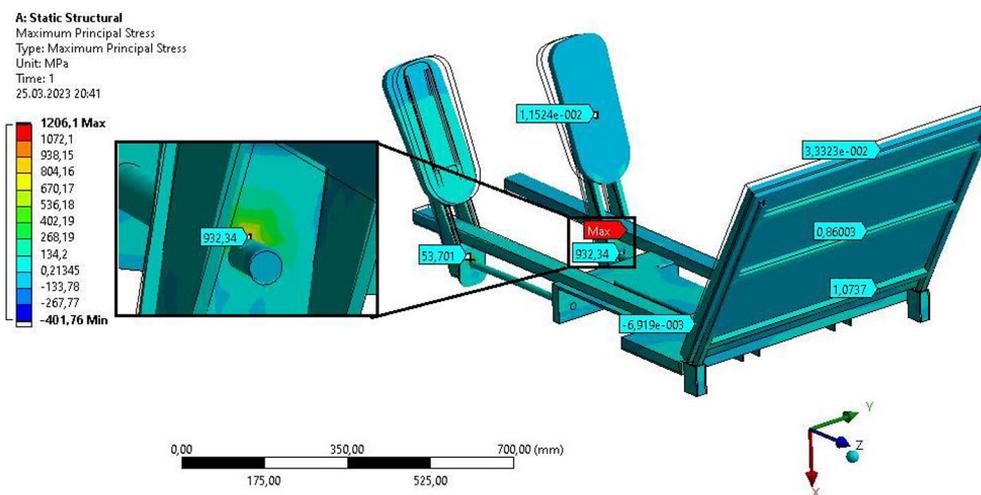


Fig. 5. Principal stress distribution

materials were used: S235 steel for the frame of the device, polycarbonate for the flat elements of the seat and the footrest, and PVC foam for the seat and backrest. The results obtained from the strength analysis in Ansys Mechanical software are presented in the figures below. The model had 353,446 mesh nodes and 702,352 elements.

Figure 5 shows the principal stress distribution, detailing the maximum stress value. As shown in Fig. 5, the maximum stress is 932.24 MPa, which is distributed between the drive piston rod and the device support. The obtained results of the numerical analysis will help in the correct evaluation and selection of the geometric and material parameters adopted for manufacturing the prototype.

Pull exercises

Figure 6 illustrates exercising both limbs at the same time, where the astronaut pulls the

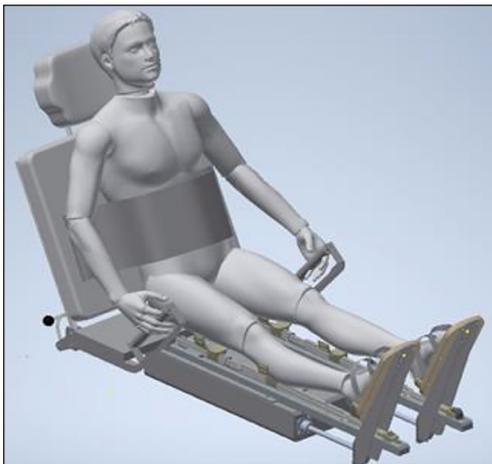


Fig. 6. Pull exercises – the feet pull the footrest towards the torso. Training for both feet At the same time

footrest towards their body with both legs. As the astronaut performs the movement of pulling the feet towards the body, they bend their legs at both the knee joints and hip joints.

While the astronaut draws the leg towards the torso (Fig. 2), the solenoid valve C is switched on, causing the reversing of the actuator towards the position opposite the exercising person. Then, group A of main solenoid valves is activated. The air is released to the atmosphere through venting of solenoid valve D. As soon as the piston reaches maximum retraction (when the leg completes its movement) solenoid valve C is activated. Then, valve D activates power pressure, which causes movement of the piston in the direction opposite to the training astronaut (the piston extends). During the course of passive exercises, if it is necessary to regulate the speed, the group of auxiliary valves (B) may be activated.

Pushing exercises

Both legs are supposed to be trained simultaneously. Pushing the footrest with both feet, moving them away from the body, the astronaut tries to straighten both the knee and hip joints.

During the exercise shown in Figure 7, the extended piston of the actuator causes extension of the leg, triggered by the activation of solenoid valve 3/2 C. The extension movement of the piston of the actuator is controlled by a group of valves of the main system A. Air is released to the atmosphere through the solenoid valve D. Then, the group of auxiliary valves B is activated. After reaching the extreme position of the piston of the actuator (depending on the training astronaut) the

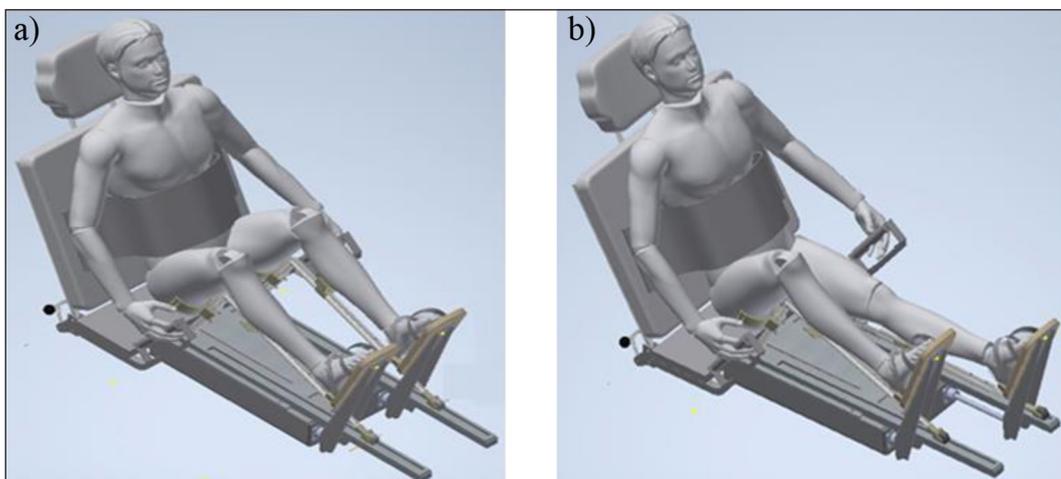


Fig. 7. (a) Pushing exercises – the feet press (push) the footrest. Training for both legs at the same time, (b) mixed exercises – one foot pushes, while the other pulls the footrest

solenoid direction valve C switches over. Subsequently, the solenoid valve D turns on the pressure causing quick motion of the piston towards the astronaut, back to the starting position.

If needed, during the training process, the auxiliary group of valves B can be activated. As the piston is moved towards the extreme position or to the retraction point, the solenoid valve C is activated for return motion (towards the astronaut). Then, the group of main solenoid valves A is activated, decreasing the flow of air at the exit of the actuator. The group of solenoid valves of auxiliary pressure B can operate at that point. Further on, the whole process is repeated.

Figure 7 illustrates the scenario when the astronaut pushes the footrest with one foot and pulls the footrest with the other foot. In addition to the parallel movements of both lower limbs there is a possibility of alternate movements. It means that one leg pushes, while the other pulls the footrest.

During the piston movement, its displacement is measured, and the microcontroller regulates the speed of the actuator piston's movement. The system works to counteract the force generated by the astronaut acting on the actuator piston, and also to counteract sudden changes in force generated by the astronaut. If the system is over-regulated, i.e. the piston moves too quickly, the control system increases the pressure in the central pneumatic circuit.

The authors of this paper intend to monitor physiological parameters and training loads using the presented device design. After conducting simulations and calculations, the authors plan to construct a prototype and test it.

CONCLUSIONS

Designing exercise devices used on a space station or during interplanetary flights requires the cooperation of physiologists, doctors, engineers, IT specialists and astronauts themselves. A pneumatic device for training lower bodily parts of astronauts was developed and presented. The steering system of the pneumatic actuator allows for cosmonauts to perform pushing, pulling, and mixed exercises.

Pneumatic exercise device use compressed air or gas as resistance, offering a different approach to traditional exercise equipment that relies on weights or gravity. One potential benefit of pneumatic exercise devices is their ability to provide

adjustable resistance without the need for heavy weights. Pneumatic systems can be designed to offer a wide range of resistance levels, allowing astronauts to tailor their workouts to their individual needs and fitness levels.

However, there are also challenges to consider when designing pneumatic exercise devices for space stations. These may include the complexity of pneumatic systems, the need for maintenance and repairs, and the potential impact on the overall cost and logistics of space missions.

Pneumatic exercise devices could be a worthwhile option for designing exercise equipment on space stations, offering adjustable resistance, compactness, lightweight, and potentially enhanced safety. Further research and testing are necessary to assess their effectiveness, feasibility, and overall value in supporting astronaut health and well-being during space missions.

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