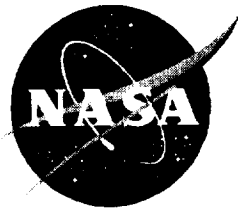


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Use of a Slick-Plate as a Contingency Exercise Surface for the Treadmill With Vibration Isolation System

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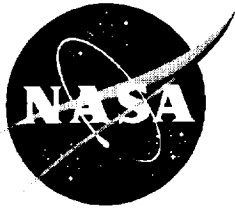
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February 2003

Dedication

This manuscript is dedicated to the memory of Patty C. Robertson.

“Keep watch over us dear friend.”

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Acronyms and Nomenclature

bpm	beats per minute
CES	contingency exercise surface
cm	centimeters
g	gravity
HR	heart rate
in	inches
ISS	International Space Station
JSC	Johnson Space Center
kg	kilogram(s)
mph	miles per hour
NASA	National Aeronautics and Space Administration
SLD	subject load device
SPD	subject positioning device
TVIS	treadmill with vibration isolation system
VIS	vibration isolation system

Abstract

The treadmill with vibration isolation system (TVIS) was developed to counteract cardiovascular, musculoskeletal, and neurovestibular deconditioning during long-duration missions to the International Space Station (ISS). However, recent hardware failures have necessitated the development of a short-term, temporary contingency exercise countermeasure for TVIS until nominal operations could be restored. The purpose of our evaluation was twofold: 1) to examine whether a slick-plate/contingency exercise surface (CES) could be used as a walking/running surface and could elicit a heart rate (HR) $\geq 70\%$ HR maximum and 2) to determine the optimal hardware configuration, in microgravity, to simulate running/walking in a 1-g environment. One subject (male) participated in the slick surface evaluation and two subjects (one male, one female) participated in the microgravity evaluation of the slick surface configuration. During the slick surface evaluation, the subject was suspended in a parachute harness and bungee cord configuration to offset the subject's body weight. Using another bungee cord configuration, we added a vertical load back to the subject, who was then asked to run for 20 minutes on the slick surface. The microgravity evaluation simulated the ISS TVIS, and we evaluated two different slick surfaces (Teflon surface and an aluminum surface coated with Tufam) for use as a CES. We evaluated each surface with the subject walking and running, with and without a handrail, and while wearing either socks or nylon booties over shoes. In the slick surface evaluation, the subject ran for 20 minutes and reached a maximum HR of 170 bpm.

In the microgravity evaluation, the subjects chose the aluminum plate coated with Tufam as the CES, while wearing a pair of nylon booties over running shoes and using a handrail, as the optimal hardware configuration.

The results indicate that the CES may provide an interim capability to counteract aerobic deconditioning until TVIS can be returned to an operational status. No indices of musculoskeletal or neurovestibular deconditioning were evaluated. Future studies are needed to validate the efficacy of CES in countering aerobic deconditioning and the effects, if any, on musculoskeletal and neurovestibular deconditioning.

Introduction

A treadmill with vibration isolation system (TVIS) currently is being flown on the International Space Station (ISS) as an exercise countermeasure device for spaceflight deconditioning, including loss of bone mineral density and muscle mass, decreased aerobic capacity, and neurovestibular disturbances associated with postflight ambulation (2,3). Recent hardware failures, such as the failure of the TVIS motor and the fracture of multiple slats of the treadmill belt, have necessitated the development of a contingency exercise substitute for TVIS.

TVIS operates similarly to a conventional nominal gravity on Earth (1-g) treadmill, but has three additional systems that differ from common treadmills. The subject load device (SLD) consists of two loading devices, each containing a cable, with each loading device and cable located on either side of the tread belt. The cables secure the user to the loading device via a harness and the loading device simulates the effects of gravity by applying a vertical load down the long axis of the body. The subject positioning device (SPD) prevents any forward or backward movement while running on the treadmill. The SPD centers the user

on the treadmill to optimize the operation of the vibration isolation system (VIS), the third system. The VIS isolates the treadmill to prevent any vibrations from being imparted into ISS. The user wears a shoulder/waist harness that has connection points for the SLD and the SPD just above the hip on the waist segment of the harness. Figure 1 illustrates the current TVIS.

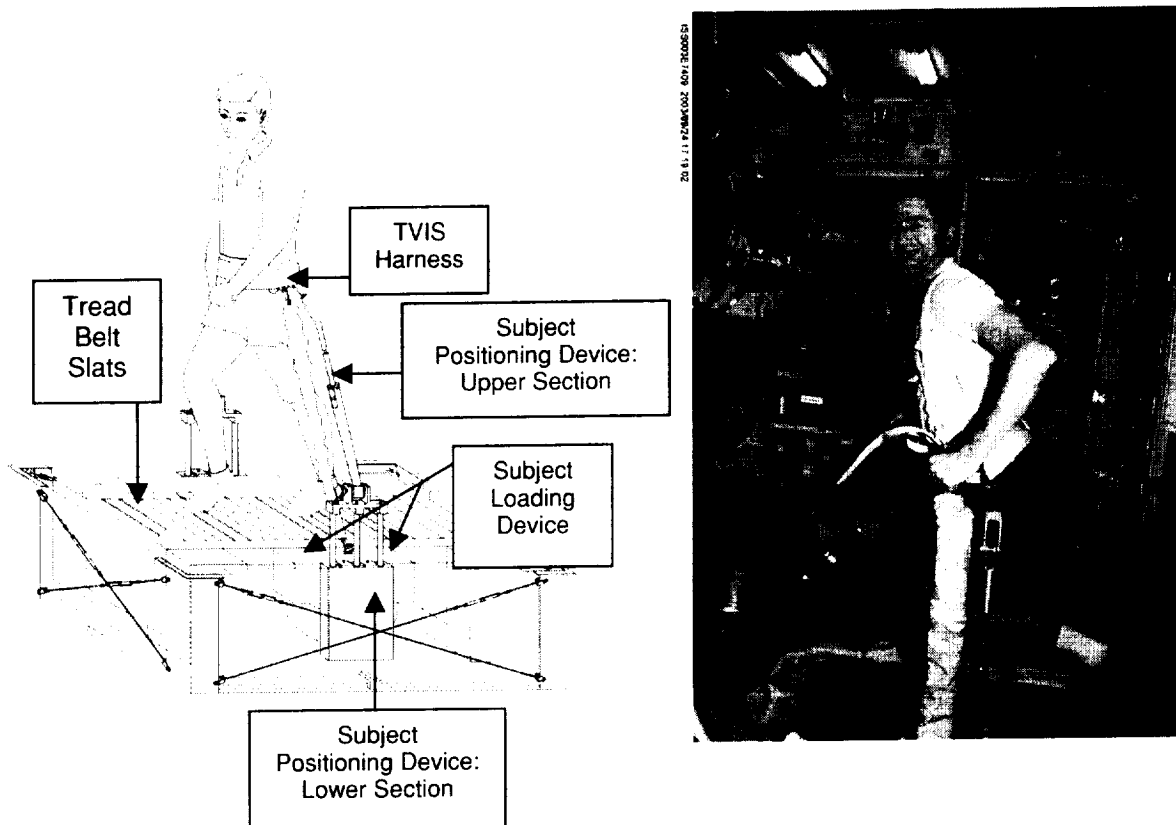


Figure 1: Treadmill with vibration isolation system

Previous spaceflight experience on Skylab 4 using a Teflon plate to simulate treadmill exercise suggests that a similar configuration may be a viable contingency option for ISS (9). The "treadmill" used during Skylab 4 consisted of a Teflon plate and four rubber bungee cords attached to a shoulder/waist

harness. The bungee cords exerted a vertical resistance of approximately 80 kg while simulating either uphill walking or running (9). The Skylab 4 crew noted several problems while using the Teflon plate as an exercise surface. First, the three crew members wore socks while exercising on the plate, and anecdotal remarks from the crew indicated that the friction between the socks and the plate caused the feet to feel uncomfortably warm. Second, due to the high loads placed on the lower limbs, especially in the calf, the crew experienced muscle fatigue after only a few minutes of exercise (9). Since the onset of fatigue was so rapid, the device could not be used for significant aerobic conditioning (9).

The purpose of this project was to evaluate the potential use of a slick-surface plate as a contingency exercise surface (CES) for ISS through investigating two main objectives. The primary objective was to establish whether a person could exercise on the slick-surface plate for at least 20 minutes at a workload sufficient to elicit heart rates (HR) of $\geq 70\%$ of age-predicted maximum HR (1). The secondary objective was to subjectively determine the configuration of the hardware, through subject comments and investigator appraisal, which would most closely simulate running or walking on a treadmill by examining the following configurations:

- a Teflon surface versus an aluminum surface coated with Tufram (Magnaplate, Linden, NJ)
- a handrail versus no handrail
- Nylon booties worn over shoes versus cotton socks worn over feet

Methods

Slick Surface Evaluation

To evaluate the primary objective, we performed the test in a ground-based procedure, rather than in microgravity, because of a lack of in-flight opportunities and the inability to simulate microgravity for 20 consecutive minutes. We used a parachute harness and bungee cords to simulate microgravity by unloading footward force as the subject was suspended in the harness system. Four bungee cords suspended the subject, simulating the unloading of microgravity (Figure 2). Based on a calibration curve for the cords, the estimated total load that all four bungee cords could displace was 145.5 kg. Therefore, the subject could not weigh more than 145.5 kg.

Subjects

One subject, a 27-year-old male, participated in the evaluation. The subject, a competitive runner who trained 30-35 miles per week, weighed 81.8 kg and was 178 cm tall. The Human Test Subject Facility at NASA-Johnson Space Center had previously medically cleared the subject to participate in this evaluation.

Experimental Configuration

We obtained a standard parachute harness (Pioneer Aerospace Corp., South Windsor, CT) and two D-rings from the NASA-Johnson Space Center Crew and Thermal Systems Division. At the top of a Safe Stress harness rack (Quinton Instruments, Seattle, WA), we attached two adjustable Nomex straps to

eyebolts, one strap per eyebolt, and then attached the free end of each Nomex strap to two bungee cords. We connected the free end of the bungee cords to a D-ring clamped around each shoulder strap of the parachute harness (Figure 2). Two 5/8-inch eyebolts were attached to the base supports of the Safe Stress rack and a bungee cord was clipped into each eyebolt, with the other end of the bungee cord attached to a second adjustable Nomex strap. Figure 2 illustrates the test setup.

We acquired a standard rehabilitation slide board and accompanying nylon booties from a Perform Better catalog (MF Athletic Co., Cranston, RI), fixing the slide board to the surface of a Quinton Q 65 Series 90 treadmill (Quinton Instruments, Seattle, WA) with standard C-clamps.

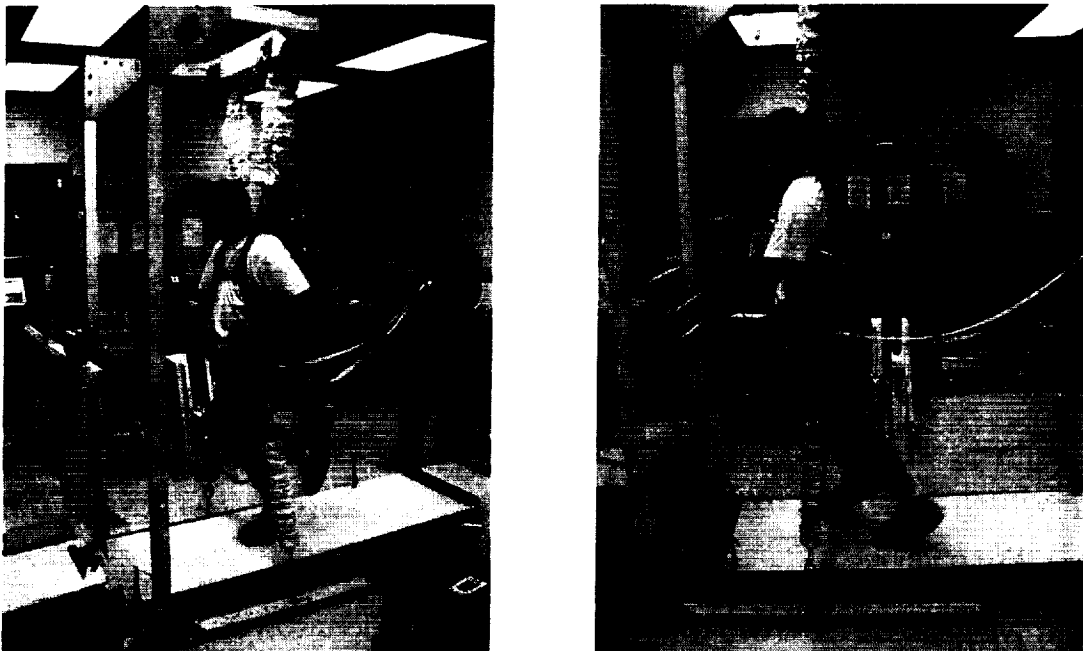


Figure 2: Test fixture design

Experimental Procedure

The subject placed the nylon booties over a pair of running shoes and was positioned in the parachute harness. We then clipped the second adjustable Nomex strap, attached at the base of the harness rack, into the parachute harness. Once the Nomex strap was attached to the parachute harness, the strap was pulled as tight as possible. The second adjustable Nomex strap and bungee cords simulated the SLDs on TVIS. Based on the stretch of the cords, the total load—estimated from a calibration curve—was between 68.2 kg and 77.3 kg. The height of the scale prevented us from measuring the actual weight of the subject in the harness system. When the scale was placed beneath the subject, the height of the scale provided enough of an elevated surface to allow the normal 1-g weight of the subject to be supported plus the load applied by the bungee cords.

The subject began running at a slow pace and, after 10 minutes, increased the number of strides and stride length, thereby increasing the intensity, to a self-reported normal training pace. The subject wore a Polar Vantage XL heart rate monitor (Polar CIC, Port Washington, NY) to provide heart rate values pre-exercise and during the final minute of exercise.

Slick Surface Configuration

Due to the lack of in-flight opportunities and the need to determine the optimal hardware configuration for use with CES during walking or running in microgravity, we evaluated the secondary objective using simulated microgravity during parabolic flight.

Subjects

Two subjects participated in the KC-135 flights, a male and a female. Subject #1, the female subject, was 38 years old, weighed 61.4 kg, and was 162.5 cm tall. Subject #2, the male subject, was 35 years old, weighed 81.8 kg, and was 167.5 cm tall. There were no fitness level restrictions to participate in this evaluation.

Experimental Design

Each subject participated in two flights, with each flight occurring on consecutive days and at the same time of day. Two flights were conducted per day. Subject #1 participated during the morning flights and subject #2 during the afternoon flights. We chose subjects according to height: the height of each subject had to be such that the distance from the floor to the subject's greater trochanter of the femur was less than the maximum extension of the upper telescoping section of the SPD, 92.5 cm (37 in.). The SPD is divided into two telescoping sections: the lower section mounts to the side of the treadmill and, when fully retracted, sits just above the TVIS platform, while the upper section mounts to the lower section at the point just above the surface of the TVIS. Due to hardware incompatibilities, we could not use the lower section of the SPD (Figure 3).

Parabolic Flight

Each flight consisted of four sets of 10 parabolas aboard NASA's KC-135 aircraft. The KC-135 is a specially modified Boeing 707 for parabolic flight. Each parabola consisted of three phases, each lasting approximately 20-25 seconds

(7,8). Phase 1 consisted of the “pull up,” which generated G-loads up to 1.8 G in the z-direction (head to toe). The second phase was the microgravity phase, or approximately 0.01 G. The third phase was the “pull out” phase, which generated G loads up to 1.8 G in the z-direction. The first and third phases occur consecutively and therefore constitute one period of hypergravity (+ G_z) (7,8).

Experimental Configuration

We designed the configuration of the test setup to emulate the ISS TVIS configuration. Each slick surface was attached to an aluminum plate simulating the attachment points where each surface would interface with the ISS TVIS. The remaining simulated ISS TVIS configuration comprised a handrail, attachment points for the SPDs, the SPDs, and attachment points for bungee cords. Bungee cords simulated the SLDs because the SLDs were unavailable for use during this evaluation. Subjects wore the TVIS harness and were loaded to approximately one bodyweight using the TVIS bungee cords to simulate ISS TVIS SLD configuration. Since the load the bungee cords provided could not be adjusted and the amount of stretch in the bungee cord will affect the load the cord provides, we estimated the loading of each subject based on a calibration curve. We were unable to verify the load due to similar measurement problems in the first part of this evaluation. The estimated total load, based on the calibration curve, was between 68.2 kg and 77.3 kg. These loads corresponded to approximately 111% - 126% of the female subject's body weight and 83% - 94% of the male subject's body weight. Figure 3 illustrates the KC-135 test setup.



Figure 3: KC-135 setup

Experimental Procedure

During the first flight, each subject tested the Teflon surface. Both subjects evaluated the aluminum plate coated with Tufam during the second flight. Tufam is a steel hard, dry-lubricated surface, which provides a smooth, slippery surface similar to Teflon. During each test, the subjects compared nylon booties versus cotton socks and handrail versus no handrail. See Table 1 for the test protocol. During flight, each subject performed walking, jogging, and running motions.

Table 1: Test Plan for KC-135 Evaluation

	Exercise Surface	With Hand Rail	Footwear
Day 1	Teflon plate	YES	nylon booties
		NO	nylon booties
		YES	cotton socks
		NO	cotton socks
Day 2	Aluminum plate	YES	nylon booties
		NO	nylon booties
		YES	cotton socks
		NO	cotton socks

At the conclusion of each flight, we instructed the subjects to write down all comments and observations and submit these remarks to the investigator(s). In order to accurately document flight activities, we videotaped all flights from a front and side view as well as from a roving camera.

Results and Discussion

Slick Surface Evaluation Results

The subject's initial resting HR, while standing in the test fixture, was 90 bpm. During the final minute of exercise, the subject's HR reached 170 bpm. The maximum HR achieved during the final minute of exercise was calculated to be 88% of age-predicted maximal HR ($220 - \text{age}$). The subject ran at this intensity for the final minute of the evaluation. The subject ran under the same load, between 68.2 and 77.3 kg, throughout the evaluation. The calculated

percentage of age-predicted maximal HR indicates that a sufficient training intensity may be achievable using a slick-surface plate (1). The subject reported that his resting HR of 90 bpm, while in the parachute harness, was higher than normal; he hypothesized this to be due to the stress of being in the parachute harness. The maximum HR achieved during the test was 5 bpm lower than the self-reported training HR of 175 bpm.

The subject performed a sustained run for 20 minutes. He increased the observed number of strides and stride lengths per minute at the 10-minute mark in order to increase the intensity of the run. Following the test, the subject indicated that, during the second 10-minute stage, he had achieved a near normal training intensity and could have maintained it for another 20 minutes. These results suggest that the CES may allow a person to perform long bouts of exercise while running in a contingency mode.

The following day, the subject reported muscle soreness in the hamstring and calf muscles. Unlike normal running, the muscle soreness experienced during CES running may have resulted from the unaccustomed resistance experienced during hip extension while drawing each foot across the running surface. One component thought to be important for maintaining bone and neuromuscular conditioning while running during spaceflight is the heel strike (4,5,6). The subject indicated that the CES provided little heel strike during ground testing.

Although not part of the evaluation, the subject commented that a handrail was necessary to stabilize posture while running on the slick plate. However, the subject also felt that, if his hips were stabilized thus simulating the SPDs on TVIS, he might have been able to run without relying on the handrail. The subject reported that the running-like motion was considerably less stable than running on a treadmill or overground; the subject felt off balance and on several occasions felt like a fall was imminent.

Slick Surface Configuration Results

Surface

Following the KC-135 flights both subjects reported that the aluminum plate coated with Tuftram provided a slicker surface than the Teflon plate. This was unexpected because Teflon has a lower static coefficient of friction, between the booties and the Teflon surface, than Tuftram and should have provided a slicker surface. Upon further investigation, we determined that the coefficient of friction of Teflon is dependent upon sliding speed. At running speeds of 5 mph, the Teflon coefficient of friction triples to about 0.24¹, whereas the coefficient of friction of Tuftram is 0.16 - 0.17².

The slickness of the surface seemed to play an important role in the subject's ability to move more freely over the top of the contingency surface. According to both subjects, the more slick the surface, the greater the range of motion that could be established. The greater range of motion allowed the

¹ Manufacturer's information, DuPont

² Manufacturer's information, General Magnaplate Corporation

subjects to increase the amount of heel strike, although still limited, and therefore maintain more normal ambulatory patterns. While running on the Teflon, Subject 2 felt the foot strike on the plate was in line with, or slightly ahead of, the long axis of the body. When the subject attempted to place the foot further forward, in a more natural location for running, the running motion was interrupted; the subject came to a stop and had to restart the running motion. While on the aluminum plate coated with Tufam, Subject 2 believed the foot was further forward from the body, allowing a more natural ambulatory pattern, while experiencing less stumbling or stopping. Both subjects stated the foot strike was in the mid- to forefoot region for both test surfaces. Both subjects felt the foot strike could be shifted toward the heel if the subjects concentrated on attaining a heel strike while running on the aluminum surface coated with Tufam.

Handrail

The subjects indicated the handrail was necessary for greatest comfort and control during exercise. Both subjects stated they could run without the handrail, but that they felt unstable and had difficulty maintaining a good running posture. When running with the handrail, both subjects leaned forward more than normal, a running posture similar to running uphill. Without the handrail, both subjects ran in a more upright position; one of the subjects compared the running gait to a “running in place, high-stepping motion.” The lack of a handrail against which to push forced the subjects to run upright to avoid falling forward. While running without a handrail, both subjects indicated they could not achieve heel strike and that their range of motion was limited or shortened due to the

feeling of instability. Subject 2 found that maintaining a body position in the center of the contingency surfaces was difficult, thereby changing the running technique. Subject 2 also noted that he was unable to achieve full hip extension without the handrail, most likely a result of trying to prevent slipping and falling. Also, the transition between running and walking motions without the handrail was more difficult than performing the same task with the handrail.

Footwear

Wearing booties with shoes during exercise was preferred to wearing just socks. Subject 1 was unable to notice a difference between the booties and the socks while running on the Teflon plate, but found that running in socks was much more difficult than in the booties on the aluminum plate coated with Tufram. The socks reportedly did not slide as easily over the aluminum plate coated with Tufram as did the booties. Subject 2 found that running in socks on both plates was uncomfortable and noticed a buildup of heat from the friction between the socks and the plates. Both subjects felt running in just socks would be difficult for a sustained period of time due to the discomfort induced by the foot impacting the CES surface repeatedly. One effect of wearing shoes with the booties was the cushioning of the foot to impacts with the slick plate. Although this would lessen the impact force on the heel, the subjects felt the cushioning would allow a person to run for a longer period. In general, the booties with shoes provided a protective barrier for the feet from the resultant friction heat buildup between the foot and the plate, and the booties provided a slick covering to slide across the CES surface.

In addition to the experimental design, each subject also attempted to walk or run on each CES with and without the SPDs. According to subject comments, the optimal configuration was to use the handrail with the SPDs. This configuration allowed the subjects to maintain balance, stay in the center of the platform, and perform walking and running-like exercise. When using the handrail and not using the SPDs, both subjects agreed that, when walking or running, the motion became unstable and it became difficult to maintain a near-normal gait pattern. Balance became difficult to maintain and an increased side-to-side motion began to develop. Neither subject was able to perform the correct running mechanics without the SPDs and without the handrail. The subjects were able to walk and run while using the SPDs with no handrail, but the motion became unstable and it became difficult to maintain a normal gait pattern. Again, a side-to-side motion developed similar to when the handrail was used without the SPDs. These results suggest that the SPDs might be necessary for crewmembers to exercise on either contingency surface with the correct running mechanics.

Summary

In the event of TVIS failure on orbit, the results of this investigation suggest that the CES could be used as a contingency countermeasure device in the following configuration: aluminum plate coated with Tuftram, with the SPDs, booties worn over shoes, and the use of a handrail for stabilization. The slick surface evaluation revealed that running on a slick surface was possible and a sufficient cardiovascular training intensity could be achieved. Whether this

training intensity could be maintained for a sustained period is unknown. Subject comments suggest the CES provided limited heel strike. Heel strike is thought to play a role in skeletal, neuromuscular, and/or neurovestibular deconditioning. If a TVIS failure occurs and contingency operations are employed, the CES potentially may provide a short-term, intermediate means to counter aerobic deconditioning until TVIS can be restored to nominal operation. Future evaluations should be conducted to evaluate the efficacy of CES on aerobic, musculoskeletal, and neurovestibular deconditioning during spaceflight.

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