CARDIOVASCULAR AND MUSCULOSKELETAL STRAINS REQUIRED TO MAINTAIN ASTRONAUT HEALTH AND PERFORMANCE DURING LONG-DURATION SPACE FLIGHT

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INTRODUCTION

Space flight causes cardiovascular deconditioning in humans, which is manifested by post-flight reduction of orthostatic tolerance and upright exercise capacity (1). During upright posture on Earth, blood pressures are greater in the feet *than* at heart or head levels due to gravity's effects on columns of blood in the body **(2).** During exposure to microgravity, all gravitational blood pressures disappear; and there is no exercise hardware currently available to provide these gravitational blood pressures in space.

Musculoskeletal loss is also experienced by crew exposed to space flight **(3,4).** Presently, exercise protocols and equipment for astronauts in space are unresolved (4,5), although recent calculations suggest that all exercise in space to date has lacked sufficient loads to maintain preflight bone mass **(6,7).** Although treadmill exercise with bungee cords (about **2** h per day) is the most common exercise for cosmonauts during long-duration Mir missions, biomechanical loads on musculoskeletal tissues of the lower body are only about **60-70%** of those present on **Earth (8).** Theoretically, an integrated countermeasure for extended exposure to microgravity should combine high loads on the musculoskeletal system **(6)** with normal regional distributions of transmural pressure across blood vessels **(2)** and stimulation of normal neuromuscular locomotor paflerns.

We have postulated that lower body negative pressure (LBNP) exercise may prevent bed rest- and niicrogravity-induced deconditioning by simulating gravity. Static ground reaction force **(GRF)** in a LBNP chamber is a product of the body cross-sectional area at the waist seal (A_{xy}) and the pressure differential between the external ambient and internal chamber environments ***(AP)***, where AP = LBNP:

$$GRF = A_{xy} \cdot AP$$

For the average male subject, **an** additional **GRF** of about one equivalent body weight (BW) is generated for each 100 mm **Hg** of LBNP when the negative pressure acts only through the cross-sectional area of the subject's waist (9). The LBNP exercise concept avoids the discomfort of localized high pressures typical of bungee cord harness systems by distributing the net force of the air pressure uniformly over the entire upper surface of the body. By expanding the area through which the pressure produces force, the amount of negative pressure required to generate one BW is decreased (10). For example, if the waist seal area equals twice the subject's waist cross-sectional area, the negative pressure necessary to produce one BW decreases from 100 mm Hg to approximately **53** mm Hg. The reduced negative pressure required to generate one BW of force lowers the risk of excessive footward fluid redistribution, syncope, hernia, and petechiae associated with higher levels of LBNP.

METHODS

Our strategy was to develop an exercise apparatus which induces cardiovascular and musculoskeletal strains equal to or greater than those on Earth without the need for a costly centrifugation apparatus. ***An*** LBNP chamber was designed to contain a treadmill upon which 8 male bed rest subjects could exercise daily in supine posture for 40 min at cardiovascular and musculoskeletal loads up to 120% of normal loads during similar exercise in upright posture on Earth (Figure 1).

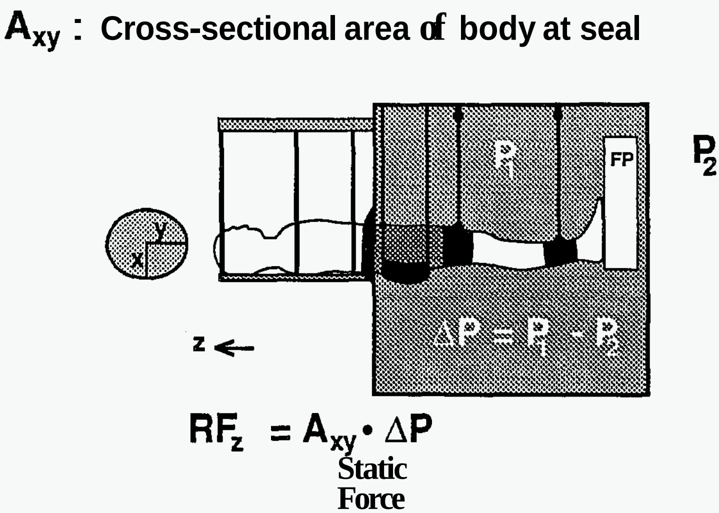

Figure I: Reaction force (RF_z) to generate body weight in supine posture equals the product of the cross-sectional area of the flexible waist seal (A) and the suction pressure (ΔP) **as** measured by a force plate (FP) within the LBNP chamber. With exercise, inertial RF_zs are added to the static force.

Eight normal male subjects were selected following a thorough medical examination to ensure their suitability for a safe and well-controlled study. Acceptable subjects were thoroughly briefed and provided informed, written consent before participating in this study. Subjects were randomly divided into two groups of four each. We undertook two 14 day bed-rest studies to investigate **the** mechanism of action and efficacy of our partial vacuum exerciser concept. These 14 day bed rest studies were chosen to simulate current microgravity exposures for Space Shuttle crew members. We examined the same ***8*** subjects in **both** 14 day bed rest (6° head-**down** tilt, HDT) studies, assigning 4 subjects to 40 nunutes of supine running exercise per day up to **1.2** BW of footward force (approximately 60 mm Hg **LBNP),** while the remaining 4 subjects constituted the non-exercise "control" group (Table 1). The interval exercise protocol was as follows: 7 min warm-up at 40% peak oxygen uptake, followed by 3 min at 60%, 2 min at 40%, 3 min at 70%, 2 min at 50%, 3 min at 80%, 2 min at 60%, 3 min at 80%, 2 min at 50%, 3 min at 70%, 2 min at 40%, 3 min at 60%, and 5 min cool-down at 40% peak oxygen uptake; 40 min total.

Three months after the first 14 day HDT study, the two groups were reversed so that the previous non-exercise group received the same 40 min of supine jogging per day up to 1.2 BW (approximately 60 mm Hg LBNP) while the previously-exercised group did not exercise during the 14 days of HDT (Table 1). This paired experimental design, where each subject is his own control, allowed for more powerful statistical comparisons. In addition to having the subjects act as their own control, both HDT sessions included a three day ambulatory control period to provide baseline data and a two day recovery period to monitor return of physiologic function.

Table 1: Overall Schedule for Two Bed-Rest Studies

	Study 1	3 Month Break	Study 2
Subjects			
Group I	NO EXERCISE (n=4)		EXERCISE (n=4)
Group II	EXERCISE (n=4)		NO EXERCISE (n=4)

All physiologic tests took place at the same time of day for a given subject. These tests were staggered so that sufficient time was allowed to complete the procedure. While the subjects lived in our Human Research Facility at NASA Ames Research Center, their diet was controlled (approximately 2500-3000 kcal per day, depending on exercise level) and their body weight, fluid intake, and urine output were monitored. During the entire period of bed rest, all subjects remained in 6° HDT except during periods for showers and exercise (0.5-1.5 h/day), when they were horizontal (0°). Pre- and post-bedrest tests of orthostatic tolerance, soleus muscle strength, coordination, gait, gastrointestinal function, and maximal oxygen consumption were used to assess the efficacy of this exercise countermeasure.

RESULTS

Although subjects with LBNP exercise maintained higher levels of fitness compared to those without exercise, not all performance parameters were maintained at pie-bedrest levels. Preliminary review of post HDT results indicate that orthostatic tolerance, as measured by supine LBNP tolerance, decreased as much in the exercise group (5.3 min less than pre-bedrest) as in the nonexercise group (5.0 min less than pre-bedrest) (not significant). However, sprint speeds were maintained in the subjects who exercised (5.5 m • sec^{-1} pre-bedrest and 5.2 m • sec^{-1} post-bedrest) but not maintained in the nonexercise subjects (5.5 m • sec^{-1} pre-bedrest and 4.6 m • sec^{-1}

post-bedrest) **($p < 0.05$).** Furthermore, exercise tolerance time was maintained in subjects exposed to the exercise **LBNP** countermeasure **(17.3 min** pre-bedrest and **17.2** min post-bedrest) but significantly reduced ($p < 0.05$) in the nonexercise group **(17.4 min** pre-bedrest and **15.6** min post-bedrest). **This** latter parameter may be a **more** important functional test to measure the astronauts' ability to escape their landing vehicle in case of an emergency.

CONCLUSION

LBNP exercise improves upon current spaceborne exercise technologies by supporting cardiovascular and musculoskeletal fitness while reducing the duration of astronaut exercise sessions.

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