NASA Conference Publication 3051

Workshop on Exercise Prescription for Long-Duration Space Flight

Proceedings of a workshop held at
Lyndon B. Johnson Space Center
Houston, Texas
1986

NASA

NASA Conference Publication 3051

Workshop on Exercise Prescription for Long-Duration Space Flight

Edited by
Bernard A. Harris, Jr.
and Donald F. Stewart
Lyndon B. Johnson Space Center
Houston, Texas

Proceedings of a workshop sponsored by the
National Aeronautics and Space Administration,
Washington, D.C., and held at
Lyndon B. Johnson Space Center
Houston, Texas
1986

NASA
National Aeronautics and
Space Administration
Office of Management
Scientific and Technical
Information Division
1989

Foreword: Exercise and Space Flight

The National Aeronautics and Space Administration has a dedicated history of ensuring human survival in space. Even before the Gemini Program, research exploring the effects of exposure to microgravity was conducted. We discovered that man could adapt to his new environment just as he has through the history of evolution. Space, however, represents yet another challenge which human beings must one day conquer in order to survive, work, and eventually live. The human dream of life in space has provided the motivation and the backdrop by which we shall venture into the galaxy.

Our concerns are no longer getting a man into space but determining how humans can live in space. What duration can man survive? What are the effects on the human body? The questions are endless and the answers will not be easy. Space flight provides a powerful stimulus for adaptation; i.e., cardiovascular and musculoskeletal deconditioning. Extended-duration space flight is expected to influence a great many systems in the human body. Previous in-flight studies have shown these effects of a weightless environment on the body. Analysis of the Skylab missions indicates greater reductions in physical fitness over time. Even when attempts were made to prevent this occurrence by various exercise regimens, the result was only a slowing of the deconditioning process. More importantly, these studies identified exercise as a potential preventive measure.

In order for us to travel beyond our world, we must understand the process by which the adaptation to space occurs. This understanding must be complete and all encompassing, defining the parameters of adaptation to the smallest levels. Understanding the human body on Earth has been a tremendous task and one which is continuous. Using this as our limited knowledge base, we must extrapolate and test the effects of zero g on the human body. This will be one of the most significant achievements in the history of medical science, and all eyes will be on this effort and its eventual outcome.

Currently, NASA is aggressively involved in developing programs which will act as a foundation for this new field of "space medicine." These programs will involve the monitoring of crew health, the provision of health care, and the adoption of measures which will retard or prevent the adverse effects of prolonged exposure to a microgravity environment. The hallmark of these programs is that which deals with the prevention of deconditioning, currently referred to as "countermeasures" to zero g. Until artificial gravity is produced and implemented for space flight, we will need countermeasures to address these problems. Exercise appears to be most effective in addressing both the cardiovascular and the musculoskeletal effects of microgravity. People and resources have been dedicated by NASA to understanding the physiology of exercise and its use as an effective countermeasure.

This document is a culmination of discussions from an exercise workshop at the NASA Lyndon B. Johnson Space Center. This workshop was composed of experts in physiology, exercise, cardiovascular, muscle, and bone disciplines from major universities and institutions in the Nation. They were charged to address the major questions of man's adaptation to a zero-g environment and to explore the usefulness of exercise as a countermeasure.

The first section of the report provides background information on the space program and NASA's efforts toward ensuring crew health. It also provides a comprehensive review of the various countermeasures used previously in the U.S. space program.

The second section is an examination of the physiological and biomechanical changes of exposure to microgravity through contributed papers.

The third section is the actual transcript from the workshop by author. In it, the comments and considerations of exercise countermeasures are addressed as they pertain to establishing a prescription for the astronauts to retard or prevent deconditioning and to preserve health.

In the fourth and final section, recommendations are offered for the various disciplines of muscle, bone, and cardiovascular systems as they relate to an in-flight exercise protocol. In addition, suggestions for an exercise regimen are offered by Drs. Thornton and Convertino. Finally, the recommendations of the workshop's participants are incorporated into a "proposed exercise prescription."

The proceedings from this meeting provide a comprehensive review of the physiology of exercise and recommendations on exercise countermeasures for adaptation to a microgravity environment. They will inform and highlight significant aspects of the ensuing problems of space adaptation.

Bernard A. Harris, Jr., M.D.

Contents

Section Page

1 INTRODUCTION

2 PHYSIOLOGICAL ASPECTS OF EXERCISE

SECTION 1

INTRODUCTION

(62)

N91-10575

526873

12P

U.S. Space Flight Experience: Physical Exertion and Metabolic Demand of Extravehicular Activity - Past, Present, and Future

Thomas P. Moore, M.D.
Department of Medical Research
Methodist Hospital of Indiana, Inc.
Indianapolis, Indiana

Extravehicular activity (EVA) has been part of the U.S. space program since the Gemini Program, when astronaut Edward White took the first space walk on Gemini IV in June of 1965 (ref.1). During the Gemini Program, five astronauts performed EVA's on five separate missions. Considerable difficulty was experienced by the crewmembers in performance of their EVA tasks. In fact, two of the EVA's had to be terminated before accomplishment of the EVA objectives because of overexertion and overheating problems. The crewmembers experienced elevated heart rates that peaked above 170 bpm, and, because of exhaustion and overheating, the astronauts could not complete their tasks (ref. 2). Some of the problems experienced could be attributed to the Gemini suit design. The Gemini space suit was designed to control astronaut body temperature with a cooling system that consisted of only a circulating gas system. The exchange of gas or oxygen being pumped into the suit was the only mechanism available to dissipate the heat produced by the astronaut. Although metabolic rates were not measured directly, it was obvious on several occasions that metabolic rates exceeded the thermal control and carbon dioxide washout capacities of the suit life-support system (ref. 3). With overheating, water vapor condensed on the inside of the helmet visor and thereby limited visibility and further added to the problems and frustration of the Gemini EVA crewmen. The suit was also found to be very stiff and cumbersome with limited flexibility about normal anatomical joint areas such as the elbow, the wrists, and the hands. Some of the Gemini EVA problems could also be attributed to the limited one-g EVA training provided the Gemini astronauts. No underwater training was available until prior to Gemini XII, the last Gemini EVA mission.

Physiologic monitoring of the Gemini EVA astronauts was by way of a one-lead electrocardiograph with heart rate being the only parameter recorded. Table I is a summary of the Gemini EVA missions and heart rates of the crewmen. The problems encountered with the Gemini EVA's led to considerable concern regarding future EVA's. It was realized that adequate body restraints, realistic preflight zero-g simulation training in a water tank, and detailed preplanning of activity were essential to ensure task performance and to reduce fatigue (ref. 5). The Gemini experience also led to the development of what is called the liquid-cooling garment

TABLE I.- GEMINI EVA EXPERIENCE

[From ref. 4]

Flight	Experience	Duration, hr	Heart rate, bpm	
			Mean	Peak
Gemini IV	Overheating during hatch closing; objectives completed	0.60	155	175
Gemini IX	Visor fogging; hot at ingress; objectives not completed	2.11	155	180
Gemini X	No problem with heat or work rate; objectives completed	.65	125	165
Gemini XI	Exhausting work; no specific mention of heat; objectives not completed	.55	140	170
Gemini XII	Good restraints; no problems; objectives completed	2.10	110	155

(LCG). The LCG is a set of full-body long underwear with a closed system of flexible tubes sewn into it. The tubes are part of a circulating system that allows liquid to flow through the underwear, providing a cooling mechanism. The astronaut can control the relative temperature of the garment and his temperature by controlling the flow of this cooling liquid.

In planning ahead for Apollo, the primary objective was to land safely on the Moon and explore its surface during a series of lunar EVA's. During the Apollo Program, 6 lunar surface missions and 14 EVA's were accomplished (ref. 6). The metabolic rates from the lunar EVA's are shown in table II. The metabolic rates are presented for four different task categories - (1) scientific package deployment, (2) geological station activity, (3) overhead activity such as working around the lunar module and ingress and egress activity, (4) lunar roving vehicle (LRV) operations - and for all activities, which is an overall average for the entire EVA. The average metabolic rate in kilocalories per hour for the scientific deployment was 244; for geological station activity, 244; for overhead activity, 270; for LRV operations, 123; and for all activities, an average of 234 (ref. 7). As can be noted, driving around the lunar surface in the LRV was by far the least stressful activity.

There are basically three methods for obtaining metabolic rates during EVA. The first method utilized was that of the liquid-cooling garment, which provided essentially a calorimeter to measure heat production. By knowing the amount of body heat produced by an astronaut and taken up by the suit LCG, one can then convert the heat to a metabolic rate. Secondly, there were the oxygen bottle pressure gauge readings. They allowed determination of oxygen utilization from the pressure differentials recorded during the time the astronaut was breathing oxygen on the EVA suit system. Astronauts would also do space-suit familiarization runs on the ground in one g prior to the mission in which a graph of the relationship between oxygen uptake and heart rate would be plotted. Investigators could then look at the EVA heart rate and get some estimation of the corresponding metabolic rate. For the tables illustrated, a combination of the temperature and the oxygen pressure differential methods was used.

It should be noted that the overall average lunar EVA metabolic rate of 234 kcal/hr is actually lower than that anticipated by investigators on the basis of Gemini experience. The EVA crewmembers' heart rates generally ran in the 100- to 110-bpm range for normal activities and would occasionally increase to the 150- to 160-bpm range during especially strenuous activity such as lunar core sampling and Moon rock collection. None of the EVA crewmen had significant complaints about the difficulty of performing lunar EVA. On a couple of occasions, Mission Control had to tell the astronauts to slow their work rates because of increasing heart rates. Other than these minor precautionary measures, there were essentially no complaints or problems with the crewmembers' ability to perform, nor with their performance of, the Apollo lunar EVA's.

Crewmembers also performed zero-g EVA's during Apollo missions. The metabolic rates from Apollo zero-g EVA's (ref. 7) are listed in table III. The zero-g EVA's were primarily to obtain film canisters from the lunar module before it was released and the crew returned to Earth in the Apollo entry vehicle. On these EVA's, one person basically stood in the hatch and observed while the other EVA crewmember obtained the film canisters. The consistent differential in the metabolic rates of the two crewmembers reflects the different activity levels as can be noted from the table. The zero-g EVA metabolic rates were also well within comfortable metabolic working limits, and there were no complaints nor any reported difficulty in performing the EVA's. The Apollo zero-g EVA's were of relatively short duration, lasting an average of 63 minutes.

In 1973, the United States launched the Skylab orbital workshop (OWS), a man-tended orbiting scientific laboratory. To date, it has been our only experience in long-duration space flight. On the three Skylab missions, SL-2, SL-3, and SL-4, astronauts manned the OWS for a duration of 28, 59, and 84 days, respectively. During the Skylab Program, 10 EVA's were performed. A number of the EVA's were for film canister retrieval, similar to those on Apollo. However, a few were performed for unexpected manual repair of the spacecraft and experiments; for example, deploying jammed solar array panels, erecting a solar umbrella, and repairing an Earth resources antenna. Some of the Skylab EVA's occurred very late in the mission just prior to the crew's return. Table IV contains an overview of the metabolic rates from the Skylab EVA's. Again, a number were film retrieval EVA's, wherein one person would stand in the hatch and watch the other person retrieve film. This activity difference is readily apparent from the table by the differential in metabolic rates between paired EVA crewmen; as, for example, EVA's 2, 3, and 4 on SL-4.

In discussions with Skylab EVA astronauts Joseph Kerwin, science pilot on SL-2, Owen Garriott,

TABLE II.- METABOLIC EXPENDITURES DURING APOLLO LUNAR SURFACE EVA'S

Apollo mission	EVA no.	Crewmen	Metabolic rate, kcal/hr					EVA duration, hr
			Experiment deployment	Geological station activity	"Overhead"	LRV operations	All activities	
11	1	CDR[a]	195	244	214	None	227	2.43
		LMP[b]	302	351	303	None	302	2.43
12	1	CDR	206	243	294	None	246	3.90
		LMP	240	245	267	None	252	3.90
	2	CDR	None	218	215	None	221	3.78
		LMP	None	253	248	None	252	3.78
14	1	CDR	182	294	219	None	202	4.80
		LMP	226	174	259	None	234	4.80
	2	CDR	118	238	213	None	229	3.58
		LMP	203	267	231	None	252	3.58
15	1	CDR	282	275	338	152	277	6.53
		LMP	327	186	293	104	247	6.53
	2	CDR	243	293	287	149	252	7.22
		LMP	265	189	266	99	204	7.22
	3	CDR	261	242	311	138	260	4.83
		LMP	230	188	234	106	204	4.83
16	1	CDR	207	216	273	173	219	7.18
		LMP	258	268	275	159	255	7.18
	2	CDR	None	223	249	112	197	7.38
		LMP	None	244	236	105	209	7.38
	3	CDR	None	231	235	124	204	5.67
		LMP	None	242	264	103	207	5.67
17	1	CDR	285	261	302	121	275	7.20
		LMP	278	300	285	113	272	7.20
	2	CDR	None	261	302	121	207	7.62
		LMP	None	300	285	113	209	7.62
	3	CDR	None	261	302	121	234	7.25
		LMP	None	300	285	113	237	7.25
Mean			244	244	270	123	234	
Total time, hr			28.18	52.47	52.83	25.28	158.74	

[a] CDR = commander.
[b] LMP = lunar module pilot.

TABLE III.- APOLLO ZERO-G EVA'S

Flight	Crewman	Metabolic rate, kcal/hr	Duration, min
Apollo 9	Schweickart	151	59
Apollo 15	Worden	<237	40
	Irwin[a]	<117	40
Apollo 16	Mattingly	<504	85
	Duke[a]	(b)	85
Apollo 17	Evans	<302	67
	Schmitt[a]	<143	67
Total time			443

[a] Standup EVA.

[b] Not measured.

SL-3 science pilot, and Gerald Carr, commander of SL-4, it was learned that all believed there was no significant increased difficulty in doing EVA's late in the mission. With their in-flight exercise program, they felt they had maintained sufficient physical conditioning such that the late mission EVA's did not present any unexpected difficulties.

Part of the improvement in EVA capabilities was attributable to improved ground-based one-g training. After the Gemini experience, training facilities and programs were developed utilizing large, specially designed water tanks. The astronauts donned their actual space suits and performed simulated EVA procedures underwater. The existing underwater training facility at the NASA Lyndon B. Johnson Space Center in Houston, Texas, is a 60-foot pool named the Weightless Environment Training Facility, or WETF. The use of the WETF remains today as the primary training method for astronauts preparing for Space Shuttle EVA's. The astronauts are

TABLE IV.- SKYLAB EVA METABOLIC RATES[a]

Skylab mission	EVA no.	Duration, hr	Metabolic rate, kcal/hr		
			CDR[b]	PLT[c]	SPT[d]
SL-2	[e]1	0.61	None	330	260
	2	3.38	315	None	265
	3	1.56	280	None	None
SL-3	1	6.51	None	265	240
	2	4.51	None	310	250
	[e]3	2.68	225	None	180
SL-4	1	6.56	None	230	250
	2	6.90	155	205	None
	3	3.46	145	None	220
	4	5.31	220	None	185

[a] Total time - 81.4 hours; mean metabolic rate - 238.42 kcal/hr.

[b] CDR = commander.

[c] PLT = pilot.

[d] SPT = science pilot.

[e] Gas cooling only.

weighted in the water tank so that they are neutrally buoyant, but differences still exist between conditions in the WETF and actual zero-g conditions. Since gravity is still present, if a subject turns upside down, blood still rushes to his head and he will fall to the top of his suit; however, he remains neutrally buoyant and free-floating. Another noticeable difference exists in the viscosity of the water as compared to the absence of any in the vacuum of space. In the WETF, the astronauts quickly learn to work within nature's physical law relative to neutral buoyancy and weightlessness. For example, they learn that if they apply a force to or torque against an object without themselves being restrained, they will rotate instead of the object they are trying to turn. The astronauts all relate that there is a definite learning process involved in WETF EVA training that correlates with actual EVA work in zero g. It is recognized that a difference in the ease with which astronauts perform nominal EVA's is related to the amount of preflight WETF suit training accomplished. The U.S.S.R. cosmonauts were actually the first to use a water tank to train for EVA, and they continue to use it today as their primary EVA training facility.

The EVA suits have been greatly improved since the Gemini Program. Engineering design improvements and the use and development of advanced materials and fabrics have resulted in increased suit flexibility, mobility, and visibility. The current suit design has positive 4.3-psi differential pressure relative to the outside environment (ref. 8). In the pressureless vacuum of space, the astronauts' suits are therefore pressurized to 4.3 psi. Consequently, because of the pressure differential with the outside environment, the suit, like an expanded balloon, will seek and take the position of least resistant tension. Hence, the astronauts' extremities will tend to assume an extended position when relaxed. To bend or flex an arm or a finger, the crewmember must bend against the suit pressure that tends to maintain an extended position. Consequently, in order to remain in any other position, the astronaut has to maintain active isometric muscle contraction. The EVA suits have joints in the fingers and at the wrists, the elbows, and the shoulders, but no joints below the waist. A lot of "hands on" training is involved in learning how to use and work with the suit to avoid expending wasted energy in what amounts to fighting the suit. Because of the described tension developed by the pressure of the suit, the EVA crewmembers' upper extremities are required to be working almost constantly either in active movement or in an isometric contraction mode.

In the Space Shuttle Program, the first EVA took place on the STS-6 mission in April 1983 The primary purpose of the first Space Shuttle EVA was to demonstrate EVA capability and to evaluate the function of the suit and various tools and restraint devices. At all times during EVA, the astronauts are tethered or attached to the Orbiter. They hook themselves to a small cable tether that is attached to a slidewire running down both sides of the Orbiter payload bay. On STS-6, the tether provided about 1 pound of pull or reeling-in force, which the EVA crewmembers found annoying and uncomfortable in the weightless environment. Conversely, during the preflight training in the WETF, the 1-pound pulling force had been hardly noticeable because of the viscosity of the water, illustrating the difference between one-g training and the actual zero-g experience. Since the STS-6 EVA, the reeling force of the tether has been reduced.

There have been a number of different and varied Space Shuttle Program EVA mission objectives. The purpose of STS 41-C, the third Space Shuttle EVA mission, was to rendezvous with and repair the Solar Maximum Mission satellite (Solar Max) utilizing the manned maneuvering unit (MMU). The MMU is a self-contained backpack that allows the astronaut to propel and maneuver himself untethered away from the Orbiter by use of the MMU gas jets. The mission plan was to rendezvous with Solar Max, fly with the MMU to the satellite, dock with the satellite, bring it back to the payload bay, repair it, and return it to space. Because of blueprint errors in the docking port on Solar Max, astronaut George Nelson was not able to dock and attach to it. Consequently, astronaut Terry Hart, operating controls from inside the Orbiter, literally had to grab the satellite in midair with the use of the remote manipulator arm. The satellite was then placed inside the payload bay, and the EVA astronauts went back out to repair it. To repair the satellite, they had to change out a small control panel, which meant fairly fine movements of their hands and fingers. Because of the EVA suit pressure exerting a force tending to open or extend the fingers, considerable concentrated effort is required in doing fine manipulative work on EVA. From attempting to dock with a large orbiting satellite to performing fine manual repairs, the STS 41-C mission is a good example of the differences in the type of work EVA astronauts have to perform.

Space Shuttle mission STS 51-A, the first satellite retrieval mission, further demonstrated the varied and valuable capabilities of EVA. Because of upper stage rocket firing malfunctions, two satellites launched on a previous Space Shuttle mission did not achieve the required altitude for geosynchronous orbit. If left as they were in low Earth orbit, the satellites would have eventually fallen into the Earth's atmosphere and would have been destroyed. The mission plan of STS 51-A was to retrieve the satellites, secure them in the payload bay, and return them to Earth for repair and reuse. For the satellite retrieval, the astronaut flew the MMU with a "stinger" mechanism attached to the front of it, impaled the rocket nozzle end of the satellite, and, with a spring-loaded grapple mechanism, latched on to the spinning satellite. The mission plan then had the astronaut fly the MMU with the attached satellite back to the Orbiter payload bay. Next, the original plan called for the second EVA astronaut to attach a holding mechanism to the other end of the satellite. From this holding device, the Orbiter remote manipulator would hold the satellite while a mounting platform was placed on the other end of the satellite. The satellite would then be placed, mounted, and secured in the Orbiter payload bay. Again, because of blueprint error, the planned holding mechanism would not fit on the satellite and consequently the EVA crewmen were not able to attach it. The crew therefore had to improvise a plan, which required that the astronaut hold the satellite in his hands while the mounting platform was bolted in place. The satellite weighed 1500 pounds on Earth but was weightless in zero g. It still had 1500 pounds of mass, however, and the laws of physics and inertia remain valid in zero g; that is, any movement imparted to the satellite would then have to be counteracted in order to stop its motion. Consequently, astronaut Joseph Allen, who at 5 feet 4 inches and 135 pounds was the smallest male astronaut, had to maintain the ability to hold and maneuver the satellite into position while the other EVA astronaut, Dale Gardner, worked on the other end attaching the mounting platform. Any uncontrolled satellite movement had the potential consequence of striking and possibly damaging the Orbiter. Allen had to maintain the satellite positioning for more than one revolution of the Earth, or approximately 100 minutes, while Gardner performed his tasks. Actually, Gardner's duties were probably more physically demanding in that he had to ratchet on nine bolts attaching the mounting platform to the bottom of the satellite so that it could then be secured into the payload bay. The experience encountered on this mission, as with the previously described Solar Max repair mission, demonstrates that EVA missions are not always nominal and that the human capability to improvise is very important. However, the experience on this mission also demonstrates that unexpected problems can add to the physical as well as the mental stresses involved during EVA and that the astronauts should be properly prepared to deal with them.

Figure 1 is a graph of the heart rates of the astronauts during the second STS 51-A EVA. The duration of this EVA was 5 hours and 45 minutes. The astronaut, Allen, who performed the isometric-type exercise of holding the satellite is represented as EV1, the solid line. Gardner, who was responsible for ratcheting down the bolts to secure the satellite, is EV2, or the dashed line. On the graph, the areas of absent data are due to what is called LOS, loss of signal, where no data are received while the Orbiter is outside the range of the receiving stations. It is evident that astronaut Gardner consistently had the higher heart rate during the EVA. As can be noted on the graphs, for a considerable amount of time, his heart rate is elevated above 100 bpm with a maximum of 168. Heart rate was recorded for 3 hours and 55 minutes of the EVA. For approximately 1 hour and 40

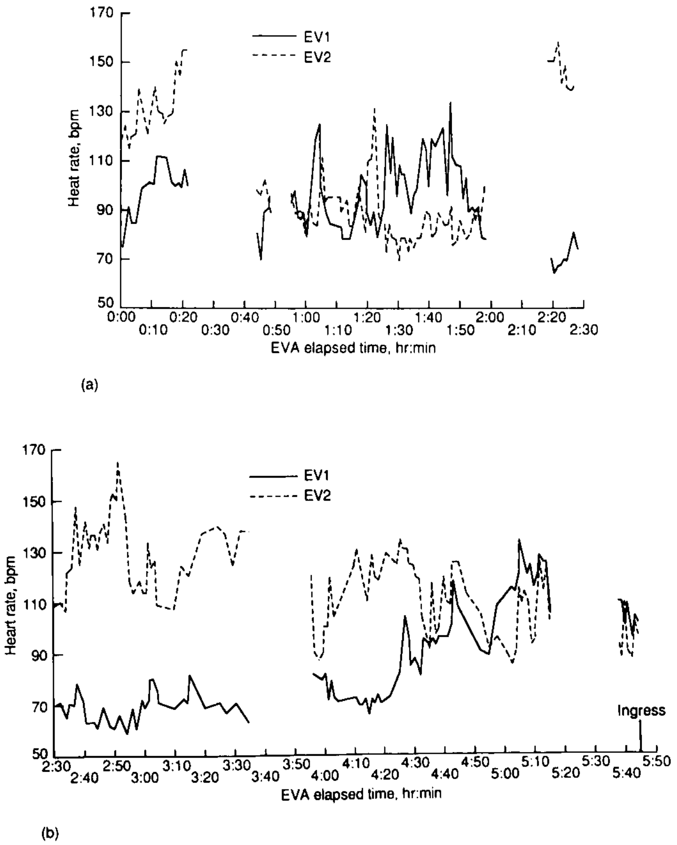


Fig. 1.- Heart rates of crewmen EV1 (solid line) and EV2 (dashed line) during second STS 51-A EVA. (a) 0:00 to 2:30 elapsed time. (b) 2:30 to 5:50 elapsed time.

minutes, or 43 percent of the EVA time, astronaut Gardner's heart rate was greater than 65 percent of his maximum heart rate, 120 bpm. Again, when considering the overall physical demands involved, the 5-1/2-hour duration of the EVA should be considered.

The two latest EVA missions, STS 51-I and STS 61-B, are also examples of physically demanding and strenuous EVA's. On STS 51-I, there were two EVA's, with the objective once again being a satellite rendezvous and retrieval with repair of a 15 000-pound satellite. The satellite, called LEASAT, launched 4 months earlier on STS 51-D, had failed to activate and fire its rocket engine upon release from the Orbiter. On STS 51-D, in an attempt to activate it, two astronauts performed the first unplanned EVA in the U.S. space program. For the STS 51-D EVA, a "flyswatter" device was devised and fabricated by the crew on orbit and attached to the Orbiter remote manipulator arm by the EVA astronauts. The arm, with the attached flyswatter, was then used in an attempt to trip the activation switch on the satellite. Although there was good capture of the switch by the use of the flyswatter, activation of the satellite did not occur, an indication that the problem probably was a malfunctioning activation switch. As with the satellites on STS 51-A, LEASAT was in a low Earth orbit and would eventually be lost if it were not repaired. The STS 51-I EVA mission plan called for astronaut James Van Hoften, who is 6 feet 2 inches tall and weighs about 210 pounds, to stand anchored on the end of the Orbiter remote manipulator arm and physically grab the 15 000-pound satellite. He then had to maintain his grip on it, stop its approximate 1 rpm spin, and hold it in position while astronaut William Fisher assisted in securing it. The remote manipulator arm was used to place the satellite in the payload bay, where it was then repaired by the EVA crewmen with the replacement of the faulty activation switch. Finally, astronaut Van Hoften manually spun the satellite and physically placed it in orbit.

To compound the problems of this EVA, the Orbiter remote manipulator arm was not functioning in its computer-assisted mode. This meant that the arm did not move smoothly, making it difficult to easily control the satellite. It abruptly moved and abruptly stopped so that astronaut Van Hoften had to exert additional force in overcoming inertia in moving the satellite and then in stopping it. As mentioned previously, the satellite had 15 000 pounds of mass and to quote Van Hoften, "We planned for the mission for 4 months, I knew it was going to be difficult, and I was ready for it and it was even more difficult than I thought it was going to be." He said that just the "grunting and groaning" of trying to move the satellite into proper position for astronaut Fisher compounded by the manipulator arm not working in its computer-assisted mode presented a significant challenge. When asked to give some indication on the Borg perceived exertion scale of 6 to 20 what level of exertion he felt he experienced, he stated that cardiovascularly, it was not that stressful. However, from a muscular standpoint, he rated the EVA at about a 17 or an 18 on the scale. On the next EVA, which took place the following day, the crewmembers changed out the activation switch on the satellite and replaced it with a new one. Then, to launch the satellite, Van Hoften again literally had to manhandle the satellite using a grip bar the astronauts had attached to its side. To provide some gyroscopic stability to the satellite, he had to spin it up to 3 rpm and release it. Van Hoften stated that just trying to spin the massive satellite so as to prevent contact with the Orbiter as well as to maneuver it into the correct position was physically very demanding. When at a safe distance from the Orbiter, the new switch was activated successfully, firing the satellite booster rocket and taking it to a geosynchronous orbit.

The last Space Shuttle EVA mission to date was STS 61-B, during which the EASE/ACCESS experiment was performed. The EVA's basically were construction engineering EVA's wherein the astronauts tested the ability to build structures in space similar to those anticipated on Space Station. The Assembly Concept for Construction of Erectable Space Structures (ACCESS) experiment was in simplistic terms very similar to a space-age erector set. The astronauts would assemble 93 stowed tubular aluminum struts into a three-sided truss that snapped together at nodes or junction points. After the 45-foot ACCESS assembly was complete, the astronauts tested their ability to maneuver and rotate the structure in the weightless environment. The Experimental Assembly of Structures in EVA (EASE) experiment was a series of six 12-foot beams that were assembled into a tetrahedron. During the first EVA, the astronauts did EASE while free-floating rather than being secured or anchored. One astronaut, the high man, would be free-floating and the other astronaut would be down below in the payload bay workstation. The low man would pull out one of the beams and transfer it up to the free-floating astronaut, who would then assemble the tetrahedron. Both crewmembers commented that it was very difficult to work free-floating without a stable, restrained base. It was difficult to try to hold on with one arm for maintaining position while manipulating the ends of the beams into their attachment nodes with the other arm in order to construct the tetrahedron.

Figure 2 shows Jerry Ross in the lower workstation and his position in foot restraints. The STS 61-B astronauts stated that the only time they got any leg exercise was when they would rock back in the foot restraint to look backward and then use the dorsi flexors of their legs to bring themselves back to the upright position. They commented that they received very little little midbody or thorax exercise. The muscles used were almost entirely upper body. They said that occasionally they would get some minimal abdominal exercise when they had to look down around their feet or below them.

The STS 61-B, EASE/ACCESS EVA crewmembers were also asked to rate their EVA's on the Borg scale of perceived exertion. They felt that from a cardiovascular standpoint, the EVA was not particularly demanding and rated it at about a 10 or an 11, which closely reflected their heart rates during the EVA. However, from a muscular standpoint, one crewmember rated the first EVA as a 20. He unequivocally stated that it was the most fatigued his arms, forearms, and hands had ever been. He rated the second EVA, in which EASE was accomplished while in a foot restraint, as an 18.

In the Space Shuttle Program, there have been 13 two-crewmember EVA's performed on 8 different missions. For the Space Shuttle EVA's, metabolic rates have been obtained by the three different methods: knowing the water temperature differential of the liquid-cooling garment, knowing the oxygen bottle pressure change, and correlating EVA heart rate with one-g measurements. Table V is a summary of the metabolic rates using the first two methods. With both of those methods, the metabolic rate is an average over the entire EVA. Until the last EVA mission, STS 61-B, the capability of downlinking periodic oxygen consumption rates did not exist. Consequently, the average metabolic rate over the entire EVA includes times of active EVA work as well as ingress, egress, and occasional times of inactivity such as occur when a crewmember may be required to

Fig. 2.- STS 61-B astronauts Sherwood Spring (upper right) and Jerry Ross (lower workstation) during EASE/ACCESS EVA.

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

TABLE V.- SUMMARY OF AVERAGE METABOLIC RATES DURING SPACE MISSION EVA'S

(a) All missions

Mission	Metabolic rate, kcal/hr
Apollo	234
Skylab	230
Space Shuttle	199

(b) Space Shuttle missions[a]

STS mission	Duration, hr	EVA no.	Metabolic rates			
			EV1		EV2	
			kcal/hr	kcal/hr/kg	kcal/hr	kcal/hr/kg
STS-6	3.75	1	146	1.96	206	2.91
41-B	5.5	2	191	2.47	239	3.33
41-B	5.67	3	166	2.15	186	2.59
41-C	3	4	204	2.60	246	2.65
41-C	7	5	235	2.99	194	2.09
41-G	3.5	6	237	3.33	159	2.23
51-A	6	7	153	2.64	202	2.72
51-A	5.75	8	159	2.74	191	2.57
51-D	3	9	222	3.04	181	2.22
51-I	7.5	10	200	2.16	192	2.69
51-I	4.5	11	211	2.28	202	2.83
61-B	5.5	12	267	3.09	196	3.14
61-B	6.5	13	230	2.66	169	2.70

[a] Summary: total duration - 67.17 hours (134.34 crewmember hours); mean metabolic rates - 201 kcal/hr and 2.65 kcal/hr/kg.

wait while Mission Control makes evaluations or decisions. The average EVA metabolic rate for Apollo was 234 kcal/hr; for Skylab, 230 kcal/hr; and for Space Shuttle, 199 kcal/hr. The mean duration of the 13 Space Shuttle EVA's is 5 hours and 10 minutes. The highest absolute Space Shuttle metabolic rate was 267 kcal/hr for EV1 on STS 61-B, and, when corrected for weight, the highest was 3.33 kcal/hr/kg for both EV2, STS 41-B, and EV1, STS 41-G.

It should be realized that doing manual, hand-intensive work in the space suit is very strenuous, particularly on the upper extremities, and primarily the hands and forearms. When looking at the metabolic rate, one should recognize the work on EVA is almost exclusively upper body work. Consequently, the musculature of the upper extremities is the primary contributor to the metabolic rates generated during EVA. When looking at maximum oxygen uptake in ground-based aerobic capacity testing, one sees an approximately 30-percent decrease in maximum oxygen uptake during upper extremity testing when compared with conventional cycle ergometry or treadmill (refs. 9 to 11). One of the EVA astronauts who is a marathon runner in excellent physical condition stated that after his EVA, he felt a level of fatigue similar to that of running 12 to 15 miles.

In looking ahead to the 1990's and the plans for Space Station, a significant number of structure assembly EVA's are anticipated, especially during the construction phase of Space Station. One of the tentative plans calls for 2000 hours a year per crewmember of EVA. Most of the astronauts feel this objective would be very difficult to achieve and is an unrealistic plan. The only back-to-back Space Shuttle EVA to date took place on STS 51-I, where Van Hoften and Fisher did the LEASAT retrieval and repair. Van Hoften felt that knowing they had to do the EVA's back-to-back, he was able to do them successfully. However, he stated that if pressed and put into a position where he would have to do EVA's 5 days in a row, he felt it would be very taxing and difficult to maintain such a schedule. Some of the other astronauts have expressed reservations regarding back-to-back EVA's. With consecutive EVA's, they were concerned that some compromise in maximal effectiveness and performance would be encountered and accepted. They all felt future flight rules, especially for Space Station, regarding the frequency of EVA need careful consideration.

Another important related area to EVA is preflight conditioning. From my discussions with the EVA crewmembers, it was learned that all of them did do preflight conditioning. Their preflight training regimes varied but consisted primarily of upper body strength training combined with aerobic training. Without exception, all of them subjectively felt their preflight conditioning helped even if solely from a psychological standpoint. They believed that knowing they had the extra reserve capacity if needed afforded them added confidence in performing their EVA tasks. They all felt upper body exercising and training were very useful and beneficial, and at least one commented he wished he had done more preflight conditioning than he had.

There were only a few medical problems encountered by the crewmembers during the EVA's. The astronauts from the EASE/ACCESS EVA had some finger numbness, primarily from compression of the digital nerves in the web space between the thumb and the index finger where their gloves creased. Because of the hand-intensive work and manipulations they did during their EVA's, both crewmembers said they experienced parastesia of their thumbs lasting for as long as 2 weeks. Improved suit and glove design is one of the necessary and ongoing areas of technological development to facilitate improved EVA capability. Two crewmembers also noted mild pressure ear blocks upon repressurization following their EVA's. These were relieved after forced clearing of their ears by the valsalva maneuver.

In conclusion, from the EVA experience and data obtained to date, the following points should be stressed.

1. Nominal EVA's should not be overstressful from a cardiovascular standpoint.
2. Manual labor-intensive EVA's such as planned for the construction phase of Space Station can and will be demanding from a muscular standpoint, primarily for the upper extremities.
3. Off-nominal unplanned EVA's can be physically demanding both from an endurance and from a muscular standpoint.

The crewmembers should be physically prepared and capable of performing these EVA's at any time during the mission.

References

1. Gemini Midprogram Conference - Including Experiment Results. NASA SP-121, 1966.

2. Roth, E. M., ed.: Compendium of Human Responses to the Aerospace Environment. NASA CR-1205, Vol. II, 1968.

3. Kelley, G. G.; Coons, D. O.; and Carpentier, W. R.: Medical Aspects of Gemini Extravehicular Activities. Aerospace Med., vol. 39, 1968, pp. 611-615.

4. Waligora, J. M.; and Horrigan, D. J.: Metabolic Cost of Extravehicular Activities. Biomedical Results From Skylab, Richard S. Johnston and Lawrence F. Dietlein, eds. NASA SP-377, 1977, pp. 395-399.

5. Machell, R. M., ed.: Summary of Gemini Extravehicular Activity. NASA SP-149, 1967.

6. Johnston, Richard S.; Dietlein, Lawrence F.; and Berry, Charles A., eds.: Biomedical Results of Apollo. NASA SP-368, 1975.

7. Waligora, J. M.; and Horrigan, D. J.: Metabolism and Heat Dissipation During Apollo EVA Periods. Biomedical Results of Apollo, Richard S. Johnston, Lawrence F. Dietlein, and Charles A. Berry, eds. NASA SP-368, 1975, pp. 115-128.

8. Nicogossian, Arnauld E.; and Parker, James F., Jr.: Space Physiology and Medicine. Extravehicular Activities, NASA SP-447, 1982, pp. 108-124.

9. Astrand, P. O.; and Saltin, B.: Maximal Oxygen Uptake and Heart Rate in Various Types of Muscular Activity. J. Appl. Physiol., vol. 16, no. 6, 1961, pp. 977-981.

10. Barror, O.; and Zwiren, L. D.: Maximal Oxygen Consumption Test During Arm Exercise - Reliability and Validity. J. Appl. Physiol., vol. 38, no. 3, 1975, pp. 424-426.

11. Davies, C. T. M.; and Sargeant, A. J.: Physiological Responses to Standardized Arm Work. Ergonomics, vol. 17, no. 1, 1974, pp. 41-49.

(63)

524875

41

N91-10576

Space Station

Judith Hayes, M.S.
Technology Life Sciences Division
Krug International
Houston, Texas

and

Don Stewart, M.D.
Medical Operations Branch
NASA Lyndon B. Johnson Space Center
Houston, Texas

Introduction

The concept of Space Station is not new. Even excluding the romantic vision of early writers, there is a rich heritage of space station engineering designs that predate the origin of the National Aeronautics and Space Administration (NASA) in 1958. These designs have advanced concurrently with the evolution of science and technology, as well as in response to historical and political circumstances.

Space station proposals generated in the early 1900's were very progressive, incorporating modular architectural structures, solar power, and simulated gravity from rotating habitable elements. The purposes of such designs have remained common: (1) celestial observation of the cosmos, (2) global communication, (3) manned Earth-orbiting service for interplanetary exploration, (4) research in a microgravity environment, and (5) military defense.

Technology spinoffs from World War II provided important contributions to space science through advances in ballistics and rocketry and thereby inspired a postwar plethora of new designs for space station. These designs were more sophisticated and included such capabilities as physiological/psychological research on space personnel, radio wave reflection/refraction studies, solar radiation and cosmic-ray investigations, orbital deployment, and simulated-gravity research. The scientific community and public opinion gradually persuaded the Congress of the United States to commit to increased support of basic research and applied science for the advancement of commerce and industry. Accordingly, in 1958, legislation created NASA with the intent to expand human knowledge and lead toward the development and operation of vehicles capable of transporting equipment, supplies, and living organisms through space. Scientists and engineers began preliminary space station studies at the NASA Langley Research Center (LaRC) in 1959, evaluating space station concepts that would best serve space exploration and interplanetary travel. Many of the space station proposals put forth by NASA incorporated concepts that were evident in earlier designs.

In 1961, when President John F. Kennedy declared that we should go to the Moon by the end of the decade, many assumed that a space station in Earth orbit would be the logical prelude to a manned lunar landing. However, the agency decided on a lunar-orbit rendezvous (Apollo) that would make it unnecessary to utilize a space station as a staging and servicing base for an Earth-lunar flight, thus diverting most of NASA's resources to the Apollo Program. At that time, emphasis on the function of space station changed from an orbiting launch site to an orbital research facility, and this change altered the requirements which would drive the space station design.

Although some space station work continued at the NASA Manned Spacecraft Center (MSC) in Houston and the NASA George C. Marshall Space Flight Center (MSFC) in Huntsville, Alabama, most of the effort was concentrated at the LaRC in Virginia. From 1963-69, NASA's space station concept was considered "a research center for space" and labeled the Manned Orbiting Research Laboratory (MORL). During this era, space science increased in magnitude and broadened the spectrum from astronomy and astrophysics to geology, oceanography, biology, physiology, chemistry, nuclear physics, and materials science. In 1963, the Department of Defense initiated the Manned Orbiting Laboratory (MOL) for the purpose of determining man's military efficacy in space. This system consisted of a modified Gemini spacecraft which would rendezvous and dock with a cylindrical laboratory. Each component would be separately launched on a Titan III rocket.

Despite the demands of the Apollo Program, some space station studies did continue at MSC and MSFC. The MSFC studies focused on an unmanned platform derived from the Saturn V spent propulsion rocket stage, termed the Spent Stage Workshop. Meanwhile, the MSC concentrated on manned operations characterized by a "Y" configuration spacecraft that included three radial arms, which would be launched by a two-stage Saturn V and would provide living and working accommodations for a crew of 24. By 1965, NASA's Office of Manned Space Flight (OMSF) considered ways to utilize its capabilities developed for the Apollo missions in an "Apollo Applications Program." Concomitantly, in 1966, NASA initiated an agency-wide space station effort that attempted to obtain the approval of the President. In 1969, the President's Space Task Group failed to support space station as a necessary portion of NASA's development plan and it became the victim of an effort to contain the Federal budget. The Space Shuttle, a reusable space vehicle, did win the approval of the administration, and NASA continued to investigate the feasibility of a manned space station through the Apollo Applications Program under the guise of Skylab.

In 1973, four successive Skylab missions were conducted, placing into low Earth orbit a laboratory and three separate three-man crews to conduct experiments for record-breaking durations: 28, 59, and 84 days, respectively. Skylab was utilized as a research facility, incorporating the Apollo telescope mount (ATM), Earth observation research, and extensive medical studies. Skylab reinforced the notion that indeed man did have a significant function in the future of long-duration space research and exploration.

Following the success of Skylab, NASA phased out the Apollo and Saturn Programs and emphasized the development of the Space Transportation System (STS) with the Space Shuttle. The capabilities of the Space Shuttle and rapid advancements in both ground-based and space-based technology presented new opportunities for developing space systems for practical use. Once the Space Shuttle system was proved successful, the emphasis was shifted toward the construction of a large manned space vehicle. In 1976, "space industrialization" was the new concept and generated some new space station designs which would ultimately incorporate the Space Shuttle Orbiter for servicing and supply. In 1977, NASA announced that the Space Construction Base would begin development in 1980 and be prepared for initial use in 1985; however, neither the exiting administration (Ford) nor the incoming Carter administration would request in the 1978 fiscal year budget the $15 million essential for preliminary space station studies. Thus, the space station effort ceased until 1979, when the NASA Lyndon B. Johnson Space Center (JSC), formerly the Manned Spacecraft Center, in Houston resumed work with a study of the Space Operations Center (SOC). Following a preliminary definition study for the SOC, NASA announced that a permanently manned space station would be the next major venture into space, and established the Station Technology Steering Committee. Finally, an agency-wide space station effort began in earnest. In the State of the Union address of 1984, President Ronald Reagan directed NASA to develop a permanently manned Space Station within the decade. This directive underscored an initiative for the United States to maintain its leadership in space.

Description

Space Station will represent the beginning of a permanent presence in space for the United States. Current plans consist of a manned base and two or more unmanned free-flying platforms. The station will be positioned in low Earth orbit at about 250 miles altitude, at an inclination of 28.5° to the Equator. Once manned, the Space Station will initially support a crew of eight, with crew rotations and resupply from the Space Shuttle Orbiter at 90- to 120-day intervals.

The initial operating configuration will be approximately a 350-foot towerlike structure that includes two logistics modules, four pressurized cylindrical modules, a power system, a propulsion system, attached pallets, a robotics system, and a communications system. These elements will be linked by a trusswork in a single-keel configuration. This configuration provides space for attachment of payloads and accommodates future expansion. Ultimately, the goal of Space Station is to provide a modular-evolutionary design that permits growth, accepts modern technology, and will have an indefinite life through in-flight repair, maintenance, and/or hardware substitution.

The components of the Space Station will be fabricated on Earth to fit into the cargo bay of the Orbiter and launched in segments for construction on orbit. Assembly of the Space Station will take place over a period of several years utilizing robotic devices and possibly the manned maneuvering unit (MMU) to assemble all of its elements. Upon initial assembly, the Space Station will weigh approximately 300 000 pounds. Because of the Space Station experiment requirements, the most satisfactory location for the pressurized modules will be near the center of the single keel (i.e., the Space Station center of gravity). To provide ease of access and operation, these modules are organized in a raft pattern conjoined by four external resource nodes. The nodes also house some of the subsystems (e.g., the exercise subsystem), while serving as a docking and berthing port for the Space Shuttle.

The four pressurized modules are cylindrical with dimensions of approximately 45 feet in length by 15 feet in diameter. Each of these modules will be internally equipped to function as either a laboratory or living quarters for the crews of the Space Station. The Space Station provides a comfortable, functionally efficient habitat that will support a crew living and working together for durations of 90 to 120 days. Ergonometric consideration has been given to crews from the 5th-percentile female to the 95th-percentile male; thus, the "average" crewmember should find the architectural elements comfortable.

The United States will provide two of the pressurized modules: the Habitation Module and the U.S. Laboratory Module. The European Space Agency (ESA) and Japan will each supply one pressurized laboratory module. The Habitation Module incorporates private crew quarters, a wardroom, a galley, and the fundamental health and recreational needs of a crew. The U.S. Laboratory Module will be used for materials research, manufacturing, and life sciences research. The Japanese Experiment Module (JEM) will provide a multipurpose research and development laboratory that will also include a local remote manipulator arm, an experiment logistics module, and an attached work deck for mounting payloads requiring direct exposure to space. Meanwhile, the ESA Module has a life sciences and materials research laboratory, a polar platform, and a co-orbiting platform. In keeping with the long-term policy of international cooperation, Canada will furnish a Mobile Servicing Center that will provide the remote manipulator system, end effectors, servicing tools, control stations, and special-purpose manipulators.

The Space Station atmosphere will be maintained by the environmental control and life support system (ECLSS). The ECLSS is a "closed-loop system" that recycles oxygen and water. This system will supply the crew with breathable air and with water for ingestion and bathing, remove contaminants from the module atmosphere, and process biological wastes. It will only be necessary to resupply the station periodically with food and nitrogen. Energy will be generated by integrating both photovoltaic and solar dynamic systems. These power modules are mounted on the tips of the single-keeled trusswork and provide a hybrid power system for the Space Station.

The United States will provide two logistics modules for resupply of Space Station consumables, storage of spare hardware, and stowage of wastes. An onboard automated logistics subsystem will assist the crew in tracking supplies, identifying trends, and predicting resupply requirements. Payloads requiring minimum disturbance and protection against contamination will be accommodated by the unmanned platforms. The Space Station crews will undertake the retrieval and deployment of the platforms into their assigned orbits and attitudes, as well as the payload servicing, repair, checkout, operations, removal, and/or replacement.

Space Station capabilities will be enhanced by the utilization of several new space transportation vehicles being developed. The manned maneuvering unit, already employed on Space Shuttle missions, consists of a self-contained backpack propulsion device that allows a crewmember to venture untethered into space. It is expected that the MMU will assist in conducting scientific research, assembling structures, and executing rescue operations in space. The orbital maneuvering vehicle (OMV), described as a "smart space tug," will be used to transport payloads between low Earth orbit trajectories. The OMV will have the potential to deliver expendable supplies to satellites, transfer crewmembers to satellites for maintenance, and move payloads from the Space Shuttle to the station. Eventually, an orbital transfer vehicle (OTV) will be incorporated into the program allowing transport of payloads from low Earth orbit to higher energy orbits, including geosynchronous transfer, ellipse, and Earth escape trajectories. Initially, the OTV will be unmanned; however, ultimately, this vehicle will be developed into a crew transport and have the capacity for boost into high-velocity orbits supporting interplanetary travel.

It is anticipated that the astronaut corps will be separated into groups for the station era, including both Space Shuttle and Space Station cadres. Both groups will share similar training initially, but much of their training will be specific to either Space Shuttle or Space Station. The Space Station astronaut corps will consist of fewer than 100 and will be further classified as operators and scientists. It is estimated that 36 months of basic station training will be necessary for the crewmembers, as well as an additional 18 months of mission-specific training. These recommendations have been based on an eight-man crew and a 90-day crew rotation, with eight Space Shuttle missions per year transporting four new crewmembers each trip. The crew will consist of a minimum of 8 persons and will eventually be increased to 18 crewmembers. Each crew will include at least two crewmembers with detailed knowledge of the Space Station systems operations and maintenance (Station Operators). The other crewmembers will primarily support user mission objectives (Mission Specialists and Payload Specialists). Each crew will operate on two 12-hour shifts, with one Station Operator on each shift. The scheduled work week for every crewmember will be 6 days. Mission durations will range from 90 to 180 days and may actually persist for as long as 120 or 150 days.

The First Element Launch (FEL) for Space Station is intended for January 1994, whereas the Man-Tended Capability (MTC) will occur 1 year later, in January 1995. The MTC incorporates the assembly of the U.S. Laboratory Module and its outfitting. The Habitation Module will be deployed in April 1995, but the Permanently Manned Phase (PMP) will not occur until the following August. The initial Space Station assembly will be completed in 1996; however, it should continue to grow in both size and capability since it is intended to operate for several decades.

Conclusion

The history of American space flight indicates that a space station is the next logical step in the scientific pursuit of greater knowledge of the universe. The Space Station and its complement of space vehicles, developed by NASA, will add new dimensions to an already extensive space program in the United States.

Space Station offers extraordinary benefits from a comparatively modest investment (currently estimated at one-ninth the cost of the Apollo Program). The station will provide a permanent multipurpose facility in orbit necessary for the expansion of space science and technology. It will enable significant advancements in life sciences research, satellite communications, astronomy, and materials processing. Eventually, the station will function in support of the commercialization and industrialization of space. Also, as a prerequisite to manned interplanetary exploration, the long-duration space flights typical of Space Station missions will provide the essential life sciences research to allow progressively longer human staytime in space.

Bibliography

O'Leary, B.: Project Space Station. Stackpole Books (Harrisburg, Pa.), 1983.

Space Station Program: Definitions and Requirements. Rep. JSC-30000, NASA Lyndon B. Johnson Space Center (Houston, Tex.), Oct. 1985.

Space Station Program: Description, Applications, and Opportunities. Noyles Publications (Park Ridge, N.J.), 1985.

Space Applications Board, Commission on Engineering and Technical Systems, National Research Council: Practical Applications of a Space Station. National Academy Press (Washington, D.C.), 1984.

Civilian Space Stations and the Future in Space. Rep. OTA-STI-241, U.S. Congress, Office of Technology Assessment, Nov. 1984.

52676

4

N91-10577

(64)

The History of In-Flight Exercise in the U.S. Manned Space Program

Thomas P. Moore, M.D.
Methodist Hospital of Indiana, Inc.
Indianapolis, Indiana

In the days before manned space flight, the physiologic consequences of weightlessness on the human body were totally unknown. Today, we find it surprising, if not amusing, to think that before the first U.S. astronaut was launched, some scientists predicted, and even President John F. Kennedy's advisory committee on space expressed concern, that the human body would not be able to withstand the rigors imposed on it during space flight and that our astronauts would not survive. As a result of these uncertainties, prospective astronauts for Project Mercury underwent comprehensive and very extensive medical testing. As Tom Wolfe documented in his book "The Right Stuff," and as was subsequently graphically depicted in the movie of the same name, every conceivable physical parameter was tested, every possible laboratory value was measured, and every orifice was probed in an attempt to find any identifiable medical or physiological flaw in the candidates. Consequently, the astronauts who survived the selection process were viewed by many as a breed of supermen. The maintenance of physical conditioning and exercise became an unwritten rule in the astronaut cadre. This esprit de corps arose partly because of the unknown possibility that physical fitness and athletic ability might become a crew selection criterion and also possibly out of the desire to maintain this superimage.

During Project Mercury, little attention was paid to in-flight exercise. The Mercury manned flight program began with two suborbital flights, progressed to John Glenn's three Earth orbits on Mercury 6, and ended with Gordon Cooper's 34-hour flight on Mercury 9. The short duration of these flights and, more importantly, the fact that these flights took place in a very small, compact, and cramped vehicle precluded the need or the ability to perform in-flight exercise.

From Project Mercury, we progressed to the Gemini Program and the development of two-man spacecraft, the first of which was launched in March of 1965. The vehicles remained extremely small and available space for unrestricted movement was still severely limited. It was, however, on the second manned Gemini mission, Gemini IV, that the first experiment using an in-flight exerciser was performed. The objective of this experiment was to make day-to-day evaluations of the cardiovascular response to a calibrated workload under space-flight conditions. The exercise device consisted of a pair of rubber bungee cords attached to a nylon handle at one end and to a nylon footstrap at the other. The flight bioinstrumentation system was utilized to obtain pulse rate, blood pressure, and respiratory rate. The exercise device required about 70 pounds of force to stretch the rubber bungee cords maximally through an excursion of 12 inches. The exercise periods lasted 30 seconds, during which time the astronauts stretched the bungee cords through one contraction and relaxation cycle per second. Each of the astronauts performed approximately 15 exercise bouts during the 4-day mission. In flight, the heart rate of the command pilot and the pilot reached 105 bpm during exercise. There was no significant difference from their preflight values for exercise heart rate or for recovery heart rate. From this minimal level of exercise, the investigators concluded that there was no evidence of "deconditioning" at any time during the Gemini IV mission. In the postflight physical exam, using a Harvard step test as an index of physical fitness, no decrement in physical condition was found. Consequently, use of the bungee device was continued on Gemini flights, including Gemini VII, which at that time was our longest stay in space, 14 days. For this 14-day flight, a simple isometric routine was designed and astronauts performed the routine about three times a day along with the bungee apparatus. This in-flight exercise program did not serve as a conditioning program but did relieve disuse discomfort stemming from both weightlessness and the relative immobilization caused by the cramped quarters.

After the Gemini Program, we moved into the Apollo Program with a three-crewmember spacecraft. The goal of Apollo was to go to the Moon, explore the lunar surface, and return safely to Earth. The Apollo Program was initially structured to have a competent exercise device on board a somewhat larger spacecraft. A small box ergometer with pedals on either side was developed; however, it contributed to spacecraft weight problems and the exercise program was canceled. Consequently, only a very informal exercise program existed through the Apollo Program. The only on-board exercise device was one of the rope-and-pulley variable-friction machines. The crew used this item sporadically, again primarily for relief of the discomfort of cramped confinement. During Apollo, two of the crewmembers on each of the six lunar landing missions received additional exercise during their lunar extravehicular activities (EVA's). The activities included collecting geological core samples, setting up experiments, and gathering various lunar samples and Moon rocks. It was during the Apollo Program that evidence began to appear and a pattern to evolve of deconditioning, weight loss, loss of muscle mass, and, in particular, decreased exercise capacity during the immediate postflight period in 20 of the 27 Apollo crewmembers tested. The exercise capacity was measured on ergometers before and after flight. Significant concerns were raised regarding space-flight "deconditioning" and about the use of exercise as a prophylactic measure, especially in planning for the upcoming long-duration Skylab missions.

Skylab was a large orbiting laboratory that to date has been the only long-duration space-flight experience in the U.S. space program. There were three Skylab missions, identified as SL-2, SL-3, and SL-4, carrying three crewmembers each on missions of 28, 59, and 84 days. Skylab missions were flown during the time period of May 1973 to February 1974. For the initial Skylab flight, a bicycle ergometer capable of a wide range of workloads was developed. Coupled with the bicycle was the capability for measuring heart rate, respiration, and blood pressure and for obtaining electrocardiograms. A mass spectrometer gas analyzer was also on board, capable of giving the crew and investigators oxygen and carbon dioxide parameters. The device was used in the experimental testing mode approximately every fifth day on all three Skylab flights. The data obtained provided a longitudinal look at exercise capacity as a function of time in weightlessness. The bicycle was also available in flight for use as a daily exercise device. All exercise done was carefully logged and reported. Consequently, a complete record of in-flight exercise was obtained. On the first manned Skylab mission, SL-2, the bicycle ergometer was the only exercise device on board. Because of problems with the design of the shoulder harness and the eventual discarding of it completely, it took the SL-2 crew approximately 10 days to learn how to ride the bicycle in zero g. From that point on, the astronauts had no difficulty in achieving the same feedout oxygen readings at the same workloads with approximately the same heart rates in flight as they had before flight. The problem with making comparisons with preflight norms was that the norms were established 6 to 12 months before flight, and because of significant improved conditioning of the astronauts prior to flight, the initial in-flight workload levels were artificially low and were subsequently corrected. The SL-2 crew improvised, with commander Charles Conrad diligently using the bicycle not only in its conventional mode but also as an upper body ergometer. After crew return, postflight testing revealed cardiovascular deconditioning and decreased upper and lower body muscle strength. As a result of this finding, along with the crewmembers' comments and recommendations, changes were made in the exercise program for SL-3. To facilitate increased upper body exercise, two devices, identified as Mark I and Mark II, were added on board. Mark I was a modified commercially available product named the Mini Gym. It was another rope-pull type of device that worked on a centrifugal braking action that approximated isokinetic exercise. The Mark II was a pair of handles between which five springs could be attached giving a maximum of 25 lb/ft that could be developed on extension. On SL-3, the crewmember's average exercise time on the bicycle was increased by more than 100 percent over that done on SL-2.

During this time, work was also begun on the development of a treadmill for Skylab 4. After returning from their 59-day mission, the SL-3 crew was found to be in better cardiovascular condition than was the SL-2 crew. Postflight muscle strength testing showed improvements in maintenance of arm strength, but significant leg strength decrements were still found. On SL-4, a Teflon treadmill devised by astronaut William Thornton, M.D., was flown on board. It consisted of a Teflon-coated aluminum walking surface attached to the Skylab isogrid floor. Four rubber bungees provided an equivalent weight of 80 kilograms and were attached to a shoulder and waist harness worn by the astronaut. By angling the bungees, the equivalent of a slippery hill was presented to the subject, who then had to climb it. Astronaut Gerald Carr, commander of SL-4, stated that he used the treadmill regularly to walk for approximately 15 minutes. He then would perform what amounted to basically a sprint on the device, the sprint being time limited to about 1 to 1-1/2 minutes because of overheating to his socks and feet. He also would use the harness/bungee setup to do squats and toe raises for additional leg muscle exercise. His recollection was that the other two crewmembers, Edward Gibson and William Pogue, used the device in a similar fashion. The SL-4 crew continued the use of the Mark I and II. In addition, they further increased the time on the bicycle to 130 percent of that of the first Skylab crew and added some improvised torso isometric exercises. After 84 days in space, the third Skylab crew returned in better condition than did the crews on the the other two missions, as evidenced by less strength loss, less weight loss, less leg volume decreases, and improved postflight exercise testing.

It was evident from the in-flight cardiovascular testing that all of the SL-4 crewmembers had actually improved their physical conditioning in flight. Commander Carr believed that other than for some unsteadiness caused by vestibular readaptation, he would have been physically able to perform emergency procedures including walking away from the spacecraft or vehicle under his own power if necessary.

After Skylab and the U.S.-U.S.S.R. Apollo-Soyuz flight, planning for the Space Shuttle Program proceeded. From the Skylab experience, a passive treadmill was devised by William Thornton, M.D., and developed and built by Henry Whitmore of Whitmore Enterprises. The Space Shuttle treadmill consists of aluminum plates with rollers on the end that are connected in a series to form a belt. The treadmill is nonmotorized and purely passive so that the astronaut must make the metal belt move by walking or jogging on it. The down-pull of the bungee/harness system can be manually adjusted by the astronaut to approximate his/her own body weight. The treadmill was first flown on STS-3 in 1982 and has been flown with a more recently improved, updated model on every subsequent Space Shuttle flight. By mission flight rules, all astronauts on a Space Shuttle mission have a daily exercise period allotted to them in their crew activity plan. The use of the exercise time is left to the discretion of the individual astronauts to be used as he or she may wish. There is no mission requirement to perform exercise in flight; however, the majority of the astronauts usually do exercise at some time during flight. The treadmill is generally used more frequently by the commander and the pilot, because these crewmembers have mission-critical duties during landing that require use of the legs to push rudder pedals, to steer, and to apply brakes. Other crewmembers on the relatively short Space Shuttle missions are sometimes willing to sacrifice their exercise time and endure some temporary deconditioning for the opportunity to take advantage of the unique sightseeing that space flight provides.

Other than comments related to the noise of the treadmill and concerns regarding the minute acceleration forces imparted to the Orbiter during its use that can disturb zero-g-critical experiments, no significant problems have been experienced with the Space Shuttle treadmill.

Extravehicular activity, or space walks, provide the only other significant in-flight exercise. The first EVA's during the Gemini Program were found to be very demanding with heart rates averaging about 150 bpm. With improved space-suit design and preflight training, EVA's have become somewhat less demanding from a cardiovascular standpoint. However, it should be recognized that essentially all of the physical work involved in EVA is performed by the upper extremities. The only real function of the lower extremities during EVA is to be anchored in foot restraints in order to facilitate working at various workstations without floating free. Some of the Space Shuttle EVA mission objectives have ranged from the manual retrieval of malfunctioning satellites to simulated space station construction activities to the fine electrical repairs of satellites. Some Space Shuttle EVA's have lasted as long as 7 hours. As a result of the duration and the varied nature of the EVA tasks and objectives, significant physical exertion can occur during EVA. This fact should be realized and taken into consideration in Space Station planning, especially during the anticipated EVA-intensive construction phase.

In this paper, I have attempted to give a historical perspective on in-flight exercise in the U.S. manned space program. We have learned a great deal in the 25 years since the inception of Project Mercury. But, as we look forward to a Space Station and long-duration space flight, we must recognize the challenge that lies ahead. The importance of maintenance of the crewmember's physical condition during long stays in weightlessness is a prime concern that should not be minimized. The challenge lies in the design and development of exercise equipment and protocols that will prevent or minimize the deleterious sequelae of long-duration space flight while maximizing valuable on-orbit crew time.

526877

8p

N91-10578

Work, Exercise and Space Flight

I. Operations, Environment, and Effects of Spaceflight

William Thornton, M.D.
Scientist Astronaut

This is a brief background of the physical realities of the current U. S. spaceflight program. The population of astronauts, their environment on earth and space, adaptation to this environment and effects of this adaptation are summarized. Companion papers which follow examine the effects of exercise on earth and in space and its use as a countermeasure to prevent undesired adaptations. The last paper describes means to make exercise in space possible.

Work and exercise have always played a significant role in spaceflight and will be crucial in extended flights of the future, possibly becoming the most important life sciences aspect of man in space. Work and exercise have already been important in the careers of astronaut candidates by the time of selection. While the role of physical fitness no longer plays the part it once did, very few unfit individuals are selected or remain in the program.

Population - There are two divisions of professional astronauts—pilots and mission specialists. The former are all male, active or ex-military operational pilots and usually test pilots. One does not survive in that environment without good neuromuscular, musculoskeletal, and cardiorespiratory capacity. Their NASA physical standards are essentially those of military pilots. (1) The second group is now far more diverse, especially as regards background. Medical standards for vision are somewhat reduced and there are essentially no size limitations, (2). The result is a significant range of physical characteristics and capacities in the astronaut population including:

Height: 5'2" (female) to 6'4" (male)

Weight: 100 lbs (female) to 210 lbs. (male)

Maximum O_2 intake: 30 to 60 ml kg^{-1} min^{-1}
(mean 43 ml kg^{-1} min^{-1})

Strength: Unknown

The payload specialists and passengers are from an even more diverse background and have to meet considerably reduced physical standards (3,4).

While no physical performance standards are specified, the ubiquitous cardiorespiratory stress tests[a] are given prior to acceptance and periodically thereafter with a few skin fold and respiratory studies. No formal attention is given to musculoskeletal performance or anthropometrics other than height and weight. We did a comprehensive musculoskeletal exam on the 200 astronaut candidates of 1978 which included complete anthropometrics and strength. NASA standards (5) are still extrapolated military anthropometric standards. Any task which depends upon strength or range of motion is usually done by cut and try. This lack of emphasis on the neuromusculoskeletal area has lead to some significant mistakes in the past and threatens to do so again.

Training - After selection, there is a candidate training program which involves flying as pilots or crewmembers in high-performance A/C, survival training, and other strenuous physical activities. It is at this point that astronaut physical training begins. Facilities are adequate with a well maintained gym with basketball, squash and handball courts, bicycle ergometers and rowing machines, weights, Nautilus, and other equipment. There is a good 1/4 mile outdoor track and plenty of roads and trails on site.

A point which always arises about this program is controlled versus uncontrolled physical training. I was surprised to arrive in 1967 and not find a rigid program but am now convinced that unstructured individual physical training is the only acceptable approach in this program. One of the best possible training programs has evolved in which everyone is responsible for his own well-being. This is one of the most competitive, individualistic, critical, and discerning groups to be found. While the researchers may argue over P and T's in exercise experiments, this group watches and listens to actual results where they happen. They know who can black them out pulling Gs in the T-38s, who can work 7 days, 80+

---

[a] Modified Bruce protocol.

hours a week and keep doing it, who walked off the spacecraft without trouble, and who was at work in the gymnasium after a spaceflight, and while they don't have statistical proof, they also know who is usually in the gym and what they do. When this group of competitive and motivated individuals see convincing evidence that exercise makes a difference, they become dedicated exercisers themselves. The individual results are frequently striking, e.g. a pear-shaped professor becoming a successful marathoner.

Next is the variety of exercise. The astronauts are also perceptive enough to select what works for them and what they can live with. What they can live with insures it will be continued. There are now many 'trainers' in the program. If you want to run, there are joggers, sprinters, and marathoners who know theory and practice, swimmers, weight lifters, and so on. The physicians in the office take fitness seriously in theory and practice. In short, it becomes a way of life for almost everyone in the office, and while no two individuals' programs are the same, they're near optimum for the tasks they must do. The astronaut's responsibility is to be fit enough to do his job, not standardized enough to fit an investigator's statistical requirements for publication. In this situation, the investigator must be capable of unobtrusively measuring and accounting for individual differences, not try to hammer them out. The misapplication of "standard protocols" to individuals with unknown capacities has been a major source of error in exercise work in space and on earth. Anyone in the Astronaut Office will do whatever is assigned; and if there is a reason to have someone or a group on a standardized program, it can be done, but not indiscriminately nor routinely.

In addition to maintaining good physical condition, there are many other aspects of training for spaceflight. One must survive psychological pressures which are typically the largest stressor. There is frequent travel, often in T-38s, all over the country at all hours of day and night and one must frequently eat what and when it is available. There are training sessions and conferences and last minute changes which may last 16 hours a day or more. The media and public demands add to the load. One also tries to maintain a home and family. The majority are type A. In spite of this regimen, they typically launch in the best physical condition of their life.

Flight - As to physical demands of the launch, there is always the possibility of trying to escape from 200 feet up the pad, fighting fire as you go to the slide wires, to a rough landing and evacuation of the escape cars. One must also be able to evacuate the Shuttle after a crash landing by hauling one's own weight over the top [Fig. 1] or swinging off a bar to the ground some 10 ft. below. [Fig. 2].

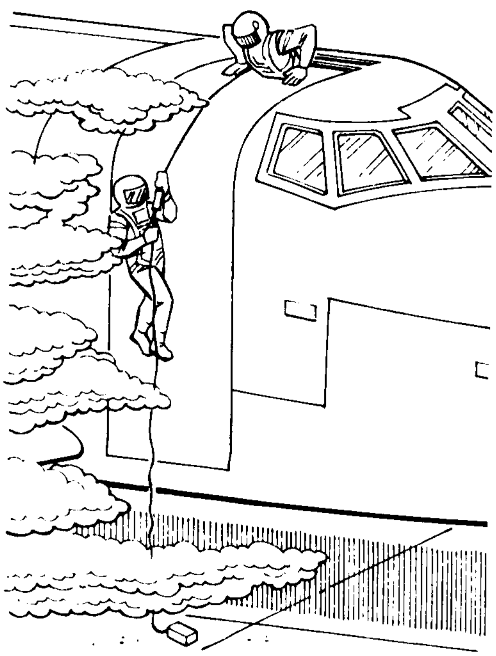


Fig. 1.- Secondary emergency egress from Shuttle. Crew lower themselves by a friction device on cable.

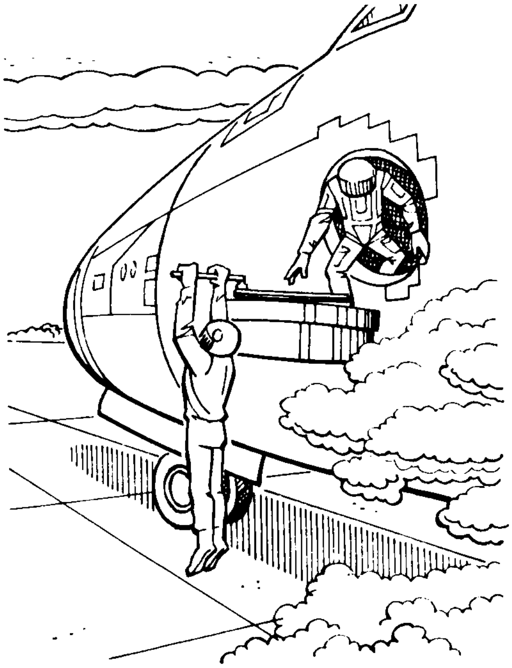


Fig. 2.- Primary emergency egress route from Shuttle. Distance between bar and ground is 10 feet. In every case, crewmen would wear emergency breathing gear.

Launch loads are modest with only +3.0 Gx and -0.6 Gz for the last minute. On orbit, the problem becomes one of keeping up with a usually jammed schedule which is busiest for the first two days and the time before entry and keeping up with a schedule which may, and often does, change from minute to minute. Food and sleep become secondary. Accommodations are limited—all decks are usually crowded with operational gear. The flight deck is occupied by 2 seats and controls, aft flight deck is ~3.5′ L × 6.5′ W × 6.1′ H and middeck is 7.3′ L × 11.5′ W × 6.9′ H. Hygiene is wash cloth or wet wipes, soap, and towel. Food is dehydrated in a myriad of plastic packages, wrappers, and appurtanences with some 'wet pack' items and a few fresh items provided for the first days. Atmosphere is composed of ppO_2 of 2.95-3.45 psi(~20%) and ppN_2 sufficient to maintain total pressure of 14.7 ± 0.2 psia. Carbon dioxide is maintained below 7.6 mmHg by LiOH scrubbing. The atmosphere is also scrubbed by activated charcoal for odor and trace contaminant control. Temperature may be selected between 65 to 80 ± 2°F. Relative humidity is typically 50% or less.

EVA operations are a class unto themselves and will be discussed by Dr. Moore. Suited operations have special physical requirements. The majority of the external loads are inertial, Force = Mass Acceleration. The largest masses may be moved by small but continued forces, however, the real problem is control both in direction and rate. Another common type of force is resistive (in terms of physics) such as repetitive motions in screwing on nuts or operating manual actuators. To date there have been no unsuited operations which require large forces nor high metabolic loads, i.e. it is a lazy environment on orbit.

On return, G-loads are +1.5Gz max. (eyeballs down) and small in terms of the normal body, but seem very large to a body adapted to weightlessness producing perceived loads of several times that. After landing unless one has prepared for it, one usually does not get out of the seat on the first attempt. In the event of an emergency, the crew could be forced to lift their body weight plus emergency breathing gear out the top hatch or swing to the ground 10 feet below from a bar on the side hatch. Such nominal emergency procedures could be complicated by incapacitated cohorts or poisonous fumes from damaged fuel tanks. The latter could require rapid locomotion for hundreds of yards or more. Immediately post landing, the perceived loads of walking are initially very large, say 2.0-3.0 G equivalent but adaptation rapidly occurs such that everyone to date has walked down the steps into the van, albeit sometimes after a period to allow recovery. Unusual weight and balance sensations occur over the next 24-36 hours.

This has been a very brief description of Shuttle operations, and there is a description of Space Station elsewhere in the report; however, Shuttle will be the transport for that operation.

Orbital Environment - Space is characterized by absence of the usual sustainers of life which must be provided by the spacecraft, i.e atmosphere, food, water, etc. Above the atmosphere the Sun's full spectrum of electromagnetic radiation is received from X-rays to far infrared with a moderate (~40%) increase over the midday visible light intensity on earth. All potentially damaging radiation is shielded or attenuated to reasonable levels by the spacecraft windows or suit helmets. The earth's magnetic field deflects and shields us from virtually all particulate radiation but great quantities are trapped in the Van Allen belts high above our usual flight level. Other than during solar storms, radiation is not a concern with a mean value of 50 m Rem dose per mission.

While current spacecraft make travel possible, their orbital mechanics provide the major challenge to man in space for long periods—weightlessness—i.e. the centrifugal force almost exactly balances gravitational force. It has become chic to speak of 'microgravity' but this is a misnomer since in earth orbit gravity is typically reduced by only a small fraction over that at the earth's surface. The very small amount of unbalanced weight ("microweight") is of no practical concern to our problem.

Adaptation to weightlessness: The effects of weightlessness are now our primary concern in long-duration[a] space flight. While these effects cascade through the body system producing higher and higher order effects, e.g. changes in heart rate or a hormone level, too often these are confused with the primary effects. The primary effects of weightlessness must be carefully considered for if not understood, countermeasures may be improperly chosen.

Effects of adaptation were initially manifest on post flight observation. The first objectively studied problem was weight loss [Fig. 3]. Even on short flights weight loss was largely regained within hours after return to 1g (6). Space motion sickness was experienced on the second manned flight by Titov (7). Orthostatic hypotension was often seen after flights of a few days (8). There was a reduction in cardiorespiratory capacity on flights of 1-2 weeks [Fig. 4] (9).

---

[a] Long distance spaceflight simply translates into long duration. The physical effects of a current flight to Mars and return would be equivalent to an ±3-year stay in earth orbit.

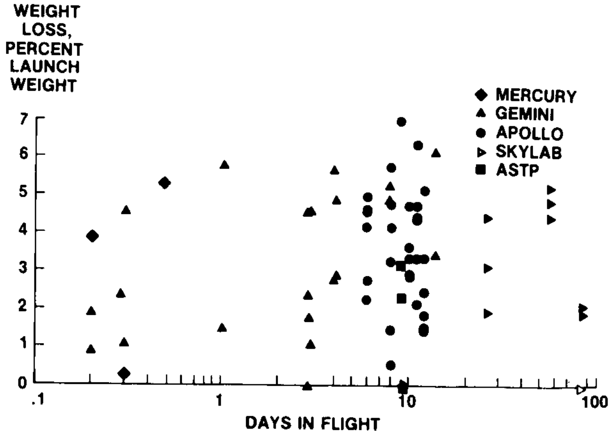


Fig. 3.- Weight losses of all crewmen prior to Shuttle. The loss consists of a 3-4% obligatory loss of fluid plus a variable metabolic loss (or gain). The time scale is logarithmic.

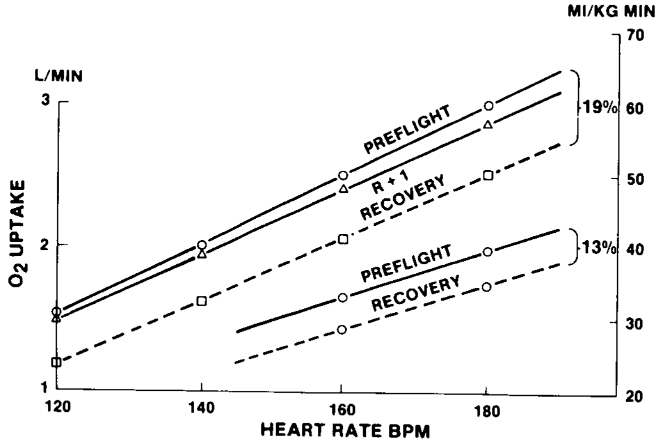


Fig. 4.- Mean of O_2 uptake versus heart rate measured pre- and postflight of Apollo crews. Scale for lower curves is on the right.

Muscle strength and mass are lost (10) as is bone calcium (11, 12). Red cell mass is reduced.

These changes may be understood in terms of three major primary effects of weightlessness:

1. Loss of hydrostatic pressure
2. Loss of locomotor function
3. Alteration of sensory inputs

In addition to these primary effects, there are several less significant ones including changes in size and shape directly caused by absence of weight [Fig. 5] (14), significant changes in height caused by unloading of the intervertebral discs (15) and reduction in girth through loss of weight of abdominal viscera and increase in truncal length.

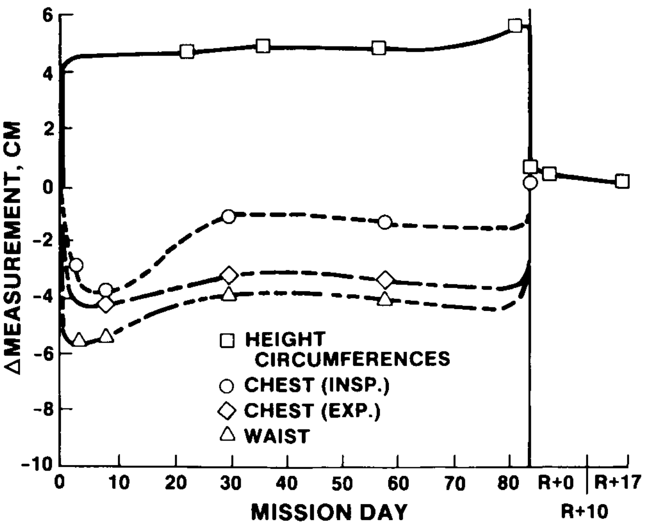


Fig. 5.- Summary of height, chest, and waist girth changes of one crewman on Skylab-4.

Loss of hydrostatic pressure in the vertical blood columns reduces both arterial and venous pressure by some 90 mm Hg at the foot level[b] while increasing cephalic arterial pressure by some 30 mm Hg and venous pressure by 8-10 mm.The result of this is an immediate shift of approximately 700 ml. of blood out of the legs (16, 17) which is followed by loss of 2-4 L. of extravascular fluid from the legs over the next several hours [Fig. 6] (14). Sometime over the next 3-5 days

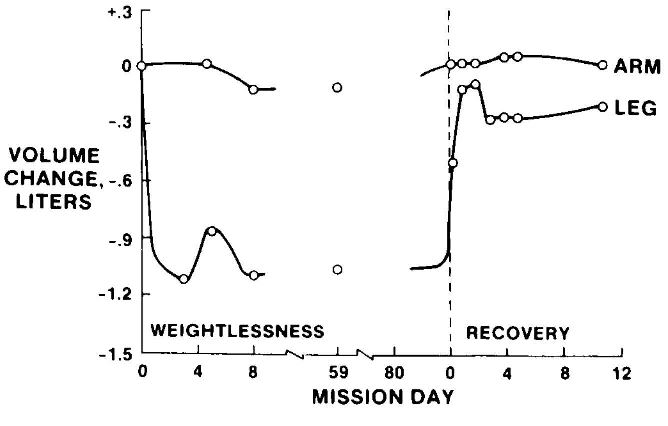


Fig. 6.- Typical volume changes in left leg and arm of Skylab crewman on orbit.

---

[b] The referenced blood pressures are those when standing in 1-g. As Gauer points out, this is the common posture of man.

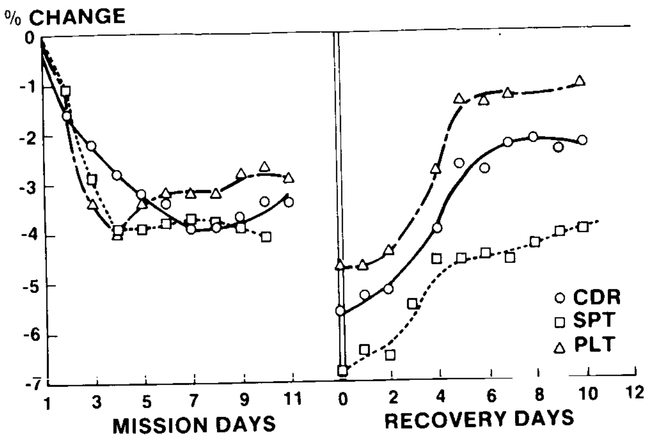


Fig. 7.- Body mass changes during early portion of flight and recovery on Skylab-4. The rapid portion of these changes is believed to represent fluid lost and gained which in these 70 kgm subjects represents approximately 2.5 liters. The absolute difference on recovery represents metabolic losses in flight.

this is lost (18) [Fig 7]. Whether this is by decreased intake or diuresis is, as yet, undetermined. A small portion of it remains as edema in the soft tissues of the head. If the subject remains in weightlessness, the blood volume will be adjusted to the effectively reduced vascular capacity, i.e. approximately 700 ml will be lost over 8-10 weeks (14). On return to 1-g, the major portion of tissue fluid volume is rapidly returned to the legs; and after body water is replenished, there will be an anemia. This redistribution of fluid, at least in part, explains the post-flight orthostasis and reduced exercise tolerance.

The neurological adaptation which has received most attention is Space Motion Sickness, a transient condition affecting some 40+% of first-time subjects in space. Symptoms are sensitivity to angular motion, malaise, lethargy, and infrequent episodic vomiting often without nausea. Etiology appears to be a sensory conflict between the semicircular canals and statolith organ outputs (19). Vomiting is caused by an upper G.I. ileus. We have neither predictive, preventive, nor curative means at this time. Typically after 36 hours, the signs and symptoms rapidly resolve without recurrence. Almost complete resistance to all forms of motion sickness follows for an unknown period of time.

Other sensory adaptations have not been adequately studied. One neuromuscular change produced immediately by weightlessness is the characteristic posture with limb segments in their midposition [Fig 8] (14). This posture is as characteristic as standing, sitting or lying in 1-g. It is of significance only when one attempts to force the body into its 1-g form, such as sitting in a 1-g chair with a lap belt, or when designing an inflight man machine interface.

A host of other neuromuscular adaptations must occur to avoid overcontrolling, e.g. if anyone ever pushed off with the force of normal walking there would be body damage on contact with the opposite wall. Much less force is required in flight. This makes itself felt during and immediately after entry. Few people leave their seat on the first try after landing. Muscle strength is not significantly reduced in 3-7 days but it is markedly inhibited. This phenomenon has a time constant of several hours, i.e. strength is rapidly returned to normal. There has been considerable comment on lack of sensibility of limb position in flight but this is not sustained by limb position studies I have done.

It is possible that cardiovascular reflexes may also be altered, for a small number of people have symptoms of orthostatic hypotension immediately postflight, yet have normal BP and normal, or slightly low, heart rate for the circumstance.

The reason for this conference is effects of weightlessness on the musculoskeletal and cardiovascular and respiratory systems. At the outset, let us establish one crucial point. Absence of weight does not directly cause the major changes in the musculoskeletal system. If we can bury the term "weight bearing bones," a significant advance will have been made. Absence of weight makes it impossible to walk/run in space. Muscle forces of locomotion are very much larger than body weight. It is the absence of these large inertial loads not absence of weight that cause muscle and bone loss. These forces develop and maintain the heavy bones and muscles of legs and lower trunk. It is also the metabolic loads from such activity that normally determine capacity, condition if you will, of the cardiorespiratory system. On

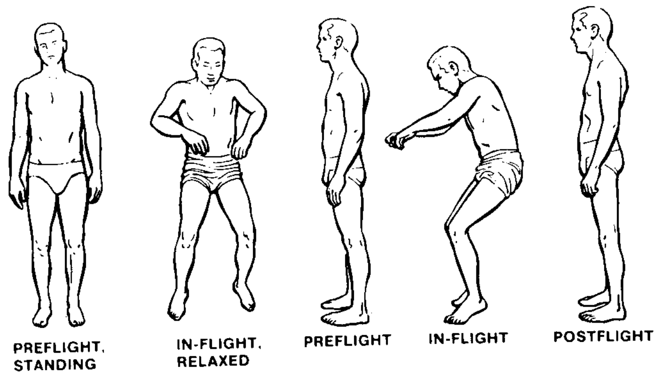


Fig. 8.- One-g and weightless posture compared. In weightlessness, the eyes were closed and body relaxed. This is the natural posture in flight and adjustment to other postures requires either force expenditures by the subject or external restraint.

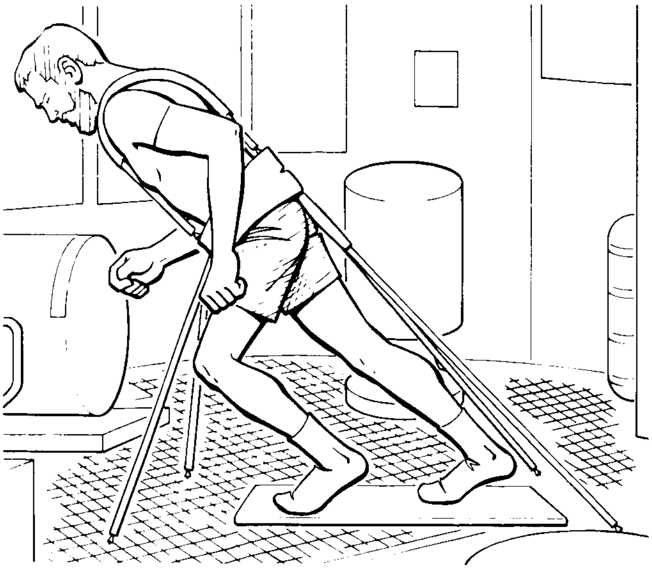


Fig. 9.- Tracing from ciné film on Skylab-4 crewman using crude locomotor exercise device consisting of bungee cords which applied force equivalent to body weight to the subject through hip and shoulder harness and a slippery Teflon plate. It was equivalent to climbing a slippery hill and very fatiguing albeit peak leg forces were probably only slightly above body weight.

Skylab we saw a marked loss of muscle strength and mass on the first two flights which had only bicycle ergometry as leg exercise. There was a sharp reduction in such loss on the longest mission (10), an 84-day flight which had a crude arrangement to allow walking/jumping [Fig 9]. Arms suffered much less loss and this was reduced to negligible amounts by exercise devices. The bicycle ergometer provided adequate cardiorespiratory load to maintain those functions. Ca^{++} was lost on all flights (11) and decreased bone density detected on the last flight (12). Dr. Schneider discusses this in detail in his paper.

Table 1. is a summary of the primary effects, the most prominent changes they produce, and the results of these changes on return to earth. Not shown are the time courses of these changes which occur at different rates and which may vary from individual to individual. Time courses of particular interest to this group will be discussed in more detail in the next section. Crucial to the understanding and dealing with these changes is the recognition that they are normal and appropriate adaptations to weightlessness, and as such, cause no difficulties so long as one remains in space. Some of these changes are incompatible with normal function on earth, i.e. viewed from a reference frame of performance on earth they represent deconditioning. In every case, with the possible exception of trabecular bone loss, they are easily reversible without any residual. It is the purpose of this meeting to decide what and how such adaptations can be prevented by exercise.

Summary - The selection, training, and operations of space flight impose significant physical demands which seem to be adequately met by the existing physical training facilities and informal individual exercise programs. The professional astronaut population has, by selection, a better than average health and physical capacity. The essentials of life on earth are adequately met by the spacecraft, however, the human body adapts to weightlessness which leaves it compromised for the usual life on earth but readaptation is rapid. Long term flight without countermeasures will produce major changes in the cardiovascular, respiratory, musculoskeletal and neuromuscular systems. There is strong theoretical and experimental evidence from 1-g studies and limited in-flight evidence to believe that exercise is a key countermeasure to many of these adaptations.

Table 1

Summary of changes produced by the major primary effects of weightlessness and effects seen on return to earth. The changes inflight are correlated to the effects seen on return to earth by their numerals.

Primary Effects of Weightlessness	**Effects on Return to Earth**	
Removal of Hydrostatic Pressures		
1. Shift and Loss of Blood Volume*	● Reduced weight[a]	1,2,7
2. Shift and Loss of Extra-vascular fluid	● Orthostasis	1,2,9(?)
	● Reduced exercise capacity	1,2,3,5,6
Loss of Locomotor Function		
Reduced Force Loads		
3. Muscle Atrophy*	● Reduced strength	3,8
4. Bone Loss*	● Reduced skeletal integrity	4
Reduced Metabolic Loads		
5. Decreased Cardiovascular capacity*	● Reduced work capacity	
6. Decreased Cardiorespiratory capacity*		
Altered Neurological Inputs		
7. Space Motion Sickness	● Altered postural and locomotor stability	3,8(?), 10(?)
8. Change in proprioceptive set points*	● Increased resistance to motion sickness	10
9. ?Change in baroreceptor set points?		
10. Changes in vestibular system		

---

[a] This is an obligatory fluid loss, majority of losses have an added metabolic loss (or gain) which is avoidable.

*Potential for modification by exercise.

Bibliography

1. Medical Standards NASA Class I Pilot Astronauts, Selection and Annual Medical Certification, JSC 11569.
2. Medical Standards NASA Class II Mission Specialist Astronauts, Selection and Annual Medical Certification, JSC 11570
3. Medical Standards NASA Class III Payload Specialists, Selection and Annual Medical Certification, JSC 11571
4. Medical Standards NASA Class IV, Medical Certification Criteria Space Flight Participant Program (SFPT), JSC 20400
5. Man Systems Integration Standards. NASA JSC-3000
6. Link, M.M., Space Medicine in Project Mercury, Chapter 10, NASA SP 4003, Washington, D.C., 1965.
7. Billingham, J., Russian Experience of Problems in Vestibular Physiology Related to the Space Environment: Second Symposium on the Role of Vestibular Organs in Space Exploration, NASA SP 115, Washington, D.C., 1966.
8. Berry, C., et al, Man's Response to Long-Duration Space Flight in Gemini Spacecraft. Gemini Mid Program Conference, NASA SP 121, pp 235-61, Washington, D.C., 1966.
9. Rummel, J., et al. Physiological Responses to Exercise After Spacefight. Apollo 7-11, Aerospace Medicine, 44: 233-238, 1973.
10. Thornton, W. and J. Rummel, Muscle Deconditioning and its Prevention in Space Flight, pp. 191-197, Biomedical Results from Skylab, NASA SP 377, 1977.
11. Weedon, G., et al, Mineral and Nitrogen Metabolic Studies, Experiment MO 71, pp. 164-173, Biomedical Results from Skylab, NASA SP-377, 1977.
12. Vogel, J., et al, Bone Mineral Measurement, Exp. MO 78, pp. 183-190, Biomedical Results from Skylab NASA SP 377, 1977.
13. Johnson, P., et al. Blood Volume Changes pp. 235-241, Biomedical Results of Skylab NASA SP 377, 1977.
14. Thornton, W., W. Hoffler, J. Rummel, Anthropometric Changes and Fluid Shifts, pp. 330-338. Biomedical Results from Skylab, NASA SP-377, 1977.
15. Thornton, W., Anthropometric Changes in Weightlessness. Anthropometric Source Book, Vol. I, Chapter I. NASA Ref. Pub. 1024.
16. Ludbrook, J. Aspects of Venous Function in the Lower Limbs, pp. 84-85 Charles Thomas, U.S. 1965.
17. Henry, J., The Significance of the Loss of Blood Volume into the Limbs During Pressure Breathing. J. Aviation Medicine. 22; 31-38, 1951.
18. Thornton, W. and J. Ord. Physiological Mass Measurements in Skylab, 175-183. Biomedical Results from Skylab, NASA SP 377, 1977.
19. Thornton, W., et al, Electronystagmography and Audio-evoked Potentials in Space Flight, Laryngoscope 95: 924-932, 1985.

N91-10579

526879

16p

Work, Exercise and Space Flight
III. Exercise Devices and Protocols

William Thornton, M.D.
Scientist Astronaut

Introduction

It has been shown that lack of usual work and exercise in space leads to adaptations of the musculoskeletal, cardiovascular-respiratory, and neuromuscular systems which are incompatible with normal function in 1-g (1). To prevent or minimize such adaptation, exercise must be supplied on orbit. This requires quantitative knowledge of the nature of work and exercise in terms of physics (forces, time, distance, etc.). Rather than try to generate *de novo* exercises and devices for space, existing exercise and devices will be examined in physical terms and matched to actual work and exercise usually done on earth. Finally, devices which can operate in weightlessness will be derived or designed, their performance determined in the physical terms and protocols designed to replace, as necessary, the original quantities lost. This brief analysis follows such plan.

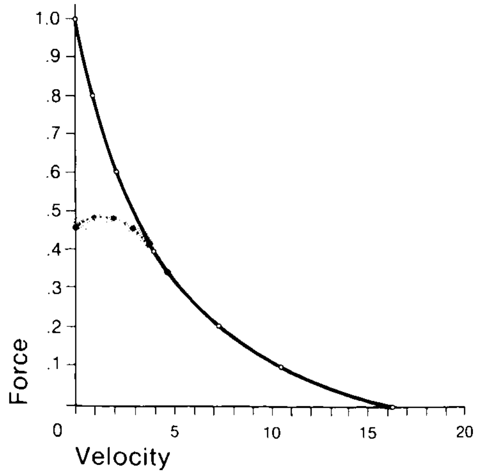


Fig. 1.- Force velocity curves from an isolated muscle fibre, dark line with open circles (A. V. Hill), and from intact limb segments measured isokinetically, dotted lines and solid circles (J. Perrine). The force-velocity ratios have been normalized in the isokinetic curve such that the final portion lies on the isolated preparation curve to illustrate the large amount of neurological inhibition present in intact neuro-muscular systems at zero and low velocities (shaded area). *From Perrine.*

Characterization of work and exercise - The primary function of muscle is to generate force and movement, hence external work and exercise can be defined in these quantities as a function of time. The generalized force-velocity curve for muscle is shown in Fig. 1. While it has long been recognized that force development of a muscle is velocity dependent (2), it is too often overlooked in practice, especially in measurement. A second characteristic is endurance which is dependent upon muscle training.

There is another crucial factor in exercise and work that is often overlooked, the nature and effect of external forces on muscle. The following is a description of commonly encountered forces. They are illustrated by a series of cartoons in Figs. 2 to 3.

1. $\text{Force}_g = \text{Constant}_{gr}$ (in magnitude and direction). F_g

Static weight is the outstanding example of this in which (Weight = mass · gravity), ideally isometric exercise is another.

2. $\text{Force}_G = \text{mass} \cdot \text{accleration}$. F_G

Such inertial force is seldom encountered in pure form on earth but is the predominant force in weightlessness.

3. $\text{Force}_R = \text{Velocity}^n \cdot \text{constant}_R$. F_R

This is a true resistive[a] force such as one encounters in wind resistance or rowing a boat. Typically n = 2

4. $\text{Force}_{Fr} = \text{Constant}_{Fr}$ velocity >0. F_{Fr}

---

[a] All external forces are still typically called 'resistance' by workers in exercise. Such generalities preclude rigorous treatment.

Frictional force such as sliding a load along a surface. Constant Fr is a function of forces between opposing surfaces.

5. $\text{Force}_{Sp} = \text{Constant}_{Sp} \cdot \text{Displacement}$. F_{Sp}

This is the relation for spring forces which are only occasionally encountered in nature but are frequently used in exercise devices.

6. Force_{IK} = muscle capacity
where velocity ≥ selected constant F_{IK}

This is isokinetic force which is seldom encountered except in testing or exercise devices. The force is small at all velocities below the selected limited velocity.

In practice, the muscle loads are usually some mix of the above, e.g. the archetypical muscle load is movement of a weight in 1-g where:

$$\text{Force}_{wt} = \text{Force}_g + \text{Force}_G = mg + ma$$

An understanding of these forces in exercise devices is as essential for success in design and application of exercise devices as is understanding of force magnitudes and kinesiology. Space is not available to describe the effect of these force types upon muscle beyond a few observations (3); type of force has great effect on endurance, i.e. forces cannot be equated on the basis of magnitude alone. Adequate inertia as part of the load is especially important. The locomotor exerciser ('treadmill') flown on Skylab 4 [Sect. 1, Fig. 9] was a friction device producing leg forces less than those developed in walking but which caused the legs to fatigue very rapidly. Cause of such rapid fatigue probably has to do with sustained force generation by the myofibrils, in contrast to brief bursts of force in normal walking or running where a major part of the energy is supplied to inertia. This 'stored' energy is released over the rest of the cycle while the fibrils rest prior to another burst of activity. Such flywheel action is somewhat analogous to that in an internal combusition engine in which the energy of a brief impulse is stored and released between impulses. The practical importance of this is that it is cheap and easy to develop forces by friction or viscous devices. Unfortunately, there are many bicycle ergometers and rowing machines and many other attempted substitutes for weights without significant inertia, all of which have major deficiencies. Such devices cannot be successfully substituted for the forces they try to mimic. It is a special temptation to try to use such devices in space flight for they are light in weight and simple but inadequate.

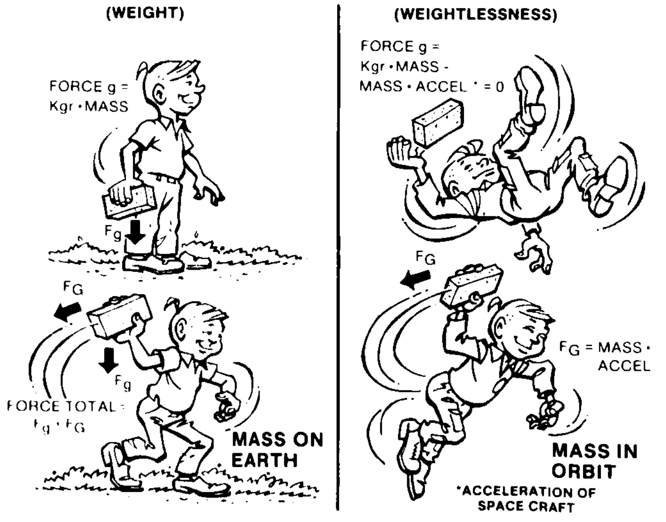


Fig. 2.- Illustrations of forces associated with mass on earth and in flight. Orbital acceleration, i.e. centrifugal force, balances weight in flight.

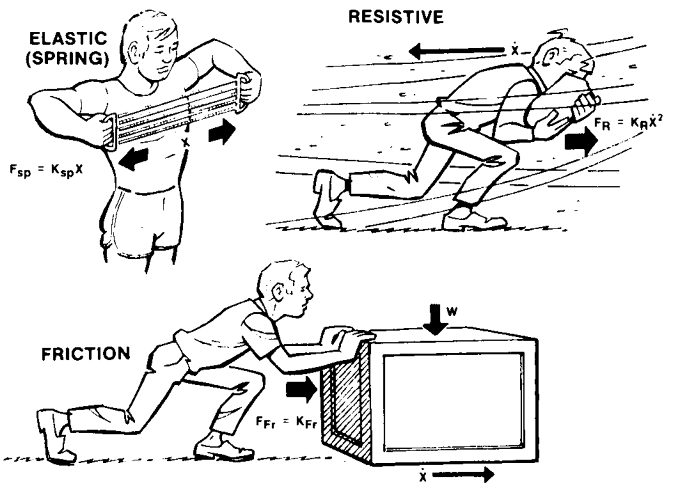
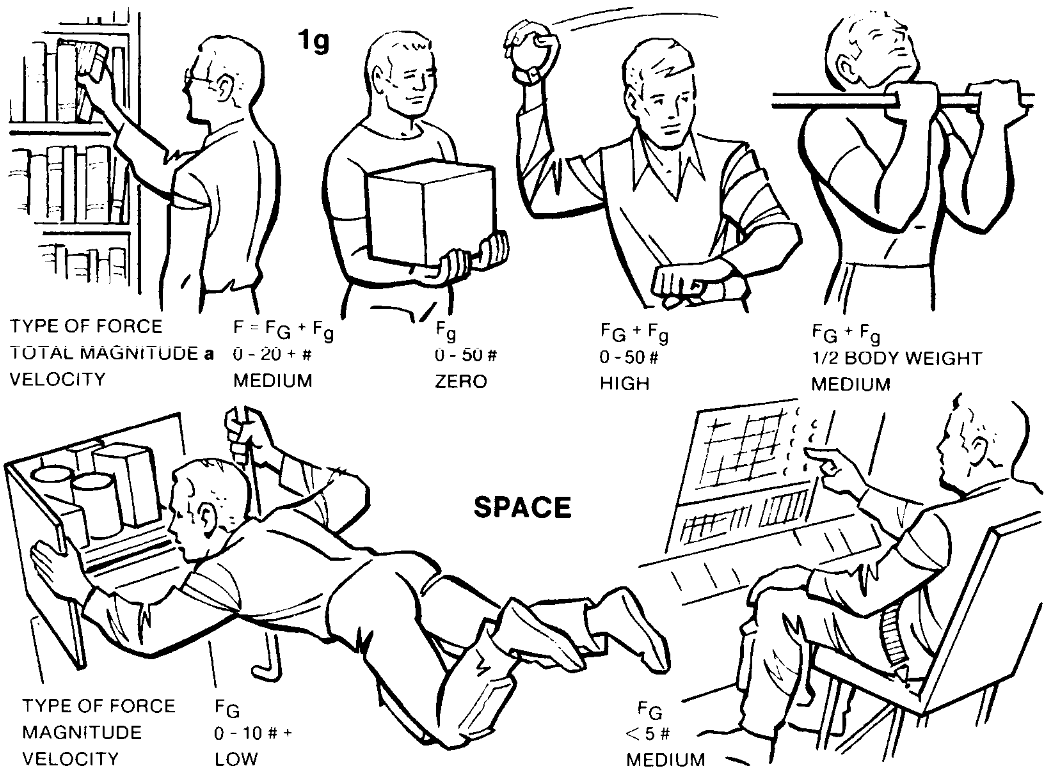


Fig. 3.- Other common forces include spring forces and true resistive forces. The latter directly dissipate energy.

Arm and Upper Body Exercise - There is great variabiity from individual to individual; however, manipulation of weights remains the archetype of all work and exercise. A wide range of other forces and motions is also encountered.

The range of arm work and exercise in 1-g is simply too extensive and variable to describe adequately. It is also individually variable in the Astronaut Office ranging from a number of competitive weight lifters to runners who do virtually no arm exercise. The archetype of arm work and exercise is movement



a - ARM WEIGHT IS NOT INCLUDED, BUT IS USUALLY AN APPRECIABLE FRACTION OF TOTAL

Fig. 4.- Illustrations of common arm forces with estimates of magnitudes on earth and in space. No large forces or rapid motions are usually generated in space.

of weight, albeit often only arm weight. Other common forces are carrying or holding weight and pushing or pulling, often times against friction or resistive forces. Throwing, frequently at large or near maximum acceleration rates, is also common. [Fig. 4].

In space, the usual arm force is fixing and maintaining body position by holding and stabilizing it with one arm, leaving the other free to manipulate objects. Arm activity is much greater in space than on earth but maximum and mean force loads are reduced. EVA operations are an exception to this and must be separately considered.

Truncal Work and Exercise - On earth, trunk[1] and vertebral muscles take part in locomotion, posture, and in supporting upper body and arm forces. Forces imposed on these muscles are often large. In weightlessness, these muscles are used but never with the loads or as frequently as in 1-g.

Arm/Trunk Exercise Devices - Rather than try to make a variety of arm and trunk exercise devices, the following arrangement is proposed as a general solution to the problem. A universal force generator -measurement unit [Fig. 5] will transmit forces to the subject through cable and pulley to handle or other means [Fig. 6]. The variety of exercise is only limited by users' imagination. Such force generation and measurement are made possible by a servo system in which the nature and magnitude of the force are controlled by electrical elements in a selectable series of feedback circuits (4). These circuits allow the system to generate exact analogs of forces normally generated by physical elements such as weights, etc. This includes an isokinetic mode. By monitoring internal signals such as force and displacement, the performance of a subject may also be monitored. Other trunk and arm exercises are considered later in this paper.

Leg Exercise - Locomotion (walking, jogging, running) is the primary exercise on earth. Forces, repetitions, and metabolic loads are briefly described in Section II, Figs. 2 thru 8. Kinesiology is relatively complex. Variants of locomotion are the games played by

---

[1] This does not consider the shoulder girdle muscles which are considered as arm muscles here.

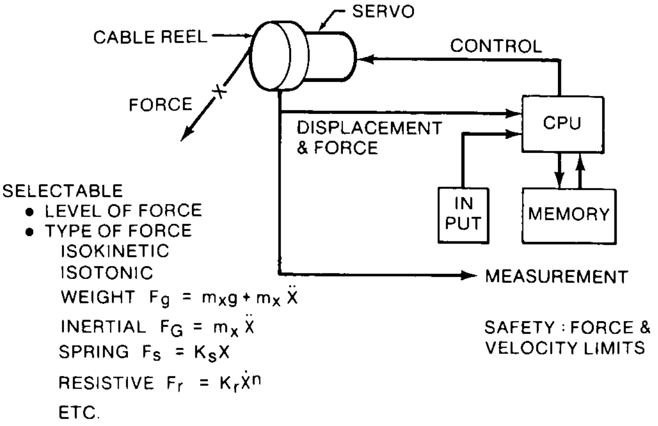


Fig. 5.- A force synthesizer made possible by efficient servo motors and feedback control. The latter is shown as a digital unit. Magnitude of the quantities such as equivalent mass and other constants plus equations of force may be set into the unit. Measurement of subject performance is accomplished from signals generated by and essential to its operation of the apparatus.

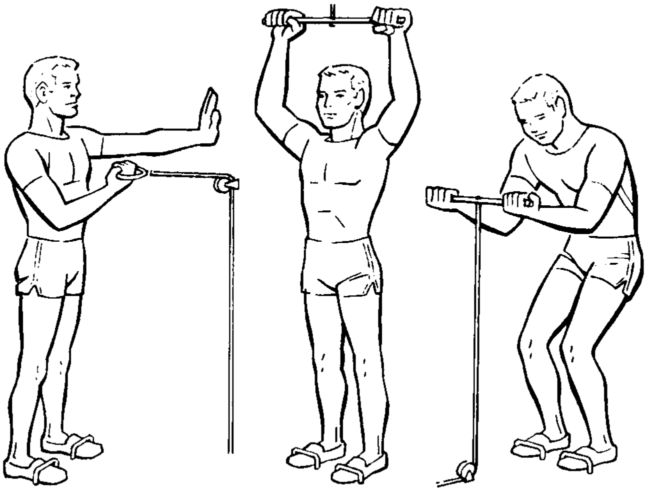


Fig. 6.- Only three of an infinite variety of exercises in space made possible by the force unit in Fig. 5 plus the necessary cable, pulleys, and restraints are shown here.

many, such as basketball and various other court and ball games. In these, action is more intermittant than in locomotion; hence, mean metabolic loads are lower but muscle involvement is more complex with occasional higher force loads.

Locomotor Exercise Devices - Currently, for a variety of reasons, replacement of locomotor exercise with a treadmill seems to be the only solution. A wide variety of leg exercise devices has advocates but when quantitatively examined without accompanying locomotor exercise, the often extravagant claims are not sustained in practice in one or more important areas. There is no currently available device which allows such a large number of repetitions at such large loads and also generates large metabolic demands.

Some of the current devices advocated are:

	Max (Usual) Peak Force Loads[b]	Similarity of Kinesiology[c]	Maximum Metabolic Loads
	X Body Weight		% Max[a]
Bicycle Ergometer$_m$	0.3 (.2)	Poor	~100%
Rowing Machine$_m$	0.5 (.3)	Poor	>100%
Continuous Stepper$_m$	~2.0 + (.8)	Poor	~100%
Simulated Skiing$_e$	1.0 + (1.)	Fair	≧100%
Climbing$_e$	1.0 + (.8)	Poor	≧100%
Treadmill$_m$			
Walk	1.8 + (1.8)	Almost exact	100%
Jog	3.0 + (3.0)	Almost exact	100%
Run	8 (3-5)	Almost exact	100%

---

[a] Referred to treadmill

[b] One leg

[c] Referred to walking/running in 1-g.

m measured
e estimated

A well-designed treadmill in 1-g allows almost perfect reproduction of locomotion [Fig. 11]. The problem is to produce a similar device in weightlessness. Major concerns are size, weight, power, and vibroacoustic properties. An additional problem in weightlessness is provision of constant vertical forces to replace weight: methodology is illustrated in Figs. 8, 9, and 10. The following is a brief description of it.

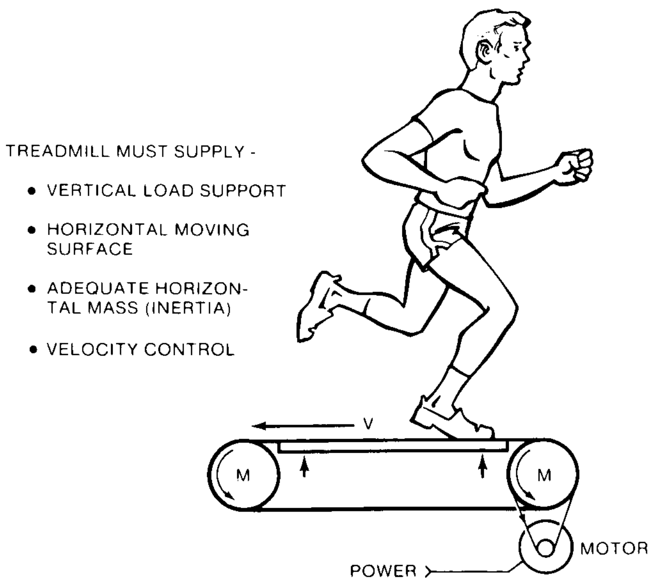


Fig. 7.- A well-designed treadmill with adequate vertical support and adequate inertia (or instantaneous power) to prevent changes in speed with the accelerations-decelerations on foot fall allows almost exact replication of locomotion on earth. This is usually provided by a belt supported by a rigid surface, a large motor (often 3-5 HP) and some form of belt speed control.

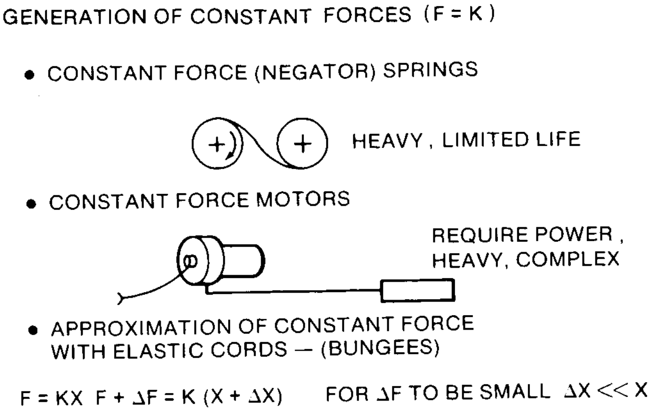


Fig. 8.- Three means of generating constant forces. Of these, bungees (springs) are the simplest but must be long for a good approximation.

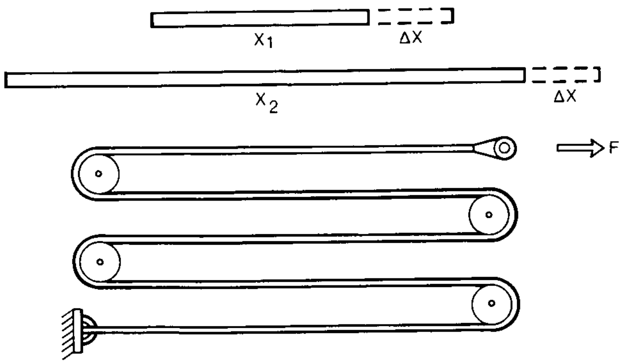


Fig. 9.- Generation of almost constant forces by elastic cords (bungees). Motion (changes in length) must be small compared to cord length as in X_2 in practice length is achieved by "folding" with pulleys.

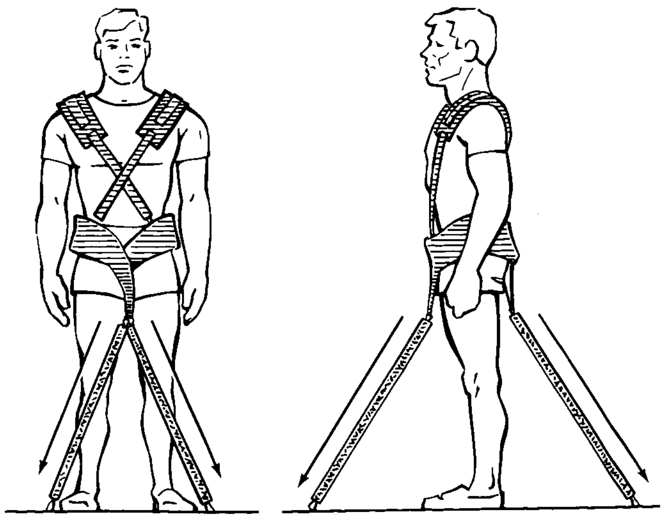


Fig. 10.- Currently used harness arrangement to provide equivalent weight on a subject. The bungees are longer and 'folded' [Fig. 9].

An initial treadmill was made for Shuttle and regularly flown since the third flight but severely constrained by size, weight, and funding. It can provide the basis for a proper design [Fig. 11].

A light rigid structure was fabricated from aluminum. The tread, which was constrained by considerations of space available is built from folded rectangular sheet metal sections running on precision ball bearing rubber shod wheels in a precision track to minimize friction. Adequate inertia is provided by a flywheel coupled to the tread by a high-ratio gear system. Speed control is provided by a centrifugally controlled mechanical brake which may be set to one of seven positions corresponding to 2.6 to 4.8 MPH. Weight equivalent force is closely approximated by four elastic bungees [Fig. 9] and a hip and shoulder harness [Fig. 10]. Force is individually adjusted to 1-g equivalent BW by setting the lengths of the straps which couple the bungees to harness at preset locations. By keeping the total length (X) of the bungee large as compared to changes in length (ΔX) during the step cycle changes in force (F) are small:

$$\Delta F \alpha F \cdot \Delta X \cdot X^{-1}.$$

1. TREAD
2. PULLEYS
3. FLYWHEEL
4. BRAKE
5. SPEED CONTROL
6. SPEEDOMETER
7. CONTROL
8. TACHOMETER GENERATOR

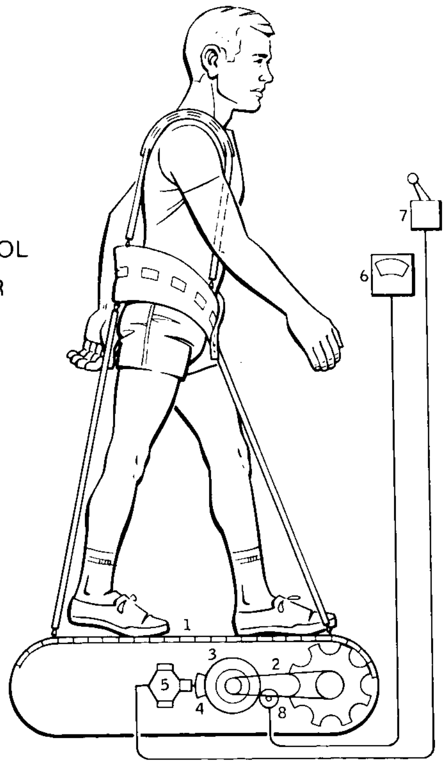


Fig. 11.- Schematic of original Shuttle Treadmill showing bungees and harness plus major components. Tread surface was 12. × 32.". It has been replaced by a smaller unit with a tread surface of 12. × 34.5", and with longer 'folded' bungees for more constant force.

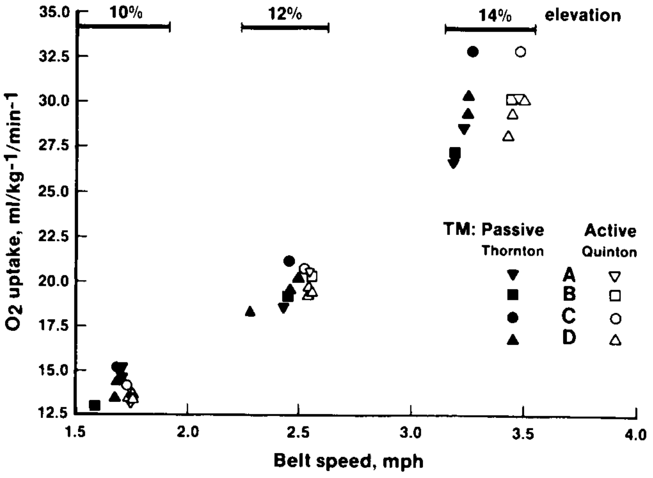


Fig. 12.- Comparison of metabolic costs for four astronauts running on an active treadmill (open symbols) and the subject driven Shuttle treadmill (filled symbols) in 1-g. The slightly increased costs on the Shuttle unit are probably caused by the small running space available resulting in extra muscular activity to stay within the area. Elevations were 12%, 14%, and 16% grade, increasing with speed.

A major point of confusion for many life scientists and even some engineers is the difference between motor driven and subject driven treadmills even to the point of causing them to make such statements as "We must have a motor driven treadmill which will not (unduly) tire the astronauts." A rough demonstration of the equivalence of active and passive treadmills is shown in Figure 12. There is no difference between well-designed motor driven and passive treadmills except at zero grade. At zero elevation, the subject's net external work is zero [Fig. 13]. At all other elevations, the subject inputs mechanical work to the treadmill, i.e. he drives the treadmill and not vice versa, whether passive [Fig. 14] or motor driven [Fig. 15]. This may be seen in motor driven treadmills by a reduction in motor power with increasing treadmill elevation. The real purpose of the motor in common treadmills is to provide the power to drag the belt over its support, to control speed and to provide inertia. A low friction arrangement such as we have on the Shuttle is more expensive to make than a belt, motor, and electric power and is not seen in the commercial market. A treadmill with no friction and adequate inertia could be run at zero grade after a starting transient in which the subject must push against a support to apply horizontal reactive forces to the tread. In practice in 1-g, the passive treadmill must be elevated to a point where the external work done in climbing is equal to the resistance losses which dissipate this work.

The gravity gradient of the elevated treadmill on earth is replaced by a slight forward tilt of the long axis of the subject to the treadmill surface in weightlessness [Fig. 16]. This is allowed by the elastic

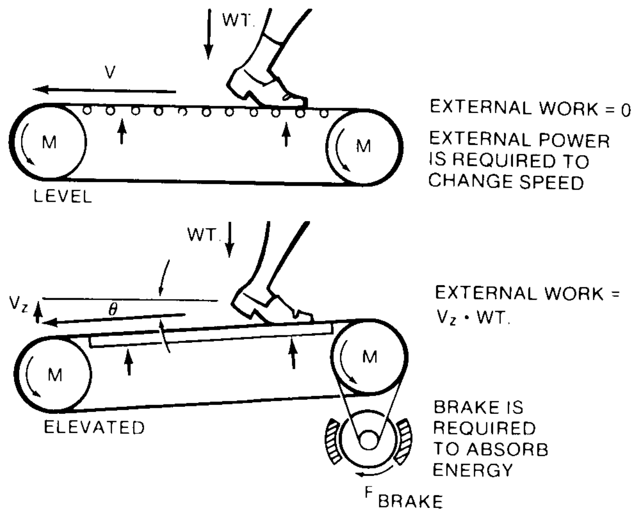


Fig. 13.- In human locomotion, the horizontal component of ground force is first negative, i.e. instantaneous deceleration followed by acceleration at each foot fall but the net force is zero. Only during changes in speed or with elevation is a net external force imparted. The external work done in climbing a grade is the vertical component of velocity V_z multiplied by the subject weight. This component is given by V_z V Sinθ and the external work, which must exactly equal energy dissipated by friction, is W_{ext} Wt · VEL Sinθ.

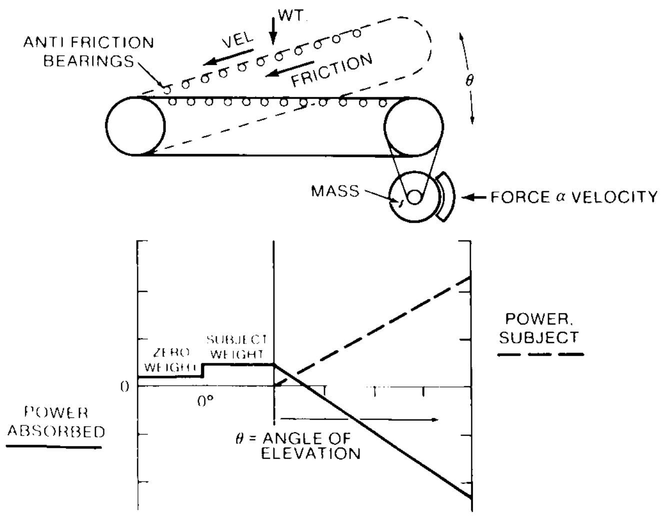


Fig. 14.- Power absorbed by the treadmill is shown by the solid line in the plot. Subject weight slightly increases the friction and at zero level can only be overcome by the subject pushing against some external object. As the elevation angle θ is increased, power into the treadmill (broken line) is increased until it equals frictional loss. Above this critical deviation, speed must be controlled by additional friction which is provided by a brake on the flywheel actuated when velocity exceeds one of seven levels (speeds) set into the brake mechanism.

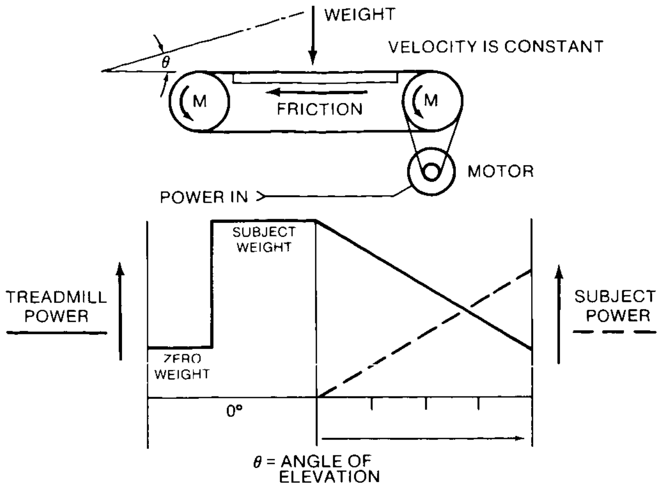


Fig. 15.- The external work relationship holds for a motor-driven treadmill but internal friction, usually a belt dragged over a support plate, is high, especially when the subjects' weight is on the tread, shown in the diagram by the step function in the power (solid line). As the angle is increased, subject input power (broken line) is increased and motor input is decreased but never below that required to overcome frictional losses.

bungees, with excellent stability. The angle is determined only by the mean force imparted to the tread, hence grade and speed are not independent on this device. While speed is controlled in 7 steps from 2.6 to 4.8 mph, this in turn requires a minimum force input at each velocity which sets the equivalent grade.

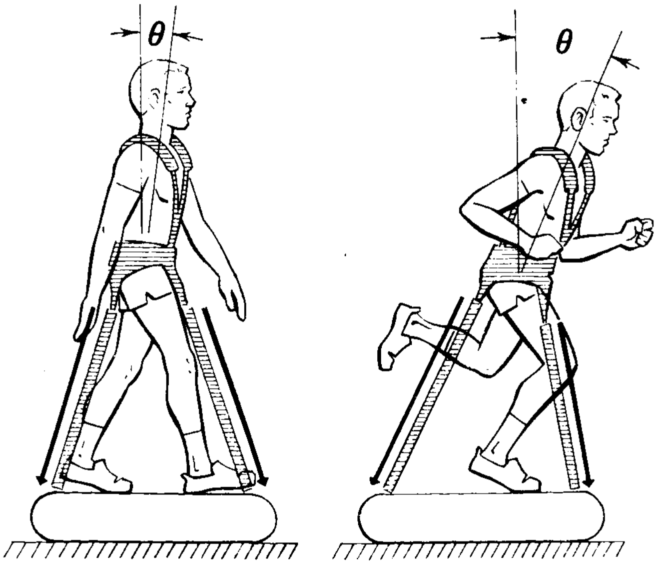


Fig. 16.- Subject on treadmill in weightlessness at two different speeds and treadmill loads. The treadmill is driven by the force parallel to the tread and this is developed by tilting the mean force vector opposite to the direction of tread movement. The tilt is handled nicely by compliance of the bungees whose expansion/contraction produces the necessary tilted force.

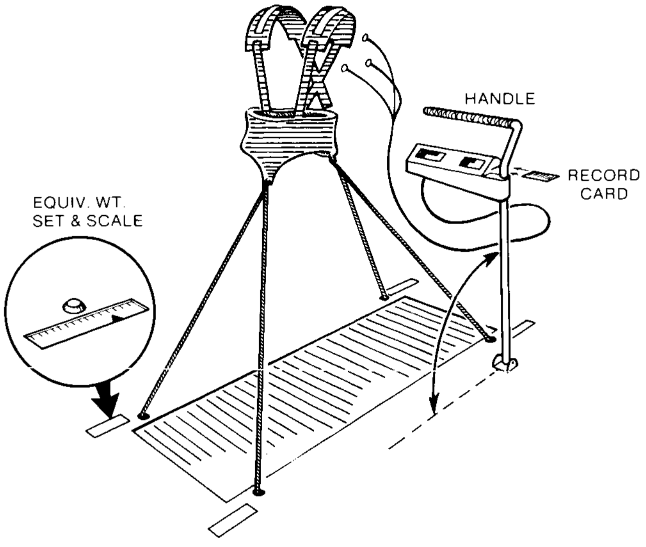


Fig. 17.- Drawing of prototype Space Station Treadmill currently under construction. Active tread area is 14 × 42".

A prototype of the treadmill suitable for use in Space Station is currently under design and construction but is hampered by lack of adequate funding [Fig. 17]. It should have an adequate tread, be flush with the floor surface, have a range of speeds from 2 to 6 mph, provide subject loading equivalent to body weight of 100 to 225 lbs., and be easily adjustable and accurately measured, have low noise, with vibration isolation from the space craft and means of monitoring, displaying, and recording speed, heart rate, and subject equivalent weight. It also has provision for a motor drive to allow operation at zero equivalent elevation.

Other Devices - The universal force generator system and treadmill should provide the core exercise for usual purposes but there are two other categories to be considered: 1) maintenance of condition for suited (EVA) operations and 2) optional exercises. Suited operations have special demands which include resistance and elastic recoil on many motions with elasticity of gloves which tire hands and fingers as well as occasional large metabolic loads. Endurance is required for good operator function. While the demands of the metabolic load may be met by training with cardiovascular-respiratory exercise, there are no exercises at this time for musculoskeletal demands of the suit. It is the feeling around the Astronaut Office, which is consistent with EVA experience on Skylab 4, that so long as usual physical condition is maintained by routine exercise, no special requirements are necessary. A possible exception is hand exercise which could be provided by a special device with multiple but individual finger loading. Should this not be the case, an exercise suit with gloves which could be pressurized to the usual differential, might be the most efficient way to maintain condition when there are significant periods without EVA activity. This applies only to those crewmen trained for EVA operations.

Other optional exercise devices might include any small personal preference items, e.g. hand grip devices, etc. In addition, we are almost certain to have a bicycle ergometer to meet the needs of investigators. It is an excellent cardiovascular-respiratory exercise when used properly but is almost worthless for leg exercise. Another favored device is the rowing machine. There are a wide variety of such devices commercially available which range from simple resistance loads without inertia to excellent simulation of rowing. No objective biomechanical information on rowing or simulators was available so I instrumented an ergometer which closely simulates rowing force. Two members of our office made some time/force records with it. A composite of one such record is shown in Fig. 18. The work level was maximum, i.e. a brief sprint, but note that maximum individual leg forces developed are ~ 100 lbs. or 0.5 BW for this subject. Arm and back loads are relatively high but the arm loads are primarily passive tension. There is some literature on metabolic loading by this device which shows that it performs well in that regard. These characteristics make it attractive as an occasional alternative to treadmill and weights. N.B. Leg loads of both this and especially the bicycle make them useless for maintenance of locomotor capacity, hence they cannot be used as alternatives.

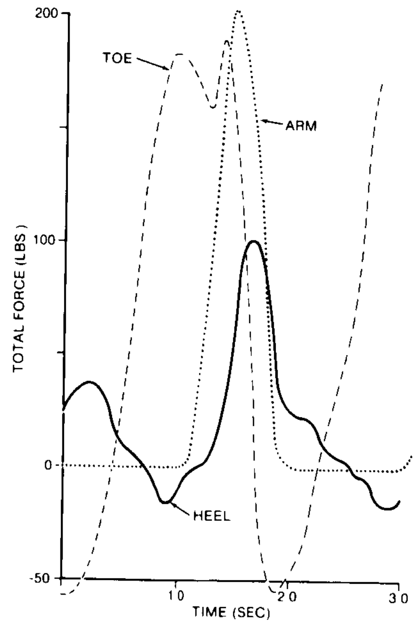


Fig. 18.- Measured forces developed at maximum effort on a rowing ergometer by 200 lb. subject in good condition. These forces are for both legs and both arms.

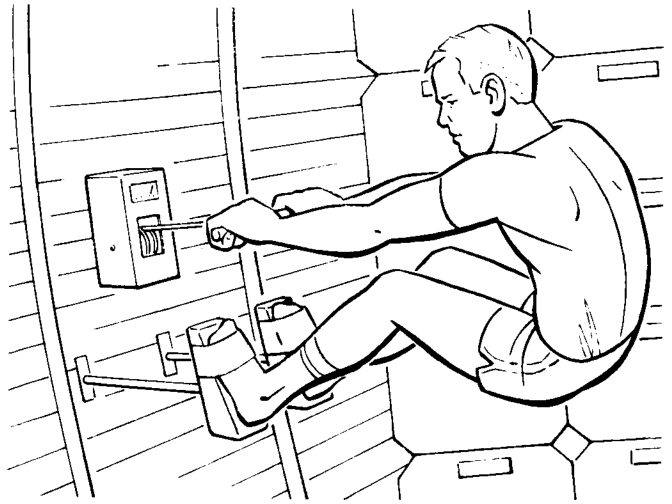


Fig. 19.- Conceptual sketch of rowing machine in use in weightlessness. Load generator has been built and is in test. Preparation for 'zero-G' flight testing is underway.

Sketch of a prototype rowing machine conceived by the author is shown in Figure 19. This used a load generator system we developed for a clinical bicycle ergometer years ago. We are in the process of testing a prototype unit which will be demonstrated here later today. The load generator can be coupled to pedals and used as a bicycle ergometer or to a cable and handle and used as a rowing machine, i.e. a dual purpose device is possible. The load consists of inertia plus a resistive load of the form;

$$F = K \cdot \text{Velocity.}$$

One aspect of force exercise which has been largely ignored, is the maintenance of strength at rapid angular rates. The Russians have found that strength is lost more rapidly at high than at low rates. (5). Maintenance of such fast twitch ability may be important to normal 1-g functions. Sprints on the treadmill should cover this concern for legs but it might be desirable to add such fast exercises to cover the arms and trunk. One possibility is use of light weights in a series of motions equivalent to the Heavy Hands$_R$ programs on earth (6). A punching bag, with certain concessions, should function in space as should tethered balls. Hopefully we can produce some competitive exercises which might be based on a closed space with struck objects which are at least partially free.

Since Space Station is years away and should then have a life of many years hence devices should not be inseparably tied to the Station, rather they should be replaceable with improved items which are sure to develop (Fig. 20).

Protocol - The first step in development of a protocol (dosage if you will) is determination of level of capacities to be preserved. To do this successfully, the individual's work and exercise regimen on earth must be known as well as his capacities. Again, it will not be practical, even if possible, to maintain extreme capacity, e.g. marathon level or 'body builder' muscle strength. Taking the guidelines in Section II as a minimum, inflight exercise should be tailored to the individual to maintain as much of his 1-g capacity as possible. On-orbit work will at least partially preserve arm capacity. Conversely, muscle capacity of the legs is not preserved at all; and in the same process, cardiovascular-respiratory capacity will be sharply reduced. Based on this, treadmill exercise must take priority. It has to be performed at the subject's equivalent weight and should be equivalent to his locomotor exercise on earth, if possible.

The following concept will be tested in bed rest to determine if it will maintain musculoskeletal and cardiovascular-respiratory level. This also represents my best estimate of times and level required to date. The mean daily time and distance of locomotor exercise in 1-g will be determined. For example an individual might be running 2.5 miles at a rate of 8 minutes per mile or 20 minutes. Also, a count of average walking steps will be determined and their effect will be reproduced at a higher force load but reduced number by:

$$\sum_{\substack{\text{earth}\\ \text{Peak force} > 0.8\text{ BW}}} \text{number of steps} \cdot \text{peak force} \cdot \text{step}^{-1}$$

$$= \sum_{\substack{\text{space}\\ \text{Peak force} > 0.8\text{ BW}}} \text{no. of steps} \cdot \text{peak force} \cdot \text{step}^{-1}$$

A typical example might be 2500 steps $\times$ 1.8 BW = n $\cdot$ 3.0 BW or 1500 steps when running[a]. This could typically result in an additional 9 minutes of running. It would be preferable to divide this into two daily sessions. It may be possible to reduce this time especially if several fast sprints are part of the regimen. The above protocol should certainly maintain cardiovascular-respiratory capacity. It should also maintain leg strength in all areas but should testing reveal that it does not, then and only then should additional mandatory specific exercises be instituted.

Arm and trunk exercise should also be individually determined. For those who routinely do reasonable amounts of such exercise, an equivalent protocol in space would be appropriate. For those who do not, some standard program to maintain strength and endurance adequate to assure successful completion of escape maneuvers will be required.

It is obvious that neither time nor loads can be standard, rather they will be a function of individual history and capacity. Unlike many medications which depend only upon exceeding some threshold with a wide range of tolerance, exercise produces results in proportion to its 'concentration'; and its upper limit is constrained by time available and facilities, i.e. one cannot shotgun here. To ensure that 'dosage' is correct, results must be measured, i.e. periodic tests must be conducted inflight and levels changed as necessary. This is discussed in the next section.

The described regimen for core exercise should be augmented with time available for personal preference exercises which could include bicycle or rowing ergometry, 'speed' exercises, 'weights', etc., but it will be a serious mistake to confuse these with core exercise. Also, an approach in which a bit of everything is included will almost ensure failure. The goal must be to know and replace what is lost in the absence of 1-g work and exercise.

Exercise Evaluation - It is crucial to understand that success or failure of this program is absolutely dependent upon the individual who is exercising. The best insurance of success is to make this individual responsible for his own well-being. He must understand what is required and be given the means to ensure it is done. The first person to be aware of exercise test results should be this person. He should be provided with the knowledge, the exercise apparatus and time, and a means to evaluate his efforts. In addition, he must be a partner in any higher level monitoring by Life Sciences. A general plan for monitoring of any effort follows.

The first step is sufficient objective monitoring of a crewman's 1-g activities to establish an individual baseline. The subject and medical officer should collaborate on this exercise profile. Data would include measurement of locomotor activity with logging of arm exercises plus recorded estimates of other activity such as significant manual labor, sports, etc. Appropriate interactive performance testing of capacities would be done, e.g. O_2 uptake, strength and endurance testing of significant muscle groups, especially those

---

[a] Running produces forces of ~ 3 BW versus 1.8 BW walking.

involved in emergency maneuvers. This would be administered by the physician and made jointly available to physician and subject. From this, a recommended baseline exercise plan would be developed with flight surgeons and subject using the guidelines developed and tested. In flight, routine monitoring and storage of all exercise data on an individual basis should be available with on-line monitoring and onboard facilities for display of the individual's stored data. A periodic self-evaluation test program should be provided which allows the subject and physician to follow significant parameters on a 'how goes it' basis. At longer intervals, physiological performance testing would occur. These results would be available to the subject. This would be an interactive program in which monitoring and test results could be modified to achieve desired levels of capacity. Any research or investigation which alters the usual protocol should be labelled and clearly understood by all involved.

Summary - The following is my estimate of a protocol based on experience to date.

Preservation of locomotor capacity by earth equivalent, exercise in space is the crucial component of inflight exercise. At this time the treadmill appears to be the only way possible to do this. Work is underway on appropriate hardware but this and a proposed protocol to reduce exercise time must be tested. Such exercise will preserve muscle, bone Ca^{++} and cardiovascular-respiratory capacity. In addition reasonable upper body exercise can be supplied by a new force generator/measurement system—optional exercise might include a rowing

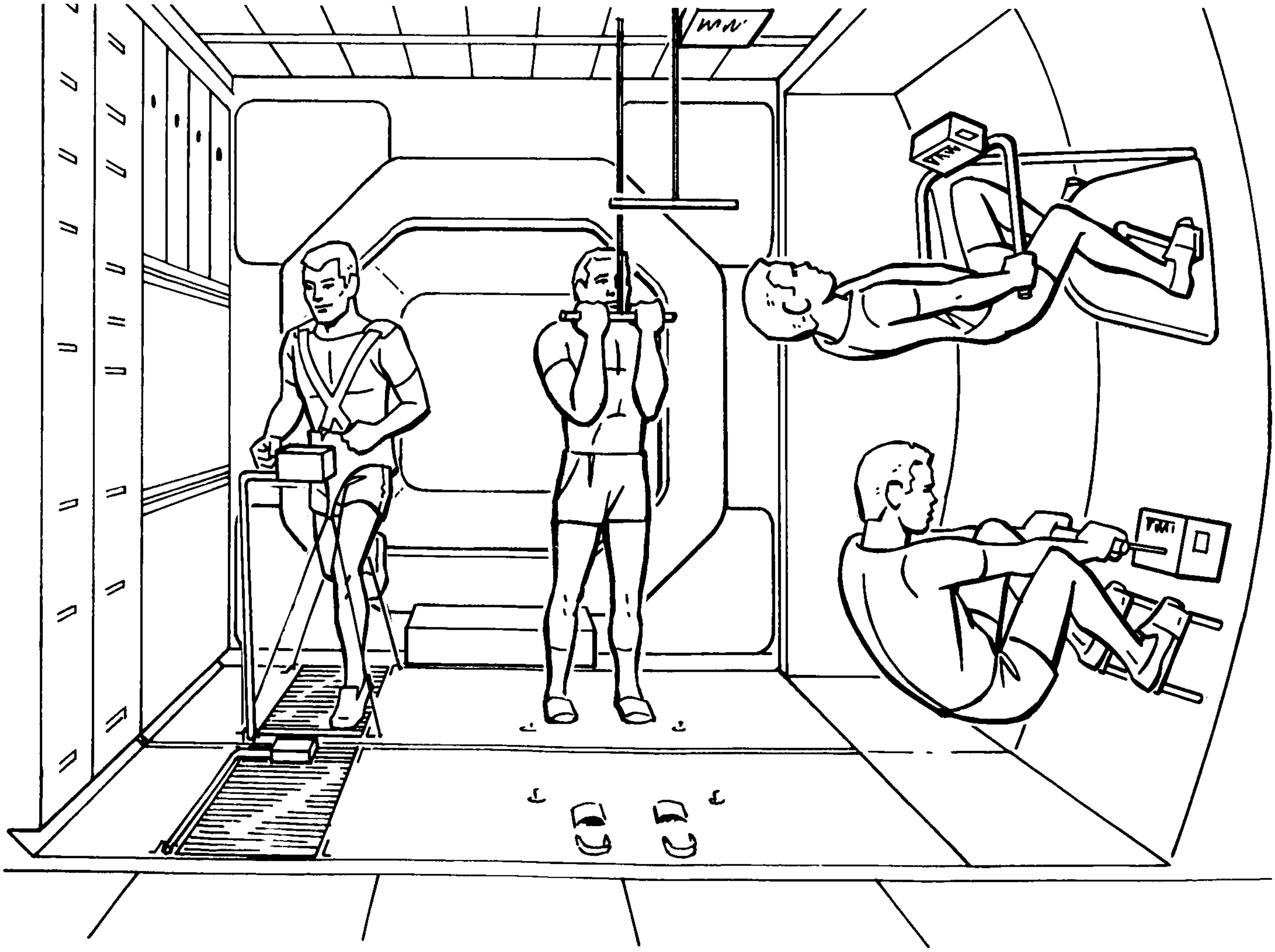


Fig. 20.- Conceptual sketch of exercise area (gym) in current space station layout. Dual treadmills, multipurpose arm-trunk ergometers, bicycles and rowing machines are available. All devices have individual crew recorders.

machine and bicycle ergometer. A subject centered monitoring-evaluation program will allow real time adjustments as required. Absolute protection for any astronaut will not be possible and those with hypertrophied capacities such as marathoners or weight lifters will suffer significant loss however the program described should return the crew to earth with adequate capacity for typical activity on earth including immediate ambulation and minimal recovery time and without permanent change. An understanding of the practical mechanics and biomechanics involved is essential to a solution of the problem.

Day	Exercise and Time[1,2]			Evaluation		
		Min-Mean-Max				
	Locomotor	Trunk & Arm	Optional	Mon.	Eval.	Test
1[3]	10 - 20 - 30		5 - 15 - 25	All		
	10 - 20 - 30		5 - 15 - 25	All		
2	10 - 20 - 30	5 - 15 - 25		All		
	10 - 20 - 30	5 - 15 - 25		All		
3	10 - 20 - 30		5 - 15 - 25	All		
	10 - 20 - 30		5 - 15 - 25	All		
4	10 - 20 - 30	5 - 15 - 25		All		
	10 - 20 - 30	5 - 15 - 25		All		
5	10 - 20 - 30		5 - 15 - 25	All		
	10 - 20 - 30		5 - 15 - 25	All		
6	10 - 20 - 30	5 - 15 - 25		All		
	10 - 20 - 30	5 - 15 - 25	All			
7	10 - 20 - 30		10 - 20 - 30	All		
	10 - 20 - 30		5 - 15 - 25	All		
8	30				Per	
	30				Per	
22						CVR
23						MS
31					Per	
					Per	

Cycles repeat in above order

NB at least 15 minutes cleanup must be allowed at each session.

[1] Time in minutes

[2] This is a function of subject's 1-g evaluation.

[3] Two sessions/day

Per - Physical Performance - strength, endurance - every 8th day
CVR - Cardiovascular Respiratory
MS - Musculoskeletal
Mon - Monitor

The foregoing is an estimate which will surely change with results from bed rest studies, further Shuttle and possibly Russian studies, and certainly on orbit; however, it has an objective basis.

Bibliography

1. Sections I and II, Work and Exercise in Space; this report.
2. Hill, A. V., First and Last Experiments in Muscle Mechanics, Cambridge Univ. Press., G.B., 1970.
3. This is largely based on unpublished work of the author done at School of Aerospace Medicine in support of USAF MOL, 1966, 1967.
4. Thornton, W., Ergometer, U.S. Pat. No. 3, 589, 193; June, 19, 1971.
5. Yegorov, A. D., Results of Biomedical Investigations during the 175-day flight of the third prime crew on Space Station Solyut-6/Soyuz. Moscow, 1980. NASA JSC Translation.
6. Schwartz, L., Heavyhands, Warner Books, USA, 1983.

SECTION 2

PHYSIOLOGICAL ASPECTS OF EXERCISE

Discussion on Muscle Atrophy

Amy Fremion
Indiana University School of Medicine
Indianapolis, Indiana

The often-used phrase "use it or lose it" was never more applicable than in the case of muscle. The most unique property of muscle is that it manifests clear volumetric change in response to the needs of the organism; i.e., atrophy when not used and hypertrophy when used. Atrophy means that size decreases but morphological characteristics are maintained. The diameter of muscle fibers is modified by exercise, general nutrition, age growth hormone, and testosterone.

Disuse atrophy is a common clinical observation. It is, however, often a diagnosis of exclusion in cases of the neurological literature. Traditional neuropathologic teaching is that the pattern of atrophy caused by disuse is type 2 atrophy (ref. 1). (See addendum.) This dogma is being challenged, however, by studies such as that by Sergeant et al. (ref. 2) using immobilization. They found greater atrophy in type 1 fibers in six of seven subjects. Patients with type 2 atrophy often have a variety of nonmuscular disorders; e.g., osteomalacia, chronic alcoholism, Cushing's disease. Consequently, the type 2 atrophy seen in these patients may be due to pain, general ill health, or the underlying disease, rather than to disuse. Patel et al. (ref. 3) selected patients free from chronic disease for their study and found group atrophy in 5 out of 14. They proposed that disuse atrophy may have a neurogenic basis, the changes in the muscle being secondary to primary, but less obvious, involvement of the nerve. The alternate explanation is that group atrophy is not specific to a motor nerve or motor neuron lesion, but can result through other mechanisms. Except for a relative increase of muscle nuclei in the atrophied fibers, there was no discernible change in the structure of the extrafusal or intrafusal fibers, connective tissue, blood vessels, or nerves.

What is clear from reviewing the literature is that the pathophysiology of muscle atrophy is not known. Atrophy is seen in suprasegmental lesions of the nervous system, in denervation, and in myopathies. Regardless of the condition determining the disuse, the muscle slowly atrophies and fibrous tissue takes its place.

In a weightless environment, the amount of muscular force required to produce locomotor activity is small enough to lie in the domain of inactivity. There is a lack of static loads and a drastic decrease of dynamic loads in the musculoskeletal system in space, resulting in hypofunction and in changes typical of disuse atrophy. Postflight skeletal muscles have glycogen and lipid accumulations which may be associated with decreased energy expenditures due to deterioration of muscle function. Such accumulations may cause an imbalance between the synthesis and the utilization of energy substrates. Muscle disuse during weightlessness also leads to depletion of almost 30 percent of capillaries (ref. 4).

Musculoskeletal changes during space flight are of dual importance: in and of themselves and as contributing to other pathogenic developments in the body during weightlessness; e.g., suppression of erythropoiesis, disturbed thrombocytopoiesis, and osteoporosis. The effects of disuse on the musculoskeletal system, as well as the regenerative potential of skeletal muscle, must be better appreciated in order to establish the most favorable circumstances for the restoration of function after weightlessness. To this end, several Earth-based models have been developed to mimic the production of muscle atrophy in weightlessness: denervation, limb immobilization, and head-down tilt suspension. Each of these models has advantages and disadvantages, but none of them can be extrapolated directly to humans during weightlessness.

Cooper (ref. 5) demonstrated that immobilization initiates muscle cell disintegration which is reflected by a decrease in weight to 30 percent of normal after 22 weeks. Immobilized muscle with an intact blood and nerve supply and intact sarcotubes has regenerative potential after release from immobilization. Restoration of damaged fibers begins 3 to 5 days after release. As a result of endomysial proliferation, tubes are formed which guide the regenerating contractile elements during a well-defined sequence of regenerative changes.

Hargens et al. (ref. 6), using head-down tilt suspension, found that type 1 fibers of antigravity muscles are more sensitive anatomically, physiologically, and biochemically to weightlessness compared to other fiber types. They presume that skeletal muscle is altered during weightlessness because of increased proteolysis and altered osmotic stages at the cellular level. Chui and Castleman (ref. 7) studied rat muscle fibers after two space flights and found trophic changes in antigravity muscles, resulting in muscle atrophy.

Since increased plasma cortisol is a well-known cause of muscle atrophy, the changes seen in cortisol levels of astronauts is something else to consider as a cause of atrophy during weightlessness. Plasma cortisol levels of astronauts have been reported to be increased by about 20 percent on day 6 of weightlessness and to remain unchanged for the next 40 days (ref. 8).

Once the pathophysiological mechanisms of muscle atrophy during weightlessness are learned, methods of prevention can be quite specific. In the meantime, countermeasures such as exercise, electrical stimulation, diet, and possibly hormones will be employed.

References

1. Dubowitz, V.; and Brooke, M. H.: Muscle Biopsy: A Modern Approach. W. B. Saunders (London), 1974.

2. Sergeant, A. J.; Young, A.; et al.: Functional and Structural Changes Following Disuse of Human Muscle. Clin. Sci., vol. 52, 1977, pp. 337-342.

3. Patel, A. N.; Razzak, Z. A.; and Dastur, D. K.: Disuse Atrophy of Human Skeletal Muscles. Arch. Neurol., vol. 20, 1969, pp. 413-421.

4. Kaplansky, A. S.; Savina, E. A.; et al.: Results of Morphological Investigations Aboard Biosatellites Cosmos. The Physiologist, vol. 23, no. 6, suppl., Dec. 1980, pp. S51-S54.

5. Cooper, R. R.: Alterations During Immobilization and Regeneration of Skeletal Muscle in Cats. J. Bone Joint Sur., vol. 54A, 1972, pp. 919-953.

6. Hargens, A. R.; Tipton, C. M.; et al.: Fluid Shifts and Muscle Function in Humans During Acute, Simulated Weightlessness. J. Appl. Physiol., vol. 54, 1983, pp.1003-1009.

7. Chui, L. A.; and Castleman, K. R.: Morphometric Analysis of Rat Muscle Fibers Following Space Flight and Hypogravity. The Physiologist, vols. 18-19, suppl., 1976, pp. S76-S78.

8. Leach, C. S.; and Rambaut, P. C.: Biochemical Responses of the Skylab Crewmen: An Overview. Biomedical Results From Skylab, Richard S. Johnston and Lawrence F. Dietlein, eds. NASA SP-377, 1977, pp. 204-216.

Addendum

Patterns of Muscle Fiber Atrophy (ref. 1)

1. Global atrophy or hypoplasia - disuse, cachexia, senility
2. Type 1 fiber atrophy - myotonic dystrophy, congenital myopathies
3. Type 2 fiber atrophy - disuse
4. Congenital fiber type disproportion - autosomal dominant, decreased type 1
5. Random distribution of round and ovoid atrophic fibers - dystrophy, polymyositis
6. Random distribution of small angulated fibers - acute denervation, both types 1 and 2 involved
7. Small group atrophy - neurogenic disease
8. Large group atrophy - Werdnig-Hoffmann type
9. Fiber type grouping - reinnervation
10. Perifascicular atrophy - dermatomyositis

N91-10580

4P 526882

Space Medicine Considerations: Skeletal and Calcium Homeostasis

Victor B. Schneider, M.D.
NASA Lyndon B. Johnson Space Center
Houston, Texas

I. Relevant Issues

A. Preventable Risks:

1. Short term
   a. Hypercalcemia
   b. Renal and other stones
2. Long term - Skeletal atrophy

B. Medical Questions:

1. Does hypercalcemia occur?
2. What are the changes in urine concentration?
3. What is the rate of an individual's bone loss?
4. How long does it take to recover bone after return to Earth? Is there a postcareer hazard regarding bone loss?
5. Is an exercise or pharmacological countermeasure needed for this length flight? Is the exercise or pharmacological countermeasure prescribed working?

C. Medical Operations Evaluation Requirements:

1. Ionized calcium determinations - in flight
2. Metabolic balance for calcium - collections in flight, analysis on Earth
3. Bone densitometry - in flight
4. Mineral and hormonal determinations - collections in flight, analysis on Earth

II. Background: Bone and Mineral Metabolism

Biomedical data from multiple U.S. and U.S.S.R. space missions are making it clear that there are continuous and possibly progressive changes in the musculoskeletal system. This effect appears in the way the body conserves calcium and other minerals which are normally stored in the skeleton. Loss of total-body calcium and skeletal changes have been observed in both animals and people who have flown from 1 week to more than 237 days in space. These alterations in bone and mineral metabolism may be among the most profound biomedical changes associated with long-duration space flight. Information on skeletal and mineral changes has been obtained from a variety of studies conducted in both simulated and actual space flight.

Bone Density Studies

During Apollo and Skylab missions, a precise method of photon absorptiometry was used to assess preflight and postflight bone mineral mass. The results of measurements of the central os calcis, which is almost all trabecular bone, for the Skylab Program (ref. 1) revealed that the largest losses occurred on the crew of Skylab 4 after 84 days of weightlessness. Bone mineral losses were not observed from the distal compact radius, however. Since these measurements were taken from different types of bone, they do not answer the important question of whether mineral loss occurs only in weight-bearing bones during space flight. Some suggestion is found from the U.S.S.R. space-flight measurements in which mineral loss was determined from the tubercle and plantar areas of the os calcis, predominately compact bone. Bone loss seemed to increase in rough proportion to the increase in mission length and ranged from -0.9 to -19.8 percent over periods from 75 to 184 days (ref. 2). Thus, both compact and trabecular bone is lost from the heel. Calcaneal mineral recovery is gradual and appears to take about the same length of time as the loss (ref. 3). This measured recovery was incomplete in at least one Skylab 4 astronaut, who, after 90 days back on Earth, had replaced only half his loss. Although U.S.S.R. investigators suggest that full calcaneal recovery occurs, spine mineral loss was seen in cosmonauts (using an x-ray computerized tomography technique) during the 6 months following flight, but, using the same technique, no loss of spine mineral was seen during flight (ref. 4).

Calcium Balance Studies

Studies of metabolic balance were conducted on the Skylab missions, during which dietary intake and urinary and fecal excretion were monitored. Daily reports of food ingested by individual crewmembers were communicated to dietary personnel, who calculated daily intake of calories, minerals, and other nutrients. Twenty-four-hour urine collections were mixed with a known quantity of a marker, and an aliquot was obtained and saved for analysis back on Earth. All stools were collected and returned for analysis. (However, enemas were used just prior to launch and the excreta discarded.) Sweat minerals were not measured, nor was any correction made for sweat losses. Vomitus may or may not have been saved for laboratory analysis. Despite the problems in balance technique, Skylab balance studies were more accurate than were the balance determination studies on the few crewmembers participating in the Gemini and Apollo missions. Results of these studies showed that space flight is accompanied by an increased excretion of calcium and phosphorus.

The changes in urine and fecal calcium content were measured in flight during Skylab 4 (ref. 5). The urine calcium content increased rapidly but reached a plateau after 30 days in flight. There was a small fecal calcium increase seen over the duration of the flight. Within 10 days in flight, the preflight positive calcium balances became less positive until the body as a whole began to lose calcium. The rate of loss was slow at first, but increased to almost 300 milligrams per day by the 84th day of flight. For the three Skylab 4 crewmen, the average loss was 25 grams of calcium from the overall body pool (about 1250 grams). Based on the trends in calcium loss during the first 30 days in flight, Rambaut and Johnston (ref. 1) calculated that 1 year in flight might result in the loss of 300 grams, or 25 percent, of the initial body pool. Similar conclusions can be drawn from U.S.S.R. research (ref. 6), in which an increased calcium excretion is attributed to weightlessness.

Results of the Skylab calcium balance studies suggest that the losses in bone mineral from the os calcis contribute relatively little to the overall calcium loss. A 4-percent loss observed in the os calcis after the 84-day mission would represent a loss of only about 100 milligrams of calcium, whereas overall calcium loss for this mission was 250 times greater. In one U.S.S.R. mission in which substantial exercise was performed by the cosmonauts, significant loss of os calcis mass was also seen, although the investigators think that an extensive exercise program on later missions did decrease skeletal loss (ref. 7). Thus, it is clear that other weight-bearing skeletal sites account for the major portion of the depleted mineral. Bone loss from other skeletal sites has not been reported.

Recovery of the lost calcium begins soon after return to one g. Urine calcium content dropped below preflight baseline by postflight day 10, but fecal calcium content had not dropped to preflight levels by 20 days after flight. The markedly negative calcium balance also had not returned to zero by day 20. Evidence from the studies on recovery of the os calcis mineral content after space flight, and evidence from bed-rest studies, suggests that after a period of some weeks or months, the astronaut would return to his/her normal os calcis bone mineral content. Nevertheless, it is possible that the calcium balance might return to zero long before the loss from space flight had been made up, and irreversible damage to the skeleton might result.

Biochemical Analyses

Analyses of in-flight urine, fecal, and plasma samples from Skylab missions revealed changes in a number of biochemical parameters (ref. 8). Urinary output of hydroxyproline gradually increased, indicating the deterioration of the collagenous matrix substance of weight-bearing bones. Output of nitrogen reflecting muscle atrophy also increased. The proportion of stearic acid in the total fecal fat increased throughout the flight as more and more calcium was available to form nonabsorbable salts. Urinary levels of catecholamines decreased but urinary cortisol was increased during space flight. Analyses of plasma revealed in-flight increases in calcium and phosphate; parathyroid hormone (PTH) levels were never increased and were decreased from preflight or early flight levels later in the flight (refs. 1, 9, and 10).

Ground-Based Simulation Models

Bed rest provides a good model for the changes of weightlessness on bone and mineral since the force of gravity is reduced on the longitudinal skeleton from one g to one-sixth g. Although the results from space-flight balance studies are not completely identical to the bed-rest model, a number of factors must be considered. These include the ability to perform a greater number of studies on Earth and thereby to minimize individual variations and the capability for more critical monitoring of subjects, minimizing mineral losses from sweat and vomitus during ambulatory control, bed rest, and recovery (compared to the lack of these controls in the astronauts before flight, during flight with early space motion discomfort or later exercise periods, and after flight during physiologic recovery). The lack of measurement of these mineral losses could become a standard error of the balance studies during space travel. Balances would initially appear positive and during space flight would remain positive, although less so. If the mineral losses from sweat and vomitus were not measured only during part of the space flight as would be seen with variation of cabin temperature changes, space motion discomfort, or exercise effort, mineral balance would appear to be inconsistent. Thus, space balance studies have pointed the way but must be interpreted with caution. Bed-rest studies have given reliable and reproducible results which have allowed us the opportunity to determine that bone loss continues unabated for at least 36 weeks with no evidence that the expected new steady state is produced. Total-body calcium stores decrease by 6 grams each month after the first month of bed rest, and by the end of 9 months, at least 50 grams of calcium have been lost. Additionally, bed rest allows us to determine results that bear on the mechanisms underlying bone loss during hypokinesic states.

Bed-rest studies have suggested a means to predict the amount of mineral that will be lost from the os calcis during bed rest or in space (refs. 11 to 15). The wide variability in the amount of lost mineral in bed-rested subjects can partly be accounted for by two other variables: (1) the initial os calcis mineral content and (2) the urinary hydroxyproline excretion rate (corrected for creatinine excretion). The regression of the prediction term (initial mineral divided by urinary hydroxyproline excretion rate) on the amount of mineral loss in subjects bed-rested for 59 days has been determined (ref. 3). The fact that data from two of the Skylab 3 astronauts fit well suggests that these variables also can be used to predict the effects of space flight on os calcis mineral content.

Studies of animals with immobilized limbs have suggested that disuse produces changes in both bone formation and bone resorption, depending upon the length of immobilization. For example, Landry and Fleisch (ref. 16) used osseous tetracycline incorporation corrected by changes in bone weight as a direct index of bone formation, and as an indirect index of bone resorption. They found a short initial phase during which formation decreased, and a second phase in which formation increased but bone weight decreased, indicating an even greater increase in resorption. After 49 days of immobilization, formation again decreased below normal levels.

Young et al. (ref. 17), through long-term immobilization of monkeys (*Macaca nemestrina*), demonstrated loss of not only trabecular bone but cortical bone in the weight-bearing areas. Moreover, full recovery of the cortical bone deficiencies may not have been complete even after 40 months of ad lib activity following restraint.

Didenko and Volozhin (ref. 18) exposed rabbits to 30 days of confinement in order to study changes in bone mineral composition. Levels of calcium in bone did not change, although calcium excretion increased. This effect was attributed to an inhibition of bone reorganization, in which bone mass was reduced without a corresponding alteration of crystalline structure.

The most pronounced changes are seen to occur in weight-bearing bones. Mechanical stimulation apparently has a critical effect on bone structure and metabolism, as numerous studies involving bone strain measurement have shown (ref. 19). There also appears to be an age-dependent variation in the relative rates of bone formation and resorption (ref. 20). Older animals show the highest net rate of bone loss during immobilization.

These and other results indicate that immobilization produces a number of time-dependent changes in bone accretion and resorption, and suggest that proportionately larger increases in resorption may be a key factor in the loss of bone mineral mass. Skeletal losses in space are likely due to relatively larger increases in bone resorption compared to bone formation (except in immature growing animals). Autopsies of the three U.S.S.R. cosmonauts who died after a 21-day flight revealed "a good number of unusually wide osteocytic lacunae," which may have been due to increased bone resorption.

In-Flight Animal Experiments

Studies of animals flown aboard the Cosmos satellites (ref. 21) and in Spacelab have also revealed changes in bone mineral content. Monkeys experiencing 8.8 days of weightlessness showed larger losses in bone mineral than did ground controls (ref. 22). Spacelab 3 rat studies as well as previous studies flown on the Cosmos biosatellites showed marked skeletal changes. For example, skeletal changes in rats exposed to as little as 7 days of space flight during Spacelab 3 included decreased bone growth, decreased mineralization, decreased bending strength, and decreased weight of the lumbar spines (L3) (refs. 23 and 24). Flight rats after 18.5 days in the Cosmos experiment showed a 30-percent decrease in mechanical bending strength (ref. 25) compared to a 28-percent reduction in rats aboard Spacelab 3 after just 7 days (ref. 26). In addition to these changes, other functional rearrangements such as depression in bone cell size and number at the bone surface have been documented (ref. 27). However, no change was seen in either qualitative or quantitative function of rat kidney calcitriol receptors and thus no causal or effectual role by the system in regulating renal calcium loss was suggested (ref. 28). These and other studies have suggested that the loss of bone mineral in growing rats might be primarily due to inhibited bone formation rather than increased bone resorption (refs. 29 and 30). Rats on the 22-day Cosmos 605 flight showed decreased metaphyseal bone in the vicinity of the epiphyseal cartilaginous plate, suggesting an inhibition of bone growth during flight. It is not yet possible to integrate these findings with the findings from hypokinesia studies on humans and animals in one g because of the complicating factors of time-dependent changes, species differences, and potential differences in the mechanisms by which bone is lost in space and in bed rest or immobilization.

Countermeasures

The major countermeasures being explored to reduce the effects of space flight on the skeleton are the use of various weight-loading exercises or artificial-gravity regimens that counteract the loss of gravitational and muscular stress, and nutritional and pharmacological manipulations. The crews of Skylab 3 and 4 exercised heavily in flight Three of these six people showed substantial mineral losses, which casts doubt on the effectiveness of the particular exercises used as a countermeasure. Findings of U.S.S.R. investigators regarding the effect of in-flight exercise during long-duration space flights have been inconsistent (ref. 7). Nutritional supplements of calcium and phosphorus for short periods of time, and drugs such as fluoride or clodronate, a disphosphonate, show some promise as countermeasures for the effects of bed rest on the skeleton and may be effective for space flight. Because of technical and hardware constraints, artificial gravity has so far been employed only in animal studies, but results have been quite promising. Centrifugation has been shown to prevent changes in calcium and phosphorus content of rat long bones (ref. 25) and to prevent osteoporosis (ref. 31).

Summary and Conclusions

Based on the information obtained from space missions, particularly Skylab and the longer Salyut missions, it is clear that bone and mineral metabolism is substantially altered during space flight. Calcium balance becomes increasingly more negative throughout the flight, and the bone mineral content of the os calcis declines. The major health hazards associated with skeletal changes include the signs and symptoms of hypercalcemia with rapid bone turnover, the risk of kidney stones because of hypercalciuria, the lengthy recovery of lost bone mass after flight, the possibility of irreversible bone loss (particularly the trabecular bone), the possible effects of metastated calcification in the soft tissues, and the possible increase in fracture potential.

For these reasons, major efforts need to be directed toward elucidating the fundamental mechanisms by which bone is lost in space and developing more effective countermeasures to prevent both short-term and long-term complications.

References

1. Rambaut, P. C.; and Johnston, R. S.: Prolonged Weightlessness and Calcium Loss in Man. Acta Astronaut., vol 6, no. 9, 1979, pp. 1113-1122.

2. Stupakov, G. P.; Kazeykin, V. S.; Kozlovskiy, A. P.; and Korolev, V. V.: Evaluation of Changes in Human Axial Skeletal Bone Structures During Long-Term Spaceflights. Kosm. Biol. Aviakosm. Med., vol. 18, no. 2, Mar.-Apr. 1984, pp. 33-37.

3. Vogel, J. M.; and Whittle, M. W.: Bone Mineral Changes: The Second Manned Skylab Mission. Aviation, Space & Environ. Med., vol. 47, 1976, pp. 396-400.

4. Cann, C.: Determination of Spine Mineral Density Using Computerized Tomography - A Report. XII U.S./U.S.S.R. Joint Working Group Meeting on Space Biology and Medicine (Washington, D.C.), Nov. 9-22, 1981.

5. Rambaut, P. C.; Leach, C. S.; and Whedon, G. D.: A Study of Metabolic Balance in Crewmembers of Skylab IV. Acta Astronaut., vol. 6, no. 10, 1979, pp. 1313-1322.

6. Gazenko, O. G.; Grigor'yev, A. I.; and Natochin, Yu. V.: Fluid-Electrolyte Homeostasis and Weightlessness. Kosm. Biol. Aviakosm. Med., vol. 14, no. 5, Sept.-Oct. 1980, pp. 3-10.

7. Gazenko, O. G.; Genin, A. M.; and Yegorov, A. D.: Major Medical Results of the Salyut-6/Soyuz 185-Day Space Flight. NASA NDB 2747. Proceedings of the XXXII Congress of the International Astronautical Federation (Rome, Italy), Sept. 6-12, 1981.

8. Leach, C. S.; and Rambaut, P. C.: Biochemical Responses of the Skylab Crewmen: An Overview. Biomedical Results From Skylab, Richard S. Johnston and Lawrence F. Dietlein, eds. NASA SP-377, 1977, pp. 204-216.

9. Whedon, G. D.; Lutwak, L.; et al.: Mineral and Nitrogen Metabolic Studies - Experiment M071. Biomedical Results From Skylab, Richard S. Johnston and Lawrence F. Dietlein, eds. NASA SP-377, 1977, pp. 164-174.

10. Leach, C. S.: An Overview of the Endocrine and Metabolic Changes in Manned Space Flight. Acta Astronaut., vol. 8, nos. 9-10, 1981, pp. 977-986.

11. Donaldson, C. L.; Hulley, S. B.; et al.: Effect of Prolonged Bed Rest on Bone Mineral. Metabolism, vol. 19, 1970, pp. 1071-1084.

12. Lockwood, D. R.; Lammert, J. E.; Vogel, J. M.; and Hulley, S. B.: Bone Mineral Loss During Bedrest. Clinical Aspects of Metabolic Bone Disease, Excerpta Med. Int. Cong. Ser., vol. 270, 1973, pp. 261-265.

13. Vogel, J. M.; Whittle, M. W.; Smith, M. C., Jr.; and Rambaut, P. C.: Bone Mineral Measurement - Experiment M078. Biomedical Results From Skylab, Richard S. Johnston and Lawrence F. Dietlein, eds. NASA SP-377, 1977, pp. 183-190.

14. Volozhin, A. I.; Didenko, I. Ye.; and Stupakov, G. P.: Chemical Composition of Mineral Component of Human Vertebrae and Calcaneus After Hypokinesia. Kosm. Biol. Aviakosm. Med., vol. 15, no. 1, Jan.-Feb. 1981, pp. 43-44.

15. Schneider, V. S.; and McDonald, J.: Skeletal Calcium Homeostasis and Countermeasures To Prevent Disuse Osteoporosis. Calcif. Tissue Int., vol. 36, suppl. 1, 1984, pp. S151-S154.

16. Landry, M.; and Fleisch, H.: The Influence of Immobilization on Bone Formation as Evaluated by Osseous Incorporation of Tetracycline. J. Bone Joint Sur., vol. 46B, no. 4, 1964, pp. 764-771.

17. Young, D. R.; Niklowitz, W. J.; Brown, R. J.; and Jee, W. S. S.: Immobilization-Associated Osteoporosis in Primates. Bone, vol. 7, 1986, pp. 109-117.

18. Didenko, I. Ye.; and Volozhin, A. I.: Chemical Composition of Mineral Component of Rabbit Bones as Related to 30-Day Hypokinesia. Kosm. Biol. Aviakosm. Med., vol. 15, no. 1, Jan-Feb. 1981, pp. 84-87.

19. Hinsenkamp, M.; Burny, F.; Bourgois, R.; and Donderwolcke, M.: In Vivo Bone Strain Measurements: Clinical Results, Animal Experiments, and a Proposal for a Study of Bone Demineralization in Weightlessness. Aviation, Space & Environ. Med., vol. 52, no. 2, 1981, pp. 95-103.

20. Novikov, V. E.; and Il'in, Ye. A.: Age-Related Reactions of Rat Bones to Their Unloading. Aviation, Space & Environ. Med., vol. 52, no. 9, 1981, pp. 551-553.

21. Kaplansky, A. S.; Savina, E. A.; et al.: Results of Morphological Investigations Aboard Biosatellites Cosmos. The Physiologist, vol. 23, no. 6, suppl., Dec. 1980, pp. S51-S54.

22. Mack, P. B.; and Vogt, F. B.: Roentgenographic Bone Density Changes in Astronauts During Representative Apollo Space Flight. American J. Roentgen. Radium Therapy Nucl. Med., vol. 113, 1971, pp. 621-623.

23. Wronski, T. J.; Morey-Holton, E. R.; Maeses, A. C.; and Walsh, C. C.: Space Lab 3: Histomorphometric Analysis of the Rat Skeleton (abs.). The Physiologist, vol. 28, no. 4, 1985, p. 376.

24. Duke, J.; Janer, L.; and Campbell, M.: Microprobe Analyses of Epiphyseal Plates From Spacelab 3 Rats (abs.). The Physiologist, vol. 28, no. 4, 1985, p. 378.

25. Gazenko, O. G.; Il'in, Ye. A.; et al.: Principal Results of Physiological Experiments With Mammals Aboard the Cosmos-936 Biosatellite. Kosm. Biol. Aviakosm. Med., vol. 14, no. 2, Mar.-Apr. 1980, pp. 22-25.

26. Buckendahl, P. E.; Cann, C. E.; et al.: Osteocalcin as an Indicator of Bone Metabolism During Spaceflight (abs.). The Physiologist, vol. 28, no. 4, 1985, p. 379.

27. Doty, S. B.: Morphologic and Histochemical Studies of Bone Cells From SL-3 Rats (abs.). The Physiologist, vol. 28, no. 4, 1985, p. 379.

28. Mangelsdorf, D. J.; Marion, S. L.; Pike, J. W.; and Haussler, M. R.: 1,25-Dihydroxyvitamin D3 Receptors in Space-Flown vs. Grounded Control Rat Kidneys (abs.). The Physiologist, vol. 28, no. 4, 1985, p. 379.

29. Morey, E. R.; and Baylink, D. J.: Inhibition of Bone Formation During Space Flight. Science, vol. 201, Sept. 1978, pp. 1138-1141.

30. Yagodovsky, V. S.; Trifaranidi, L. A.; and Goroklova, G. P.: Spaceflight Effects on Skeletal Bones of Rats. Aviation, Space & Environ. Med., vol. 47, 1976, pp. 734-738.

31. Stupakov, G. P.: Artificial Gravity as a Means of Preventing Atrophic Skeletal Changes. Kosm. Biol. Aviakosm. Med., vol. 15, no. 4, June-July 1981, pp. 62-63.

68 4P 526884

N91-10581

Changes in Mineral Metabolism With Immobilization/Space Flight

J. C. Gallagher, M.D.
Creighton University
Omaha, Nebraska

Introduction

What I would like to do is review briefly some of the studies that have been done on the effect of immobilization and weightlessness on bone. Only limited information is available on bone loss in zero g since relatively few subjects have experienced this situation.

Much of the useful information comes from the bed-rest model, which appears in many ways to be similar to the weightlessness situation. There are a number of interesting changes in mineral metabolism that occur with weightlessness. Urine calcium increases each week that the individual is immobilized (refs. 1 to 6), as does fecal calcium. Consequently, immobilized individuals develop severe negative calcium balance. This disturbance in calcium homeostasis has been shown to be associated with marked bone loss from the skeleton (refs. 5 and 6). Many years ago, it was shown that the immobilization effect on mineral metabolism was minimized by weight-bearing, but not by supine, exercises (ref. 7). Similar metabolic findings to those seen in immobilized patients were found in astronauts on the 84-day space flight (refs. 8 to 11). In some but not all individuals, bone loss was regained. In some respects, a parallel situation is seen in osteoporotic patients. These patients often have severe malabsorption of calcium, high urine calcium, and marked negative calcium balance (ref. 12). Possibly, some of the metabolic changes in these patients are due to partial immobilization caused by chronic and severe backache. Women at the time of the menopause also have rapid bone loss associated with high urine calcium levels but interestingly do not show any obvious change in absorption of calcium. The most obvious explanation for the changes that accompany immobilization is that rapid bone resorption leads to an elevated serum calcium, depression of parathyroid hormone, reduced formation of 1,25-dihydroxyvitamin D, malabsorption of calcium, and negative calcium balance. It appears that the metabolic changes associated with bone loss during weightlessness are closer to the findings in osteoporotic patients. What is interesting is why women who have rapid bone loss at the time of the menopause do not have malabsorption of calcium. Perhaps other hormones, such as cortisone, which affects absorption of calcium, may be contributors in weightlessness or immobilization. It is not clear at this moment whether the changes seen in vitamin D metabolism and malabsorption of calcium are primary or secondary phenomena subsequent to bone resorption, and more work is needed in that area.

Bone Loss in Weightlessness

There is little information on changes in bone itself during weightlessness. The results of one experiment, performed on rats in a U.S.S.R. spacecraft, showed a decrease in bone formation measured by tetracycline labeling during space flight, and this type of change in bone dynamics could contribute to bone loss (ref. 13).

The earlier space flights showed that loss of bone occurred in the radius and the os calcis (refs. 14 to 16). Further followup showed that the decrease in bone mass was reversed in some but not all astronauts (ref. 17). The last 5 years has seen the advent of new techniques for measuring bone density which are better than those used 10 years ago. These new methods include dual photon absorptiometry and computerized tomography. It has become clear from recent experimental work in osteoporosis that one cannot predict the rate of bone loss in one part of the skeleton from changes in other parts. For example, in osteoporotic patients, one sees normal radial density in about one-third of patients but very low spine density in all of them (ref. 18). Thus, I am not sure that one can assume that significant losses of bone occur in the femur or the spine during space flight even though decreases in bone density have occurred in the os calcis and the radius. Further prospective studies are needed to establish this point. Future studies should be planned to include measurement of density at multiple sites in the skeleton including the femoral neck, the spine, the os calcis, and the radius as well as measurement of total-body calcium. These measurements would give a more complete understanding of skeletal changes in immobilization. The use of total-body calcium would be especially valuable since regional changes also can be measured with the same technique.

Prevention or Treatment of Bone Loss

Other questions that need to be answered are the effects of intervention therapy on immobilization. A number of valuable experiments have examined the effect of various therapeutic agents in bed-rest studies (ref. 19). There are few data on the value of exercise in preventing bone loss. This lack partly reflects the fact that the technology for measuring different sites of the skeleton has only been available during the last 2 to 3 years. A recent study showed a correlation among spine density, femoral neck density, and fitness as measured by maximum ventilatory oxygen uptake (ref. 20) suggesting that fitness is a contributor to bone density. Presumably, most astronauts are extremely fit individuals who have probably maximized their potential for increasing bone density. Now that we have the ability to measure femoral neck density, we can look at the effect of an exercise program on the legs more carefully, since hip fracture would be one of the more severe complications of bone loss from the legs. Future experiments in space which involve prolonged space flight should provide answers to these questions. Also, since previous results were not accurate enough, one should look more closely at the recovery phase on bone since we are not sure whether bone loss due to weightlessness returns to normal. At the same time, bone density measurements can be used to detect individuals with low bone density, and I think it might be unwise to have those individuals undergo weightlessness repeatedly for several months if further studies show decreases in spine and femur density.

If significant bone loss does occur in space despite an exercise program, a strategy for preventing bone loss may be pretreatment of astronauts with agents such as the disphosphonates that significantly retard bone turnover. This idea is speculative and there are few animal data to support it, but work on immobilized animals could easily test this hypothesis.

Conclusion

We are still unsure of the accuracy of previous bone density measurements or their significance following a period of weightlessness. Rapid technological advances in the measurement of bone density will enable us now to measure bone density accurately at multiple sites in the skeleton with doses of radiation less than that given by a spine x-ray. It may not be possible to obtain this type of information before the next series of space flights take place, although the bed-rest model may provide supporting information. Extensive testing of bone density on every astronaut should be performed before and after the space flight. Prevention and treatment can only be undertaken after gathering sufficient baseline information. The use of exercise in preventing bone loss is still highly speculative, but represents a relatively easy approach to the problem in terms of study.

References

1. Deitrich, J. E.; Whedon, G. D.; and Shorr, E.: Effects of Immobilization Upon Various Metabolic and Physiologic Functions of Normal Men. J. Clin. Invest., vol. 4, 1948, pp. 3-36.

2. Whedon, G. D.; and Shorr, E.: Metabolic Studies in Paralytic Acute Anterior Poliomyelitis. II. Alterations in Calcium and Phosphorus Metabolism. J. Clin. Invest., vol. 36, 1957, pp. 966-981.

3. Donaldson, C. L.; Hulley, S. B.; et al.: Effect of Prolonged Bed Rest on Bone Mineral. Metabolism, vol. 19, 1970, pp. 1071-1084.

4. Hulley, S. B.; Vogel, J. M.; et al.: The Effect of Supplemental Oral Phosphate on the Bone Mineral Changes During Prolonged Bed Rest. J. Clin. Invest., vol. 50, 1971, pp. 2506-2518.

5. Hansson, T. H.; Roos, B. O.; and Nachemson, A.: Development of Osteopenia in the Fourth Lumbar Vertebra During Prolonged Bed Rest After Operation of Scoliosis. Acta Orthop. Scandinavia, vol. 46, 1975, pp. 621-630.

6. Krolner, B.; and Toft, B.: Vertebral Bone Loss: An Unheeded Side Effect of Therapeutic Bed Rest. Clin. Sci., vol. 64, 1983, pp. 537-540.

7. Issekutz, B.; Blizzard, J. J.; Birkhead, N. C.; and Rodahl, K.: Effect of Prolonged Bed Rest on Urinary Calcium Output. J. Appl. Physiol., vol. 32, 1966, pp. 1013-1020.

8. Whedon, G. D.; Lutwak, L.; et al.: Mineral and Nitrogen Metabolic Studies on Skylab Orbital Space Flights. Trans. Assoc. American Physicians, vol. 87, 1974, pp. 95-110.

9. Leach, C. S.; and Rambaut, P. C.: Biochemical Observations of Long Duration Manned Orbital Spaceflight. J. American Med. Women's Assoc., vol. 30, no. 4, 1975, pp. 153-172.

10. Rambaut, P. C.; Leach, C. S.; and Whedon, G. D.: A Study of Metabolic Balance in Crewmembers of Skylab IV. Acta Astronaut., vol. 6, no. 10, 1979, pp. 1313-1322.

11. Rambaut, P. C.; and Johnston, R. S.: Prolonged Weightlessness and Calcium Loss in Man. Acta Astronaut., vol. 6, no. 9, 1979, pp. 1113-1122.

12. Gallagher, J. C.; Riggs, B. L.; et al.: Intestinal Calcium Absorption and Serum Vitamin D Metabolites in Normal Subjects and Osteoporotic Patients. J. Clin. Invest., vol. 64, no. 3, Sept. 1979, pp. 729-736.

13. Morey, E. R.; and Baylink, D. J.: Inhibition of Bone Formation During Space Flight. Science, vol. 201, Sept. 1978, pp. 1138-1141.

14. Mack, P. B.; and Vogt, F. B.: Roentgenographic Bone Density Changes in Astronauts During Representative Apollo Space Flight. American J. Roentgen. Radium Therapy Nucl. Med., vol. 113, 1971, pp. 621-623.

15. Vogel, J. M.; and Whittle, M. W.: Bone Mineral Changes: The Second Manned Skylab Mission. Aviation, Space & Environ. Med., vol. 47, 1976, pp. 396-400.

16. Stupakov, G. P.; Kazeykin, V. S.; Kozlovskiy, A. P.; and Korolev, V. V.: Evaluation of Changes in Human Axial Skeletal Bone Structures During Long-Term Spaceflights. Kosm. Biol. Aviakosm. Med., vol. 18, no. 2, Mar.-Apr. 1984, pp. 33-37.

17. Tilton, R. E.; Degioanni, J. J. C.; and Schneider, V. S.: Long-Term Follow-Up of Skylab Bone Demineralization. Aviation, Space & Environ. Med., vol. 51, 1980, pp. 1209-1213.

18. Riggs, B. L.; Wahner, H. W., et al.: Differential Changes in Bone Mineral Density of the Appendicular and Axial Skeleton With Aging. J. Clin. Invest., vol. 67, no. 2, Feb. 1981, pp. 328-335.

19. Schneider, V. S.; and McDonald, J.: Skeletal Calcium Homeostasis and Countermeasures To Prevent Disuse Osteoporosis. Calcif. Tissue Int., vol. 36, suppl. 1, 1984, pp. S151-S154.

20. Pocock, N. A.; Eisman, J. A.; et al.: Physical Fitness Is a Major Determinant of Femoral Neck and Lumbar Spine Bone Mineral Density. J. Clin. Invest., vol. 78, no. 3, Sept. 1986, pp. 618-621.

52 6885

4P

N91-10582

109

A Unique Problem of Muscle Adaptation From Weightlessness - The Deceleration Deficiency

William T. Stauber, Ph.D.
Department of Physiology and Neurology
West Virginia University Medical Center
Morgantown, West Virginia

Skeletal muscles perform multiple functions in man including mechanical, thermogenic, protein storage, and even cosmetic. It is generally the mechanical function that has priority in the discussion of muscle physiology, since all interactions of man with his environment require coordinated muscle actions and without which we could not even breathe. From the viewpoint of the space traveler, it is most likely that the mechanical function of muscles needs to be given the most consideration especially considering the known effects of weightlessness on muscle atrophy. The mechanical actions of muscle can be separated into three categories: motor, spring, and shock absorption. It is primarily the latter two that are discussed in this presentation since they both concern the action of muscles in opposing external loads or eccentric loading. The use of eccentric loading (muscle lengthening while maintaining tension) as a diagnostic aid and a therapeutic intervention in musculoskeletal disorders has been of recent interest and is discussed as it relates to space travel.

A few years ago, while sitting on a panel evaluating some research sponsored by NASA (ref. 1), I became aware that the only established benefit of an exercise program for astronauts was treadmill running with a bungee cord simulating a one-g environment. Even 2 hours of bicycle ergometry did not have the positive effect of a treadmill run. Was there a difference in the type of exercise that could account for this differential response? It was obvious that certain muscle groups, particularly the extensors of the lower limb, are normally involved in deceleration of the body. Dr. Cavanagh has reported that a basketball player lands with approximately 9 times his body weight with no difficulty. Yet, this force must be absorbed primarily by the muscles of the lower limbs. Even during normal locomotion, a sizable force must be decelerated with each heel strike; descending stairs requires even more force absorption. Thus, deceleration and muscle-lengthening activities are important physiological events when gravitational effects are operational - more so if emergency egress requires the individual to drop from any significant height out of the space vehicle in a gravity-influenced environment.

From a physiological standpoint, two unique events occur when a muscle is stretched while maintaining tension: (1) the tension per myofiber is greater than that produced even during maximal isometric conditions (refs. 2 and 3) and (2) sensory receptors responding to both length (stretch) and tension are stimulated simultaneously. Since tension is generally accepted as the stimulus for muscle growth (ref. 4), muscles undergoing eccentric contractions and, thus, experiencing higher forces during normal locomotion should be stronger or more susceptible to atrophy when the stimulus is removed. Documentation for both conditions exists (refs. 5 to 7). Likewise, additional sensory input is derived from muscle-lengthening activities (e.g., walking) as compared to muscle-shortening activities (e.g., bicycle exercises). Could it be possible that the decrease in ambulation performance seen in astronauts and cosmonauts upon return to Earth (ref. 6) was due to a combination of muscle atrophy and sensory derivation?

With the advent of machines that can test muscle activities in all modes of dynamic and static muscle function in combination with electromyographic (EMG) data, it should soon be possible to document deficits and plan rehabilitative or preventative exercise programs suitable for in-flight use. One such device, the Kin/Com, has been used by us for approximately 4 years. The machine (a robotic dynamometer) employs standard hydraulic and computer systems, both of which might be expected to be present on an aircraft. The first series of studies on the Kin/Com involved testing subjects without any deficits or symptoms. These led to some surprising observations. Force oscillations were noted to occur in the knee extensor musculature only during eccentric contractions of maximal effort. Further investigations supported the hypothesis that these force oscillations were induced by actions of sensory receptors because they were of a frequency excessively high for voluntary control and were diminished with cooling (ref. 8) - a known inhibitor of stretch reflexes.

The presence of force oscillations during eccentric exercise resulted in force-velocity relationships (Stauber, unpublished observations) that were not expected from the studies on isolated muscles or calculations from the Hill equation. The extremely high forces predicted from in vitro experiments did not occur - perhaps because of reflex-mediated inhibitions. Deviations from the predicted force-velocity relationships have also been observed to occur during concentric exercises of the quadriceps muscles when performed at very slow speeds (ref. 9). Thus, complex neurologic control mechanisms exist for intact muscles which need to be studied before the function of sensory input and muscle output can be fully understood.

In another series of experiments, a patient population was identified which had a deficit in the eccentric loading capability of their quadriceps muscles that occurred along with their knee pain. Exercises designed to alleviate this deficit also relieved their knee pain (ref. 10). These observations supported the theory that a decelerator deficit can occur and lead to musculoskeletal problems.

What was the mechanism for such a deficit? The accepted rationale for the occurrence of anterior knee pain syndrome was a biomechanical disorder resulting from large patellofemoral reaction forces causing an irritated and inflamed surface to scrape past another. However, in our study, these forces would have been created during the concentric loading where there was not a deficit. Alternatively, this problem might have to do with the control of the muscles during muscle-lengthening activities causing patellar malalignment.

Evidence for a motor control problem was confirmed when an individual without symptoms but having a history of multiple subluxations of one patella was tested with EMG recordings along with the force records. As with the patients in the study (ref. 10), he demonstrated a marked force drop only during eccentric exercises and in the range of motion between 30° and 60° of knee flexion. The EMG recording illustrated that this force deficit was preceded by a silent period in muscle action potentials even though the subject was attempting a maximal effort (ref. 11). Since there was no such absence of EMG's during the concentric exercise, primary neuromuscular disease can be ruled out. Instead, some type of motor control problem below the level of conscious activation of muscles seemed operative.

There have been reports that this predisposition to subluxing patellae has a genetic component and is often present in members of the same family (ref. 12). Next, we tested three generations of one family because the youngest member had a marked force deficit and had been the subject for the EMG study mentioned previously. The other members of the family were asymptomatic at the time of the test, but one member of each generation nevertheless demonstrated some measurable deficit, although the magnitude of the deficit was quite variable. Could it be possible that the problem arises if the individual with such a deficit either becomes fatigued or loses muscle strength because of atrophy? Unfortunately, insufficient evidence is available at this time to answer this question. However, the incidence of patellar subluxations reported by the subjects used for EMG testing always occurred when the subject was most fatigued (i.e., at the end of a day of water skiing, etc.). In addition, Dr. Walsh of the Houghston Clinic reported (personal communication) that anterior knee pain did result in patients who were immobilized for orthopedic problems not related to the knee, as if a loss of a certain amount of protective force capability might place these asymptomatic but predisposed individuals into the symptomatic group. Could this also be a potential problem for space travelers - especially related to their ability to perform an emergency egress where a subluxed patella might prevent escape from the area around a disabled spacecraft? This possibility certainly needs further investigation.

In summary, the focus of this report has centered around decelerator problems of the knee, since the lower leg musculature is known to atrophy in response to weightlessness. However, other important decelerator functions are served by the shoulder muscles, in particular the rotator cuff muscles. Problems in these muscles often result in tears and dislocations as seen in baseball pitchers. During this workshop, we have seen photographs of astronauts holding satellites. Would fatigue in their shoulder muscles have the potential for shoulder subluxations and how could these be prevented?

Obviously, many questions have been raised that need further documentation. Since this workshop has been designed around providing information as to the existence of problems that might need exercise prescriptions as well as indicating which devices might be used to measure and exercise space travelers in an attempt to mitigate potential problems, it is noteworthy that at least one device currently exists that can measure concentric and eccentric muscle loading including a submaximal simulated free weight exercise (i.e., force-controlled) and simultaneously record integrated EMG analysis appropriate for assessment of all muscle functional activities. Studies should be undertaken to provide information as to the performance of maximal and submaximal exercise in space travelers to define potential problems and provide rationale for prevention.

References

1. Herbison, G. J.; and Talbot, J. M.: Research Opportunities in Muscle Atrophy. Life Sciences Research Office, Federation of American Societies for Experimental Biology (Bethesda, Md.), 1984, pp. 1-83.

2. Katz, B.: The Relation Between Force and Speed in Muscular Contraction. J. Physiol. (London), vol. 96, 1939, pp. 46-64.

3. Curtin, N.; and Davies, R. E.: Chemical and Mechanical Changes During Stretching of Activated Frog Skeletal Muscle. Cold Spring Harbour Symposia on Quantitative Biology, vol. 37, 1973, pp. 619-626.

4. McDonagh, M. J. N.; and Davies, C. T. M.: Adaptive Response of Mammalian Skeletal Muscle to Exercise With High Loads. European J. Appl. Physiol., vol. 52, no. 2, 1984, pp. 139-155.

5. Sale, D. G.; and MacDougall, J. D.: Isokinetic Strength in Weight-Trainers. European J. Appl. Physiol., vol. 53, no. 2, 1984, pp. 128-132.

6. Sandler, H.: Effects of Inactivity on Muscle. Inactivity: Physiological Effects, H. Sandler and J. Vernikos, eds., Academic Press, Inc. (Orlando, Fla.), 1986, pp. 77-98.

7. Convertino, V. A.: Exercise Responses After Inactivity. Inactivity: Physiological Effects, H. Sandler and J. Vernikos, eds., Academic Press, Inc. (Orlando, Fla.), 1986, pp. 149-192.

8. Hart, D. L.; Miller, L. C.; and Stauber, W. T.: Effect of Cooling on Force Oscillations During Maximal Eccentric Exercise. Exp. Neurol., vol. 90, 1985, pp. 73-80.

9. Perrine, J. J.; and Edgerton, V. R.: Muscle Force-Velocity and Power-Velocity Relationships Under Isokinetic Loading. Med. Sci. Sports Exer., vol. 10, 1978, pp. 159-166.

10. Bennett, J. G.; and Stauber, W. T.: Evaluation and Treatment of Anterior Knee Pain Using Eccentric Exercise. Med. Sci. Sports Exer., vol. 18, 1986, pp. 526-530.

11. Stauber, W. T.: Measurement of Muscle Function in Man. Sports Physiotherapy, International Perspectives in Physical Therapy, V. Grisogono, ed., Churchill Livingstone (London) (in press).

12. Fox, T. A.: Dysplasia of the Quadriceps Mechanism. Surg. Clin. N. America, vol. 55, 1975, pp. 199-226.

70

N91-10583

53-48899
16P

Biomechanical Perspectives on Locomotion in Null Gravity

Peter R. Cavanagh, Ph.D.
Center for Locomotion Studies
The Pennsylvania State University
University Park, Pennsylvania

1. Introduction

The current interest in locomotor activities in space is motivated, in part, by similar imperatives that fueled the terrestrial "running boom" of the 1970's. Running and walking are multidimensional forms of exercise that provide muscular, cardiovascular, and psychological benefits - all of which are essential to the well-being and optimum performance of astronauts. But these benefits could be obtained by a number of exercise modalities. What makes locomotion in space so attractive is the possibility that applying one-g locomotorlike forces to the lower extremity during space flight will reverse the losses of bone mineral that are of such great concern in the planning of long-duration missions in the Space Station or on interplanetary voyages (ref. 1). If such a preventative role for locomotion in disuse osteoporosis is indeed confirmed, then simulated one-g locomotion could indeed be the complete exercise for the astronaut.

In this paper, some of the biomechanical factors that must be considered in the study of locomotion in a zero-g or reduced-gravity environment are examined. The overall purposes are to achieve a description of those aspects of one-g locomotion that may be relevant to an understanding of the problem and to suggest experimental models. Comments will also be made on certain biomechanical aspects of cycling since it is also a candidate for use as an in-flight countermeasure against the various deconditioning effects that occur.

2. Biomechanical Hypotheses for Bone Demineralization

Although the discussion in this article is focused on biomechanical factors, this emphasis is not intended to imply that these are the primary etiological determinants of bone demineralization. It is likely that bone demineralization during weightlessness is a multifactorial problem with endocrine (ref. 2), nutritional (ref. 3), neuromuscular (ref. 4), biomechanical, and other factors interacting to produce the changes that have been observed (refs. 5 to 7). It is accurate to say, however, that of these various possible causes, least attention has been focused on those of a biomechanical nature.

Although we may not realize it, life in a one-g environment is characterized by a series of collisions (ref. 8). Each time the foot hits the ground in walking or running, shock transients are experienced by the lower extremity. As we shall discuss later, these shocks can be measured by accelerometers attached to the lower extremity either by Steinman pins (refs. 9 and 10), by surface mounting (ref. 11), or by attaching accelerometers to the shoe (ref. 12). Various experiments have shown that transients as great as 40g may be experienced at the shoe in running (refs. 12 and 13) and as great as 8g at the tibia in walking (ref. 13).

Although no measurements of lower extremity accelerations have yet been made in space, it is reasonable to suppose that the orbital transients will be much less than those on Earth. We know from observation of in-flight films and from anecdotal reports from astronauts that the upper extremities become the main locomotor organs in space. The body is set into motion by arm forces, and when the destination in the spacecraft is reached, deceleration is again performed by the arms. The legs are simply used to "perch." Thus, the absence of skeletal transients is one "functional" theory to explain bone demineralization.

Skeletal transients are not, however, the only mechanical consequences of locomotor exercise on Earth which are absent in space. It is quite probable that the muscles of the lower extremity are only called upon to generate a fraction of the forces that they routinely exert on Earth. The skeletal implications of this state are that the tensile stresses at muscle attachments and the compressive stresses and bending moments that develop as result of muscular

PRECEDING PAGE BLANK NOT FILMED

forces are also absent. Thus, a second biomechanical hypothesis for the loss in bone mineral is that the absence of normal internal stresses in the bone due to reduced muscle forces is responsible. As a perspective on the testing of these hypotheses under a variety of conditions, methods for the study of locomotor activities and results from terrestrial experiments are now discussed.

3. Biomechanical Studies of Terrestrial Locomotion

If a force platform is interposed between the foot and the floor during running and walking, the typical results shown in figures 1(a) and 1(c), respectively, can be obtained (refs. 14 and 15). These diagrams show the vertical component of force in the two activities, both of which are characterized by sharply rising initial peaks resulting in the skeletal transients mentioned earlier. The more slowly rising peaks later during the contact phase are larger in both activities, reaching approximately 1.2 times body weight (BW) in walking at 1.5 m/s and 2.5 to 3.0 times body weight in running at 3.8 m/s. Nigg (ref. 16) has described the two distinct peaks in the running curve as the "impact" peak and the "active" peak, respectively.

Our own studies have shown that running technique can drastically affect the nature of ground reaction forces (ref. 14). Individuals who strike the ground with the rearfoot display patterns similar to those shown in figure 1(a), but in a runner who makes first contact with the midfoot or the forefoot, the "impact" peak tends to be diminished or absent and the "active" peak tends to be larger (fig. 1(b)). This result has obvious relevance to the design of in-flight exercise since, if the transients are necessary, care should be taken to design the exercise system such that the astronaut cannot avoid heel contact.

It is instructive at this point to make a comparison of the reaction forces experienced by the foot during cycling (ref. 17) with those just described for running and walking. A force-measuring pedal has been designed and built in our laboratory, and typical results from a recreational cyclist pedaling at 90 rpm with a power output of 130 watts (about 50 percent of his maximum) are shown in figure 1(d) (from ref. 18). It is clear from figure 1 that the forces during cycling are different from those during walking and running in two important ways. First, during all phases of the pedaling cycle, the rate of change of force in cycling, the *dF/dt*, is considerably smaller than that in walking or running. There is no rapidly rising force analogous to the initial transients seen in figures 1(a) and 1(c) during foot-ground contact. Second, the absolute magnitude of the forces in cycling are small - approximately 3 and 6 times smaller than those in walking and running, respectively.

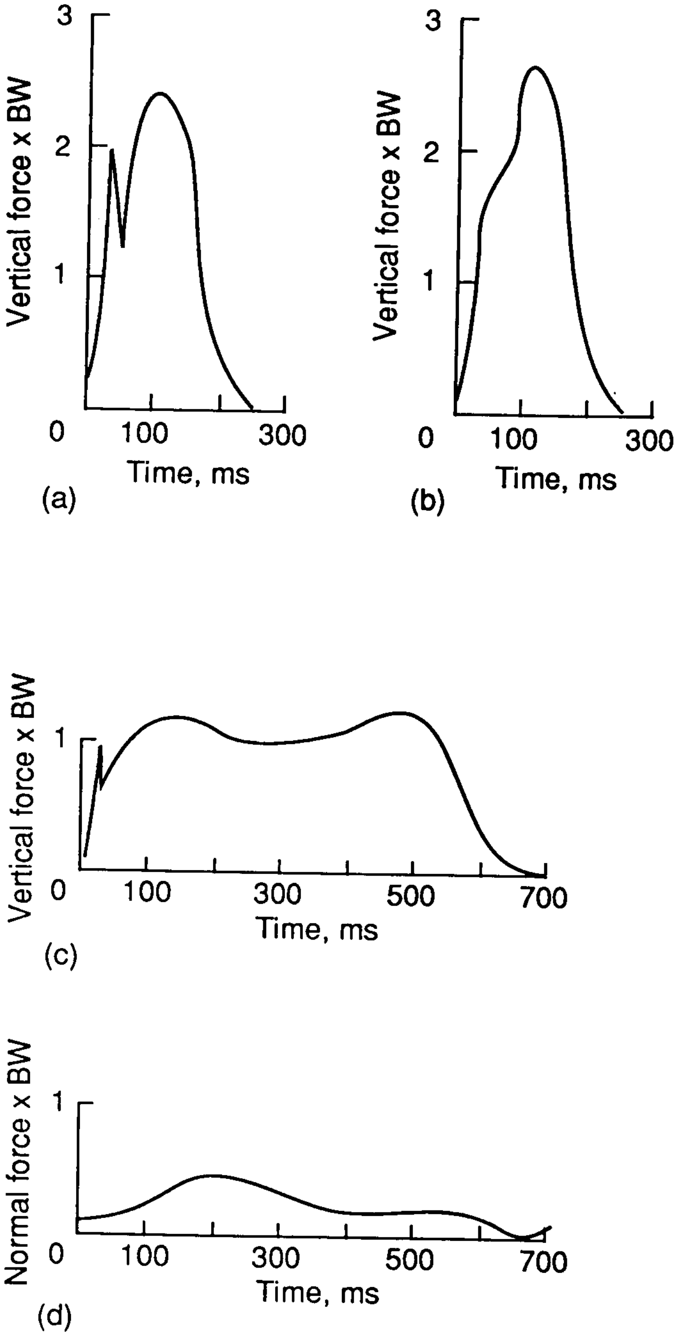


Fig. 1.- Force-time curves for various modes of exercise. Note the brief early transients in figures 1(a) and 1(c) and the increasing peak forces and rates of change of force as the progression from cycling to walking to running occurs. (a) Rearfoot running at 3.8 m/s. (b) Forefoot running at 3.8 m/s. (c) Walking at moderate speed. (d) Cycling at 90 rpm and 130 watts.

The absence of transients is, of course, due to the fact that the body weight is supported during cycling and not used as an inertial mass which collides with the supporting surface. The smaller "active" forces in cycling are also related to this fact, but, at a muscular level, there are important differences which must be considered in the design of exercise protocols in space. The period of weight acceptance or cushioning in both walking and running is characterized by eccentric muscle action that is immediately followed by concentric action as the body is propelled upward and forward. Such a "stretch-shorten" cycle (ref. 19) is entirely absent in cycling. It is well known (ref. 19) that the largest muscular forces can be generated during eccentric action. Thus, even at high power outputs and low pedal rates, lower extremity muscle forces in cycling will never approach those of walking or running. Future studies may well demonstrate the absence of, or reduction in, the number of eccentric muscle actions to be a primary difference between terrestrial and reduced-gravity locomotion.

Once ground reaction forces have been determined, the addition of kinematic data and body segment parameter information enables some first-order estimates of the bone-on-bone articular forces to be made (refs. 20 and 21). Although such estimates have large error bounds, it has been estimated that forces at the talocrural joint during slow running may [illegible]eed 12 times body weight (ref. 22). Thus, forces of [illegible]n could exist between the tibia and the head of [illegible]talus of a 180-pound individual. This result [illegible]phasizes the importance of large muscular forces which are principally responsible for the bone-on-bone forces in the joint being approximately 4 times greater than are the ground reaction forces at the foot.

4 Studies of Locomotion in Zero g and Reduced Gravity

[illegible] Modeling

The tremendous advantage of modeling in the present context is that gravity can be removed by the stroke of a pen. One does not need orbital experiments or brief moments of weightlessness during aircraft flight to test the hypotheses. All that is needed is to set a single variable to zero in the model. Unfortunately, the complexity of most biomechanical models of locomotion cannot approach that of the intact human locomotor system (ref. 8); this tends to limit their "ecological validity." There have been some successes, however. Kane and Scher (ref. 23) predicted arm and leg movements that would generate self-rotation in a weightless environment using linked rigid-body models and Lagrangian mechanics. In 1964, Margaria and his coworker (refs. 24 and 25) correctly predicted that a "bounding" gait would be appropriate for the lunar environment and pointed out on the basis of ground reaction forces and frictional considerations that the maximum speeds for lunar running would be 1.7 m/s and 3.4 m/s on loose and firm terrain, respectively . Margaria's predictions were largely confirmed by the subsequent locomotor experience of astronauts on the lunar surface.

Despite the successes mentioned previously, there are two areas critical to the current topic that have not been well served by biomechanical models. These are the consequences of impacts to the skeleton (ref. 26) and the solution of individual forces in lower extremity muscles (ref. 22). The implication of both of these shortcomings is that, in the near future, direct experimentation is more likely than modeling to lead to operationally significant results.

4.2 Direct Experimentation

A passive tethered treadmill has already been flown on most Space Shuttle missions since STS-3. The device, shown schematically in figure 2(a), incorporated elastic bungee cords attached both to a harness and to the treadmill to accelerate the astronaut back to the treadmill bed after pushoff (ref. 27). The only biomechanical information available from treadmill running during these missions is lower extremity kinetic data that are currently being obtained from the analysis of short clips of 24-frame/s 16-millimeter film taken with a wide-angle lens (ref. 28). Other possible in-flight data that could be collected from Space Shuttle or Space Station missions in the future are shown in figure 2(b).

Tibial transients could be monitored by surface-mounted accelerometers, whereas accelerometers mounted on a bite bar or a helmet could detect cranial accelerations. The mounting of the treadmill to the deck via force transducers should be explored, although this method may not be practical because of storage requirements. A more satisfactory solution may be to instrument the footwear of astronauts with pressure-sensitive insoles or with inertia switches. Figure 3 shows plantar pressure distribution obtained on Earth between the bare foot of a running subject and the ground (ref. 29). If a similar technique could be developed for in-shoe

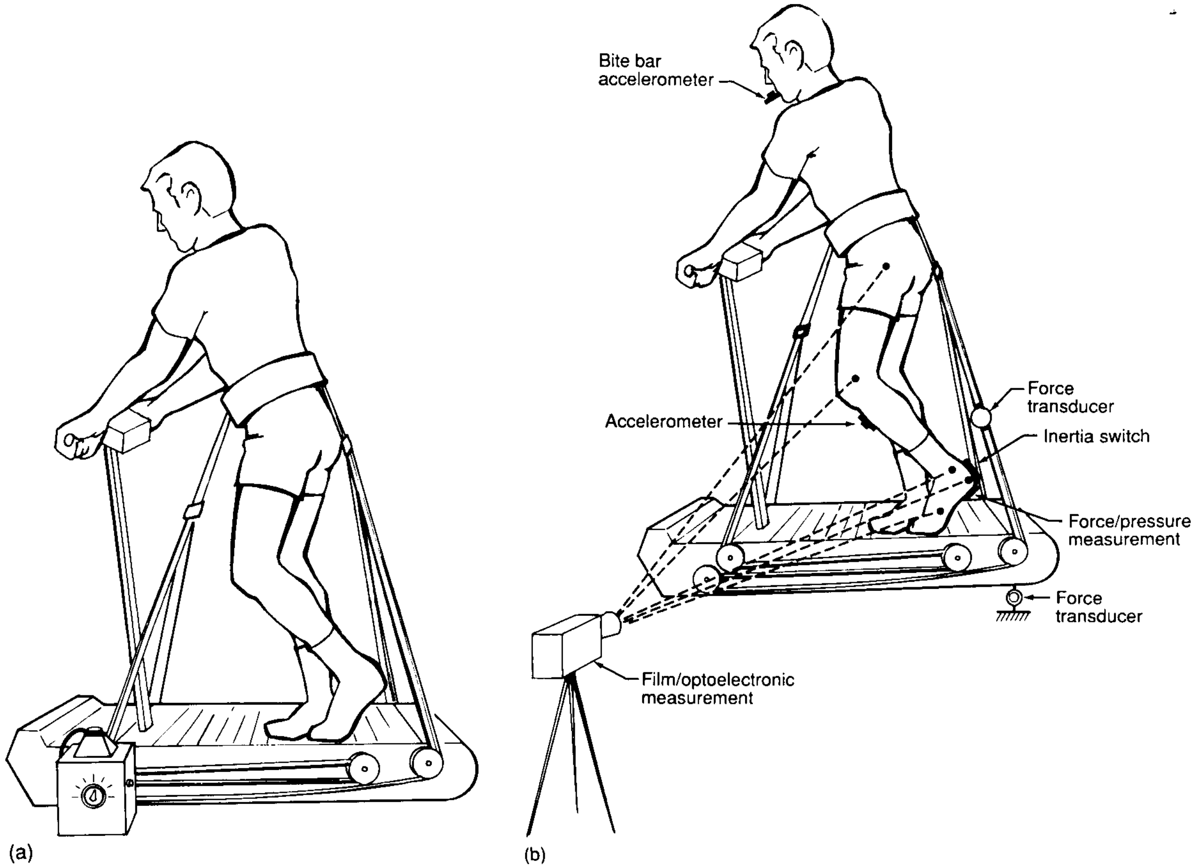


Fig. 2.- Use of treadmill under weightless conditions. (a) Schematic diagram of passive tethered treadmill used on Space Shuttle missions. (b) Possible methods for monitoring the biomechanics of locomotion in space. See text for further details.

monitoring (ref. 30), it would offer the possibility of collecting a complete history of lower extremity loading during typical activities in space.

A simpler, though less complete, technique might involve the development of a battery of inertia switches. These switches, typically used in emergency locator transmitters for aircraft and in weapons applications, can be designed to close at a predetermined acceleration. Thus, an array of shoe-mounted switches with thresholds of, for example, 5g to 20g and associated accumulating registers could collect information on the number of transients above certain levels experienced by the lower extremity during flight. Kinematic data from film, video, or other optoelectronic devices (ref. 31) could also be collected using instrumentation capable of fulfilling several other purposes during the mission. Any of these techniques could also be used during aircraft flights that offer brief periods of weightlessness.

4.3 Ground-Based Experiments

There are two major reasons why ground-based experiments should be pursued in the near future. First, flight experiments are extremely expensive to conduct and involve considerable lagtime between planning and the availability of data. A second and more urgent consideration is th ground-based experiments are needed to provi design information for exercise devices to be built in the Space Station. Although occurrence of the fir Space Station mission is not anticipated until the lat 1990's, the basic design requirements for in-flight exercise equipment must be finalized soon.

The principles of ground-based zero-g locomotion simulation devices have already been elucidated (ref. 32), and it appears that such a device has been used in the U.S.S.R. for ground-based experiments. A typical system, shown in figure 4,

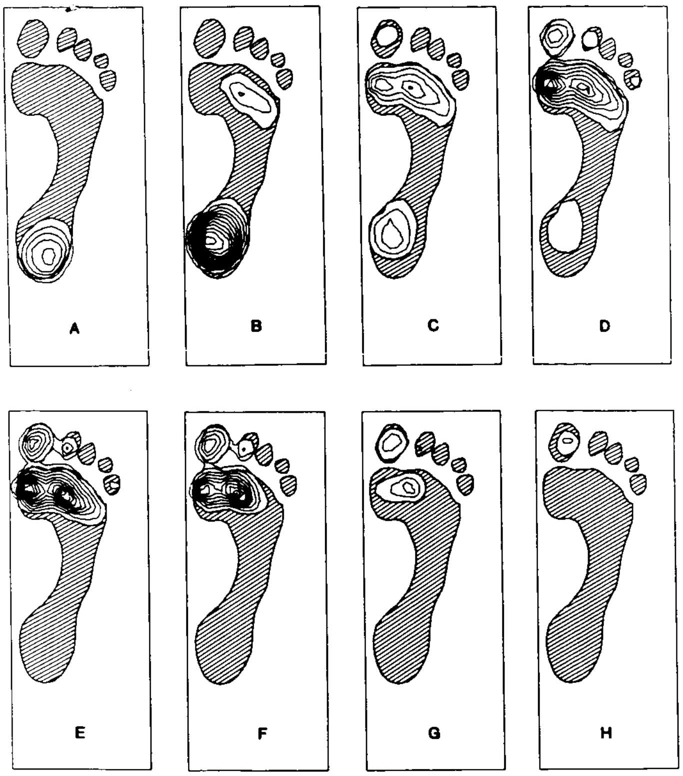


Fig. 3.- Plantar pressure distribution at eight instants of time during foot contact in barefoot running. If such measurements could be made under weightless conditions, a complete loading history for the lower extremity could be developed.

would involve supporting the trunk in either a prone or a side-lying position with the weight of the head, the trunk, and the arms totally supported by stiff suspension cables. Part of the weight of the lower extremities could be supported by compliant cables. A treadmill would be mounted vertically on the wall via force transducers, and bungee cords attached to a harness would provide the major means of applying axial loads to the lower limbs. The subject could be instrumented using any of the methods described previously.

This kind of experimental arrangement could provide answers to important questions regarding locomotion in reduced-gravity situations. For example, can passive elastic restraints generate sufficient forces to apply one-g locomotor forces to the lower extremities? What influence does the technique of the subject have on the forces and accelerations experienced by the lower limb? What effect does equipment modification have on the locomotor pattern? Once these and other questions are answered, the device could then be incorporated into bed-rest studies so that the effectiveness of quantifiable locomotor exercise as a countermeasure to bone demineralization could be investigated.

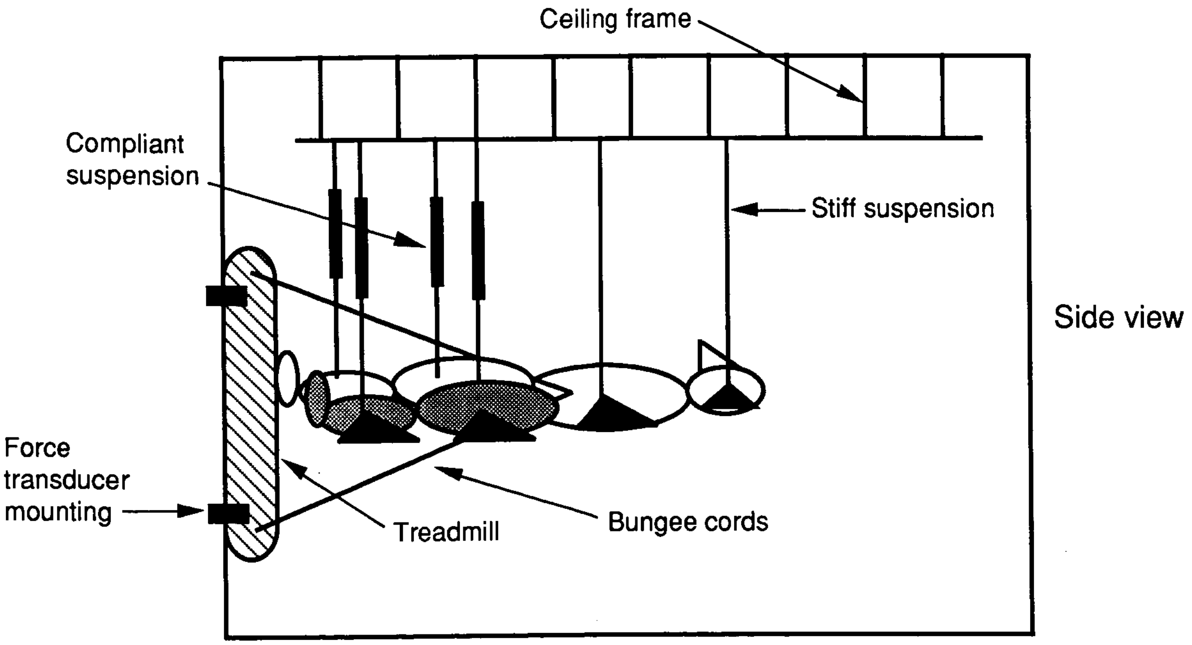


Fig. 4.- Schematic diagram of a "vertical" tethered treadmill that would enable study of the mechanics of zero-g locomotion. See text for further details.

5. Summary and Concluding Remarks

A number of important features of various locomotor activities have been discussed in this paper, and approaches to the study of these activities in the context of space flight have been suggested. In particular, the magnitude of peak forces and the rates of change of force during terrestrial cycling, walking, and running were compared. It was shown that subtle changes in the conditions and techniques of locomotion can have a major influence on the biomechanical consequences to the skeleton.

The various hypotheses that identify locomotor exercise as a countermeasure to bone demineralization during weightlessness deserve to be tested with some degree of biomechanical rigor. Various approaches for achieving such scrutiny have been discussed.

References

1. Goode, A. W.; and Rambaut, P. C.: The Skeleton in Space. Nature, vol. 317, 1985, pp. 204-205.

2. Cann, C. E.; and Arnaud, S. B.: Calcium Metabolism and Correlated Endocrine Measurements in Nonhuman Primates During Hypokinesia. A 14-Day Ground-Based Hypokinesia Study in Nonhuman Primates: A Compilation of Results, L. Kazarian, C. Cann, M. Parfitt, D. Simmons, and E. Morey-Holton, eds. NASA TM-81268, 1981, pp. 29-33.

3. Rambaut, P. C.; Smith, M. C., Jr.; and Wheeler, H. O.: Nutritional Studies. Biomedical Results From Apollo, Richard S. Johnston, Lawrence F. Dietlein, and Charles A. Berry, eds. NASA SP-368, 1975, pp. 277-302.

4. Herbison, G. J.; and Talbot, J. M.: Muscle Atrophy During Space Flight: Research Needs and Opportunities. The Physiologist, vol. 28, no. 6, 1985, pp. 520-526.

5. Vose, G. P.: Review of Roentgenographic Bone Demineralization Studies of the Gemini Space Flights. American J. Roentgen. Radium Therapy Nucl. Med., vol. 121, 1974, pp. 1-4.

6. Vogel, J. M.; and Whittle, M. W.: Bone Mineral Changes: The Second Manned Skylab Mission. Aviation, Space & Environ. Med., vol. 47, 1976, pp. 396-400.

7. Volozhin, A. I.; Didenko, I. Ye.; and Stupakov, G. P.: Chemical Composition of Mineral Component of Human Vertebrae and Calcaneus After Hypokinesia. Kosm. Biol. Aviakosm. Med., vol. 15, no. 1, 1981, pp. 60-63.

8. Nokes, L. D. M.; Williams, J. H.; et al.: A Literature Review of Vibration Analysis of Human Limbs. IEEE Trans. Biomed. Eng., vol. BME-31, no. 2, 1984, pp. 187-192.

9. Ziegert, J. C.; and Lewis, J. L.: The Effect of Soft Tissue on Measurements of Vibrational Bone Motion by Skin-Mounted Accelerometers. J. Biomech. Eng., vol. 101, 1979, pp. 218-220.

10. MacLellan, G. E.: Skeletal Heel Strike Transients, Measurement, Implications, and Modifications by Footwear. Sport Shoes and Playing Surfaces, E. C. Frederick, ed. Human Kinetics Publishers (Champaign, Ill.), 1984.

11. Clark, T. E.; Cooper, L. B.; Hamill, C. L.; and Clark, D. E.: The Effect of Varied Stride Rate Upon Shank Deceleration in Running. J. Sports Sci., vol. 3, 1985, pp. 41-49.

12. Gross, T. S.; and Cavanagh, P. R.: The Acceleration of the Shoe at Foot Strike During Running (abs.). Proceedings of the Mid-Atlantic Chapter, American College of Sports Medicine, 1985.

13. Light, L. H.; and MacLellan, G.: Skeletal Transients Associated With Heel Strike (proc.). J. Physiol. (London), vol. 272, no. 1, Oct. 1977, pp. 9P-10P.

14. Cavanagh, P. R.; and Lafortune, M. A.: Ground Reaction Forces in Distance Running. J. Biomech., vol. 13, no. 5, 1980, pp. 397-406.

15. Mann, R. A.: Biomechanics. Disorders of the Foot, M. H. Jahss, ed. W. B. Saunders Co. (Philadelphia), 1982.

16. Nigg, B. M.: Biomechanics of Running Shoes. Human Kinetics Publishers (Champaign, Ill.), 1986.

17. Cavanagh, P. R.; and Sanderson, D. J.: The Biomechanics of Cycling: Studies of the Pedaling Mechanics of Elite Pursuit Riders. Science of Cycling, E. R. Burke, ed. Human Kinetics Publishers (Champaign, Ill.), 1986.

18. Gregor, R. E.: A Biomechanical Analysis of Lower Limb Action During Cycling at Four Different Loads. Unpublished doctoral dissertation, Pennsylvania State University, 1976.

19. Komi, P. V.: Physiological and Biomechanical Correlates of Muscle Function: Effects of Muscle Structure and Stretch-Shortening Cycle on Force and Speed. Exercise and Sport Science Reviews, R. L. Terjung, ed. D. C. Heath & Co. (Toronto, Canada), vol. 12, 1984, pp. 81-121.

20. Winter, D. A.: Biomechanics of Human Movement. John Wiley & Sons (New York), 1979.

21. Stauffer, R. N.; Chao, E. Y.; and Brewster, R. C.: Force and Motion Analysis of the Normal, Diseased and Prosthetic Ankle Joint. Clin. Orthop. Rel. Res., vol. 122, 1977, pp.189-196.

22. Burdett, R. G.: Biomechanical Model of the Ankle Joint. Unpublished doctoral dissertation, Pennsylvania State University, 1979.

23. Kane, T. R.; and Scher, M. P.: Human Self-Rotation by Means of Limb Movements. J. Biomech., vol. 3, Jan. 1970, pp. 39-49.

24. Margaria, R.; and Cavagna, G.: Human Locomotion in Subgravity. Aerospace Med., vol. 35, no. 12, 1964, pp. 1140-1146.

25. Margaria, R.: Biomechanics and Energetics of Muscular Exercise. Clarendon Press (Oxford), 1976.

26. King, A. I.; and Chou, C. C.: Mathematical Modeling, Simulation and Experimental Testing of Biomechanical System Crash Response. J. Biomech., vol. 9, 1976, pp. 301-317.

27. Thornton, W.: Rationale for Exercise in Spaceflight. Spaceflight Deconditioning and Physical Fitness, J. F. Parker, Jr., C. S. Lewis, and D. G. Christensen, eds. NASA Contract NASW-3469, 1981.

28. Thornton, W.; and Cavanagh, P. R.: Lower Extremity Kinematics of Tethered Treadmill Running in Zero g. In preparation, 1987.

29. Cavanagh, P. R.: The Biomechanics of Lower Extremity Action in Distance Running. Foot & Ankle, vol. 7, no. 4, 1987, pp. 197-217.

30. Hennig, E. M.; Cavanagh, P. R.; Albert, H. T.; and Macmillan, N. H.: A Piezoelectric Method of Measuring the Vertical Contact Stress Beneath the Human Foot. J. Biomed. Eng., vol. 4, no. 3, July 1982, pp. 213-222.

31. Atha, J. P.: Current Techniques for Measuring Motion. Appl. Ergonom., vol. 15, no. 4, 1984, pp. 245-257.

32. Thornton, W.: A Device for Locomotor Exercise Under Reduced Weight. U.S. patent application, 1987.

SECTION 3

CONSIDERATIONS AND COMMENTS PERTAINING TO AN EXERCISE PRESCRIPTION FOR LONG-DURATION SPACE FLIGHT

Comments

Michael W. Bungo, M.D.
Space Biomedical Research Institute
NASA Lyndon B. Johnson Space Center
Houston, Texas

We're going to utilize a bit of participatory management here. I have a question that I'd like to pose to everybody before I start, so that we can temper some of our discussions. The question is, "Do we need an exercise prescription for space flight?" I'd like to take the opportunity to go around the room and take a poll.

(Dr. Bungo polls meeting participants.)

Okay, I would like everybody who answered "yes" and everybody who answered "no"- both of those groups - to go home because we don't need you anymore. What we need is the correct answer to the question, and further, what we need is some critical thinking. The real answer to the question is "maybe." And the reason I say that is that I want to urge this group to do some very critical thinking on this issue, which I think is avoided when people answer the question yes or no. Now, I would not like to influence anybody's opinion at this point in time, but I think there are some critical things that have to be considered. And that is, we've heard some review of the data that says we really don't know what's happening in space flight. We've had some other people say exercise doesn't really seem to affect orthostatic tolerance. We've seen presentations of some U.S.S.R. studies which indicate that even after 180 days of bed rest, the muscle strength is still maintained at 75 percent maximum. I've heard somebody else say, "We need to work on this problem." What's the problem? Is muscle atrophy the problem or is it a description of the physiologic change? Because cardiovascular deconditioning in space flight so far hasn't been a problem, it's been a description of a physiologic change. Orthostatic intolerance has been a problem. People lying flat down on the floor, that's a problem. So when you think about this subject, and when you discuss what's going on, and what I've heard a lot of what's been going on today is saying, "You know, we really need to do a study." I said, "Let's answer this question; let's do muscle biopsies." I've heard somebody else describe the work of some of the experiments they've been doing, so this is what I'd propose for space flight. Well, that's the main issue that I have with what's been going on. My position here is such that I don't answer it yes or no. I answer it maybe, and I would have wished that there's some consideration for that approach. I've heard talk of individualizing prescriptions as opposed to regular standards. What's the tradeoff? Well, when you individualize prescriptions, you get a lot of good psychologic reinforcement. Everybody likes what they're doing. They're more apt to participate in that kind of program; therefore, the psychologic benefit of exercise is maximized. But when you give a rigorous prescription, you have a small *n* that you're dealing with in space flight, and the only way - and that may not even be the way - but the only way you're going to draw a conclusion is if you have something rigorous which you can go on, with some kind of controlled circumstances. So you can see you've traded away. And I'm not going to stand here and try to support one aspect of the question versus another. But you've made the trades, and unless the group sits here and says "maybe," and critically thinks about the issues, then they've already made the trades in their mind. And they've gone beyond the usefulness to NASA of critical thinkers.

A lot of people stood up last night and said, "I'm not an expert in this field," and I'm going to stand up today to tell you, "I am." Okay, because it's my job to be on top of the physiologic changes that occur in space flight and what possible countermeasures are. So I'm going to tell you, "I'm an expert." I'm going to tell you right in the second sentence before I even stop that I know very little about this topic because I would submit that it is a new topic that we need a lot of learning to develop.

Discussion

F. Andrew Gaffney, M.D.
Associate Professor of Medicine
Payload Specialist, Spacelab Life Sciences 1
University of Texas, Southwestern Medical School
Dallas, Texas

The purpose of the symposium, as I understand it, is to advise NASA on the development and implementation of an "exercise prescription." This prescription, a countermeasure against the physiological effects of weightlessness, should maintain normal physical function in crews during long-duration space flights, reentry, and ground egress, and minimize recovery times following return to Earth. Since many of the speakers today have addressed specific physiological problems associated with weightlessness, I will be more general in my comments and will try to provide a perspective gained from training both as a university researcher and as a Spacelab Life Sciences 1 crewmember. Although we have been charged with providing an operational answer for NASA, I think our most important task is first to define the questions the agency should ask. Our recommendations for a prescription are not likely to produce the desired operational objectives, nor will they result in any significant science, if we do not phrase the questions properly.

Before defining an exercise prescription, we must consider the specific purposes of an exercise regimen in space. Previous speakers have told us that long-term exposure to weightlessness is associated with demineralization of the skeleton, significant atrophy of postural muscles, and cardiovascular deconditioning, characterized by decreased exercise capacity and orthostatic intolerance on return to one g. Thus, an exercise prescription may be required to prevent or correct a variety of physical problems. Unfortunately, a program which protects one physiological system may not offer the same efficacy for maintaining function in the other systems. Let's look at the requirements for each of these physiological systems separately.

Cardiovascular deconditioning has been well documented following U.S. and U.S.S.R. flights of both short and long duration. It must be noted, however, that the testing for this deconditioning has been done only in a one-g environment. Results from Skylab experiments indicate an absence of changes in cardiovascular responses to submaximal exercise on orbit, but maximal testing was not performed. The deconditioning we've observed after flight may be a one-g problem only. If so, crewmembers would not be expected to have any on-orbit decrease in exercise capacity, but could have problems with reentry and ground egress, especially in an emergency situation. This problem, if unresolved, will require significant restrictions on the availability of returning Space Station crewmembers to fulfill duties on the Orbiter during reentry and landing. This will almost certainly be the case until our countermeasures are proven effective. The inability of returning Space Station crewmembers to have Orbiter duties on return to Earth could cost NASA billions of dollars in added numbers of flights required to supply crews for the Space Station. We must therefore design experiments which differentiate zero-g and one-g deconditioning effects and their underlying pathophysiological mechanisms.

The nature and extent of cardiovascular deconditioning is even more difficult to determine because of the confounding effects of muscle atrophy. Subjective and objective methods both confirm a significant loss of muscle mass in crewmembers, but the precise nature of the atrophy is totally unknown. The rapidity with which the legs shrink would suggest that a major component of the atrophy is water loss due to decreased intravascular and tissue pressures in the lower extremities. As simple as it might seem, preflight and postflight strength measurements have not been made systematically, and computer tomography or magnetic resonance imaging have not been done to assess the loss of mass in specific muscle groups. Experience with casted human limbs and hypokinetic rodent models (tail suspension) would predict a preferential loss of fiber volume in the soleus, a muscle composed predominantly of type 1 muscle fibers, but this is only speculation. The relative contributions of water loss versus true fiber loss to this apparent decrease in muscle mass, and a differentiation of morphological from neurogenic factors in the subjectively reported postflight weakness, will have to be determined before an exercise prescription can be written.

Bone demineralization is expected to occur in all hypokinetic situations, but its extent varies dramatically, depending on the method by which bone stress is removed. The worst losses of body calcium are seen in patients with cord-transections or similar lesions producing flaccid paralysis and immobility. Less severe losses are seen in normal subjects following bed rest and in crewmembers during weightlessness. The time course of the loss of bone density, the distribution of demineralization in the skeleton and in a given bone, the presence or absence of an asymptote in bone mineral loss, effects on collagen content in bone, and age and sex variables are all undefined.

A final indication for an exercise prescription is that of crew mental health and morale. The psychological benefits of regular exercise in one g are well known. Similar positive effects also seem to be present in space flight, but the required duration, pattern, and frequency of the exercise for flight are unknown. Crewmembers already consider aerobic exercise so important that they have made it a required, scheduled activity on all Orbiter flights. Consider the value of a well-constructed, efficient prescription of the 90- to 120-day and longer duration flights expected when Space Station becomes operational. It could save many crew hours for science and other activities by decreasing the total time devoted to countermeasures on orbit.

Although we lack information to provide a comprehensive recommendation which would satisfy requirements in most physiological systems, we do have some U.S. and U.S.S.R. data on which to base our initial recommendations. We know from Skylab experience that it is possible to ride an exercise bicycle ergometer in weightlessness and achieve substantial workloads. It would also appear from the same data that exercise capacity in flight is relatively well maintained. Similar success has been seen with the use of the self-powered treadmill, routinely flown on Space Shuttle missions, although fitness data are not available for these Space Shuttle flights. Other exercise devices should be easy to construct, once we've determined what it is we are attempting to accomplish.

The U.S.S.R. data have tended to be anecdotal and fragmentary, not only in terms of reports on effectiveness of countermeasures, but also in descriptions of exactly which countermeasures are used and for what duration. Hopefully, our relationship with the U.S.S.R. life sciences community will continue to improve and we will learn as they do from the major opportunities offered by Mir. Nonetheless, the United States should develop a major ground-based program to evaluate various zero-g models. Obvious areas of focus would be in determining answers to the questions already stated for bone and muscle loss and cardiovascular deconditioning. A focused research program, begun now, would allow us to define our flight studies in a more pathophysiological fashion. One could expect substantial progress from only a few Space Shuttle flights if crews of five to seven members are available for study. Special use of Detailed Supplemental Objectives and Spacelab missions can be used with expanded preflight and postflight measures. Again, these missions should be given a high priority by NASA if we are to meet our goals for a permanently manned Space Station by the mid-1990's. Failure to do the needed ground-based and short-duration flight experiments now will push the development schedule for 90- to 120-day operational Space Station duty tours well past the year 2000.

The need for adequate pre-Space-Station experiments is in contrast to the usual situation, in which long leadtimes for equipment drive the composition and timing of the science. There is no obvious need for exotic equipment or unproven technologies in this area. Equipment fabrication will probably have to await further understanding of the physiological needs, but work in some areas can be started now. One must develop a system which offers as much variability as possible. Ground-based exercise program selection is a highly individualistic matter and is often the subject of intense feelings. Any imposition of undesired programs is likely to result in substantial noncompliance despite the presence of a highly trained and motivated crew. Variety would improve participation and adherence to a regimen. The system should provide transparent monitoring capability, so that data on function, work levels, time, etc., can be collected with minimal crew effort. Placement of exercise devices near windows or in proximity to video screens or audio equipment to permit diversion during what may be prolonged periods of exercise is important. Interactive video systems for a treadmill or cycle ergometer could provide diversion as well as incentives to meet goals such as "racing" phantom opponents, besting previous times, etc. Such concepts might seem trivial, but the maintenance of an alert, satisfied crew is of great importance for reasons of safety and productivity. Inspection of the Mir space station suggests that the U.S.S.R. has devoted substantial effort and resources to these areas of human factors and performance. Finally, in looking at the period beyond permanent manned capability on the Space Station, one should keep in mind that stays of 120 to 250 days are only the beginning if humans are to explore their solar system. Careful attention to dose-response relationships and asymptotes in terms of loss of strength, mass, and fitness should tell us what is needed to readapt quickly, whether it be in a 0.2g, 0.4g, or 1g environment. It is truly an exciting problem. Thank you for inviting me to participate in this conference. I hope it is only the beginning.

22P

N91-10584

52691

Exercise Issues Related to the Neuromuscular Function and Adaptation to Microgravity

Reggie Edgerton, Ph.D.
Department of Kinesiology
University of California, Los Angeles
Los Angeles, California

Introduction

One of the basic problems in life sciences facing NASA is performance. There is the issue of performance in space as well as when astronauts return to Earth. Can they function safely in their two environments, particularly during the adaptive phases? My general impression is that the operational question has been, "Can one perform the tasks required and survive?" I would like to suggest that we assess the efficiency and effectiveness of performance in space more quantitatively while maintaining an acceptable margin of safety.

There are remarkable expectations for productivity from humans in space even though there are few data to suggest that humans can meet those expectations. When this issue has been raised previously, the usual response is essentially, "We know that it can be done. We have done it." Generally, I would agree that a number of specific tasks can be done. But given the magnitude of the work to be done, particularly during extravehicular activities (EVA's), and given the high cost of labor in space (thousands of dollars per hour), we should be concerned with more than simply surviving and whether or not you can perform some function. We should be concerned about productivity. How efficiently and effectively can it be done? How can the productivity of man in space be improved?

Neuromuscular Function

As one goes from one g to virtually zero g, the central nervous system must make rapid and accurate adjustments. Based on my discussions with astronauts who have had some experience in space, I believe that it is remarkable how well and rapidly the central nervous system can adapt to weightlessness. Within hours, they can perform exceptionally well under unique circumstances. However, it is important to recognize that we're expecting virtually flawless performance continuously over a prolonged period of time, particularly during the construction phase of the Space Station when EVA is required. These EVA tasks require detailed manipulation of instruments in a pressurized suit and glove in which the fingers are difficult to control. For these reasons, we need to understand how the central nervous system manages these skill requirements. After 4 or 5 hours of EVA, can one perform with the proper safety margin given the consequences of making a mistake? On Earth, a variety of mistakes can be made in attempts to complete a task and rarely will the results be fatal. However, during EVA particularly, mistakes must be avoided.

Concerns related to movement skills are justified also by the likelihood of a dramatic change in mass of some muscles. Some experiments on rats suggest that the amount of atrophy that occurs within 1 week of hindlimb suspension is almost as much as that seen in 4 weeks normally. Most of the space-related data on protein metabolism are consistent with the view that there are marked changes in muscle within the first few days of flight. Experiments on rats demonstrate that about 35 percent of the mass of a slow muscle is lost within a week of exposure to a microgravity environment.

The loss in muscle mass is related to movement control, in that 35 percent less tension will be produced when these muscles are activated. Thus, the nervous system must adjust its neural commands in movement and in postural control. It appears that the central nervous system is quite capable of making the necessary adjustments. More muscle fibers can be recruited for a given task to compensate for the loss in force potential. So, in summary, it appears that even though remarkable changes occur in the muscle tissue in flight, the nervous system is able to adjust remarkably well to weightlessness and upon return to one g. Maintenance of posture is a potential point of concern, largely because of the loss of muscle mass noted previously. Many of the muscles involved in maintaining the position of the head, the shoulders, the trunk, and the hip consist of a large proportion of slow-twitch fibers. These muscles are the most susceptible to a loss in mass in a variety of models of atrophy. This atrophy is unlikely to be a problem in space, but it probably will be a problem upon return to a one-g environment. This requires a readaptation of the musculature to avoid problems in the realignment of the vertebrae, which could eventually be manifested as low back pain.

It is commonly assumed that prolonged periods in space will result in "disuse" and probably increased fatigability. However, there are a number of experiments which suggest that the fatigability of atrophied fibers does not increase necessarily. For example, the soleus muscle of a rat that atrophies 35 percent in 1 week is no more fatigable than a normal soleus muscle. However, it is likely that upon return to one g, the astronaut will be more fatigable than when doing the same amount of exercise prior to flight. This may occur because in order to compensate for the small muscle mass, one has to recruit more muscle fibers, and those additional muscle fibers that are recruited are the more fatigable ones. Generally, there are sound bases neurologically on which to develop hypotheses to explain some of the observations related to the neuromuscular system. Further, there seem to be reasonable ways to address and solve these particular problems.

Injury

There is some evidence that there are adaptations in tendons and bones as well as muscle as a result of space flight. Injuries may not be a problem during space flight because generally the muscle forces produced will be less than at one g. To produce more force, one recruits more muscle fibers. In low-level activity, theoretically, one is using the lowest threshold motor units, which consist of the muscle fibers that are the most susceptible to atrophy during flight. Interestingly, the largest fibers normally are the strongest ones and are used the least often and atrophy the least in space. Obviously, the total amount of activity or the total amount of force can affect how much a muscle fiber atrophies in space, but there are other factors to consider as well. Some muscle fibers are more sensitive to the changes imposed by space flight than others. For example, it appears that some muscle fibers can be activated for a few seconds a day and still be maintained, whereas other muscle fibers must receive activation for longer periods of time. It is not clear why these differences in sensitivity exist among fibers and muscles.

The NASA needs to know exactly what is needed to maintain the normal size of muscle fibers. One of the exciting aspects of this problem is that it is technically feasible to solve; NASA has an opportunity to attack this problem given the vast amount of useful and basic information available. Although muscle atrophy is a recognized problem in space endeavors, it can be managed effectively if NASA supports an aggressive and coordinated effort among its investigators.

Many of the issues noted in this paper can be addressed using animal models of space flight. However, eventually, there must be full participation of the astronaut corps. A simple and direct way to address the problem in astronauts is to study muscle tissue taken from needle biopsies. Despite the fact that it has not been a preferred approach by NASA, it is a direct one. It is economically very feasible, it is safe, and most importantly, it represents the best way to solve the problem.

Discussion With Questions and Answers

Gunnar Blomqvist, M.D.
Division of Cardiology
University of Texas Health Science Center
Dallas, Texas

Some very important points have been made during this symposium. Dr. Thornton demonstated that we are dealing with a large matrix of organ systems, stimuli, and possible countermeasures. The degree of complexity of the task that we have to perform is very high if we are going to design an effective and efficient set of countermeasures for each system that needs attention. I am very pleased that this effort is starting out here as a joint enterprise involving operational medicine, in-house and outside investigators.

Dr. Edgerton and his colleagues have an easier time than do the cardiologists. Skeletal muscle is generally more predictable in terms of stimulus-response characteristics. Loading conditions are also much easier to regulate than for the intact cardiovascular system. It has become obvious that both the heart itself and the vasculature have much more plasticity than previously assumed. Sudden imposition or removal of overloads have the capability to cause large changes in vascular and cardiac anatomical characteristics over a few days. Aortic banding even causes a demonstrable change in cardiac protein synthesis within hours. We are clearly dealing with a system that responds vigorously to various stimuli.

The ability to transport oxygen is relatively easy to maintain. Ground-based experience indicates that an increase in maximal cardiac output can be produced in a variety of ways. The precise characteristics of the stimulus do not seem to be excessively critical. We have in our laboratory trained various groups of subjects using running, bicycle exercise, and lately a combination of swimming and weight lifting. All of these modalities have produced the standard 15- to 20-percent increase in maximal oxygen uptake after 6 to 8 weeks. About half of the improvement can be attributed to improved cardiac pump capacity. This may mean that the maintenance of cardiac pump capacity and systemic oxygen transport capacity can come as a byproduct of other types of exercise regimens that have to be more specific than the wide variety that has potential to maintain the cardiovascular system.

There are nevertheless some significant concerns regarding the cardiovascular system. There may be a progressive loss of myocardial mass during prolonged space flight. Also, there are data which suggest that even short flights produce measurable losses. However, it has not been established that preservation of myocardial mass is a necessity.

There is no question that one can apply stimuli that will increase myocardial mass at normal gravity. Dr. Mitchell in our laboratory is interested in isometric exercise and has trained cats to lift weights (which they will do very well if properly rewarded). Weight lifting that occupied less than 5 minutes per day produced a significant increase in myocardial mass. However, the increase in myocardial mass produced by isometric exercise served primarily to increase the ability to generate left ventricular systolic wall tension and a large increase in arterial pressure. A large increase in left ventricular wall thickness may decrease diastolic compliance. This may be a significant disadvantage in space, where a contracted blood volume limits cardiac filling pressures. A high compliance may be needed to take best possible advantage of the Starling mechanism during physical activity and to maintain stroke volume even at a low filling pressure.

Nevertheless, to maintain cardiac pump capacity is probably a relatively easy task. It is much more difficult to manage the interactions among the heart, the vasculature, and the various cardiovascular control mechanisms. A prime example of the complexity is that superior cardiac pump capacity is a prerequisite for high levels of physical fitness but may predispose to orthostatic intolerance as documented by Dr. Tipton and others.

There are good reasons to explore alternatives to endurance-type exercise when the primary objective is to define efficient ways of expanding blood volume to prevent orthostatic intolerance. The whole question of artificial gravity enters into this equation. One could also argue that the rapid in-flight loss of intravascular volume and the associated changes in the hemodynamic state form a very appropriate adjustment. Postflight orthostatic hypotension may be the price one has to pay for not getting into pulmonary edema during extravehicular activity. Pharmacological prevention of a chronically vasoconstricted state in flight has an interesting potential. There is a very clear inverse relationship between blood volume and systemic vascular resistance which applies equally to people with hypertension and to normal subjects.

A number of conflicts and interactions will have to be considered when designing an exercise regimen. It is obvious that we really are facing a giant therapeutic trial. I would not be surprised to learn that a statistical consultant, after reviewing all the tentative protocols, would conclude that we need a minimum of 600 subjects in the primary set and repeat studies in at least 200 to examine adequately various alternatives for a Space Station exercise program. We will have to manage with a slightly smaller set of subjects. That is a reason why it is extremely important that we all talk to each other and collaborate effectively to come up with a good design.

Q. Say again on the isometric exercise with the cats and the cardiovascular response.

A. Less than 5 minutes of isometric exercise per day in behaviorally conditioned cats produced a significant increase in myocardial weight relative to sedentary control cats.

Q. How do you keep a control cat sedentary?

A. They were kept in cages, not totally separated from emotional and physical stimuli but less active than the cats in the experimental group.

Q. There is a real uncertainty about the functional impact of loss in myocardial mass.

A. This may have something to do with the manner in which cardiac function is measured. Cardiac output by itself is not a good measure of function for at least two reasons that tend to minimize the effect of mass loss. There is after flight often a decreased systolic blood pressure (i.e., decreased afterload) that enables the myocardium to shorten more and eject a relatively larger stroke volume from any given diastolic volume. Furthermore, loss of myocardial mass and decrease in wall thickness may be partly offset by enhanced diastolic compliance and larger end-diastolic volume for any given filling pressure.

The possibility of an altered relationship between anatomy and function is very important and interesting. It is well established that all kinds of bad things happen when myocardium hypertrophies, some of which are irreversible, occur. There is an increased content of connective tissue in the heart which probably does not go away once it has been deposited. This may cause a change in mechanical properties even if the cardiac myocytes return to normal size. On the other hand, I am not aware of any correspondingly bad things happening to a heart that is unloaded over a period of time.

Q. What impact do you think that the rapid atrophy of slow-twitch fibers in skeletal muscle has on the blood vessels? The slow-twitch fibers would normally have the greatest blood flow during exercise.

A. The loss of skeletal muscle mass is likely to have minor effects on the cardiovascular system. Maximal exercise of the two quadriceps muscles, which together weigh about 4 kilograms (some 10 percent of the total muscle mass), can produce a maximal oxygen uptake and a fairly maximal cardiac output. There is plenty of muscle mass left to create a peripheral oxygen demand even after significant peripheral atrophy. Adaptations occurring in the vasculature of skeletal muscle may have a greater impact in the systemic circulation than changes in muscle mass. We have recently demonstrated that there is a strong relationship between skeletal muscle vascular conductance and systemic oxygen uptake and that skeletal conductance increases after physical training.

Discussion With Query and Answer

Mary Anne Frey, Ph.D.
NASA John F. Kennedy Space Center
Kennedy Space Center, Florida

I will discuss some of the ongoing research at the NASA John F. Kennedy Space Center (KSC) which is relevant to the answers we seek here. In one study at KSC, we've examined the muscular and the systemic effects of a 12-week lower body strength training program which was followed by a 6-week period during which the strength training was discontinued. Sixteen men trained, and eight were age-matched controls. These men ranged in age from 26 to 56 years, which approximates the age range of the U.S. astronaut population. Each subject trained 1 hour a day, 3 days a week for 12 weeks. The exercises were leg curl, knee extension, leg press, hip flexion, leg abduction and adduction, and abdominal exercises. The subjects performed repetitions at 65, 75, and 85 percent of their one-repetition maximum for each exercise. This was an overload program, wherein we increased the resistances throughout the program.

We monitored the following variables before and after the training period and then again after detraining.

1. Leg strength - We used the Cybex isokinetic dynamometer.
2. Maximal aerobic capacity determined by the treadmill
3. Body density and composition by underwater weighing and some anthropometrical measurements
4. Muscle cellular characteristics from biopsies of the vastus lateralis - This testing was performed by Dr. David Costill's laboratory at Ball State University.
5. Levels of several electrolytes, hormones, enzymes, and lipids in the blood
6. Responses to a lower body negative pressure test

To quickly summarize the results, leg strength was significantly increased in the training subjects, by about 15 percent, and this strength was not reversed during the 6 weeks after training. We observed other characteristics you might expect, such as an increase in thigh circumference and a decrease in percent body fat. Aerobic capacity (VO_2 max) was not changed. Unfortunately, I cannot report to you on the biopsy data or the blood data, because these are not completely analyzed.

One interesting aspect of this study was the opportunity to examine responses to the stress of lower body negative pressure, which is a simulation of orthostatic stress. We performed this test before and after the 12-week strength-training program. The tolerance of astronauts to orthostasis on their return to Earth is a matter of some concern. One question that has received the attention of researchers is whether or not aerobic or strength fitness affects this tolerance to orthostatic stress in some meaningful way. Our strength-training study was an opportunity to shed some light on this question. The 16 trainees provided a good sample size. We measured heart rate, stroke volume and cardiac output by impedance cardiography, arterial pressures, leg volume by Whitney strain gauge, and thoracic fluid volume by impedance. We calculated total systemic resistance. The lower body negative pressure, or LBNP protocol as we call it, was a stepdown protocol with regard to pressure in the LBNP device; and we recorded variables at control (that is, atmospheric pressure) and at 30, 40, and 50 mm Hg below atmospheric pressure. We observed no differences between the training and the control subjects, and we observed no differences in the trainees from before training to after training. Others have shown improved tolerance to centrifugation after lower body strength training. However, stresses of centrifugation and LBNP differ. Subjects are encouraged to contract their abdominal muscles during centrifugation, but subjects are requested to remain completely relaxed during LBNP.

We have performed other studies at KSC for investigating the relationships between strength and aerobic fitness and responses to orthostatic stress. We used LBNP to simulate orthostatic stress in these studies as well.

Forty-five women ranging in age from 23 to 45 years participated in one study. This is the general age range of the female astronaut population. The maximal aerobic capacities (VO_2 max's) of these women ranged from 23 to more than 55 milliliters of oxygen per kilogram per minute (ml/kg/min). We used the same LBNP protocol that I described to you before, and we measured the same cardiovascular variables. Six of the women became presyncopal during their LBNP tests. The mean VO_2 max of the presyncopal groups of women was the same as the VO_2 max of the group of women who did not become presyncopal; that is, 38 ml/kg/min. We calculated responses to LBNP by subtracting the value of each variable during control from the value during "negative pressure" levels of minus 30, minus 40, or minus 50 mm Hg. For example, if the heart rate was 120 bpm at minus 50 mm Hg and was 40 bpm at control, our response value would be 80 bpm. We tested the correlations of these responses in each variable with the VO_2 max of these 45 women. The only measured response variable which was significantly correlated with VO_2 max was the percent change in calf circumference at minus 30 and minus 40 mm Hg. From these data, we feel that orthostatic tolerance need not be a concern with regard to prescribing aerobic fitness for women astronauts.

In another cross-sectional study, we are comparing responses to LBNP among four groups of men. These groups comprise men with high lower body strength and high aerobic capacity, or low strength with low aerobic capacity. High strength was defined as leg extension strength of both legs of more than 103 percent of their body weight (average 115 percent). Low strength was defined as leg strength less than 91 percent of body weight. High-aerobic-capacity groups were more than 50 ml/kg/min (mean = 55) and low aerobic capacity less than 45 ml/kg/min (mean = 40). In this study, we measured hormones (catecholamines, renin, and vasopressin) in addition to the cardiovascular variables I described before. Seven of the subjects became presyncopal. They represented all four groups; in fact, two each from three of the groups and only one in the high-aerobic-fitness/low-strength group became presyncopal. So, in terms of tolerance to LBNP, we could identify no differences among the groups within the limits of this protocol. Thus, we feel this is additional evidence that orthostatic tolerance need not be a major concern when prescribing aerobic or strength training for astronauts.

We have also performed some very preliminary investigations of electrical stimulation of muscle (EMS) as a potential countermeasure to muscle atrophy. We have developed a combined system for sequentially stimulating and monitoring the hamstring, quadricep, gastrocnemius/soleus, and anterior tibialis muscles. Load cells can monitor torque about the ankle and knee axes during stimulation and during voluntary contraction.

In a pilot study, we stimulated one leg of ambulatory subjects for 1 hour a day, four times a week for 8 weeks. Even in this group of noncompromised, ambulatory subjects, we observed some increase in muscle size and strength after the stimulation. Subjects performed as well or better on mental tasks (computer presented) during the stimulation as they did while not being stimulated.

We anticipated that EMS would be more effective in maintaining muscle function in compromised subjects, such as astronauts in microgravity, than in building muscle in these ambulatory subjects. This potential countermeasure has the benefit that stimulation time can be productively used for other activities such as work or sleep. Thus, it may be an effective adjunct to exercise which would not heavily impact the crew work schedule.

We are presently planning additional studies using subjects whose legs are kept immobile by a cast and subjects who are confined to bed for a prolonged period.

I hope that these highlights from our research at the Kennedy Space Center will be helpful to you in your considerations, and I look forward to gaining information and insight from you to guide us in our future research. If you have any questions, my colleagues and I will be glad to answer them.

Q. Did you measure electromyographic activity during these tests?

A. We measured plasma volume in the study of four groups of men with high and low strength and aerobic fitness.

I want to mention one of our findings that partly corroborates Dr. Blomqvist's earlier report. We have examined responses to orthostatic stress in individuals over an age range of 20 to 56 years. In agreement with Dr. Blomqvist's report, we found that in the younger subjects, a heart rate response predominated, and in the older subjects, there was more of a peripheral resistance response. But that's for men only. The older women didn't have an increased response in peripheral resistance.

Discussion

Ron Bulbulian
Department of Physical Education
Kansas State University
Manhattan, Kansas

Seems like everything the latter speakers have time to say has in one way or another been touched upon. So I'll try to make my comments brief and maybe allow Dr. Tipton additional opportunity to use the time. I might just say a few words to explain how I came about in the picture here. I myself am a physiologist from Kansas State University, but, during the summers, I've had the opportunity to work at the Aerospace Research lab with the Navy down in Pensacola. Last summer, I got interested in high-performance flight and orthostasis and - having done some reading in the area - this summer, I had the opportunity to work with NASA and John Greenleaf's program with the bed-rest study. That's how I came into the picture. Having arrived there somewhat late in the planning, I was wondering where I would fit into the picture, and this is really the flowchart or the organizational chart for the countermeasure study they're doing. John Greenleaf is the principal investigator, and here are all the people that are working on that project, and I guess the way I fit into this is way down here. I'm not even on the chart, and they've got me doing the review of literature, which John felt might be a good idea for me to at least very briefly encapsulate some of the things I've had a chance to read in the last month. I guess I've looked through at least 300 or 400 abstracts and articles basically emphasizing studies related to exercise and space flight and bed rest. And so the information I share with you will come from that source of knowledge and things I've also read in the past.

Why should we be concerned with exercise countermeasures to zero g? What I've done here is outline some of the changes that occur with either bed rest or space flight, water immersion, or any of the problems that we've been discussing thus far. We have orthostatic intolerance that can be measured in tilt tables, and, of course, we also have the positive-g centrifuge problems: muscular weakening, vascular deconditioning, incoordination, gait problems, especially reentry, electrolyte shifts. Victor's talked about plasma concentrations being a key problem; we have already mentioned some changes in respiratory parameters which we haven't said a lot about during this conference, but there are some changes that take place. They aren't really major problems. Blood chemistries will change. Loss in body weight occurs in some studies. Some of the data suggest that may be a problem, particularly with loss of lean body weight. We've talked somewhat about bone loss, calcium loss. It's interesting that I came across one study that showed these changes are more pronounced in males than in females and that the females seem to be more resistant to bone loss under these conditions. Also, very fit individuals were a little more resistant, I believe. Okay, so we continue with this outline of changes that we've come across, and some of these I might underline I'm not totally familiar with. Some of you with medical degrees might be better equipped to deal with the subjects; however, I'm just bringing to your attention things that are in the literature related to the present concerns we have: bacterial activity on the skin, phagocytic activity of neutrophils, tolerance to coriolis and linear acceleration, glucose intolerance we've touched upon, reduced erythropoiesis, sleep disturbances which are limited, and that's one area in which I think maybe a bit more work could be done because the U.S.S.R. literature has reported sleep disturbances much more than the literature in our journals. And, also, with the information we have from the space-flight program, we report relatively small or almost nonexistent sleep disturbances in space flight. I expect that exercise might be one of the variables there that is giving us this difference. Most bed-rest studies that have not incorporated exercise as part of the treatment show sleep disturbances. On the other hand, when you incorporate exercise, subjects seem to sleep better. And, of course, if we're going to put men in flight, or in space for 90 days or more, you want to ensure that they'll be getting sufficient rest. Other factors are electrocardiography and cardiac muscle deterioration, and nervous system asthenization. We've certainly suspected that the nervous system is being affected during zero-g or simulated zero-g conditions. Some of the U.S.S.R. investigators have looked into it in a little more detail than we have in the past, and it does appear that there are some deteriorative processes taking place there. Endogenous stores of norepinephrine are depleted. Also occurring are loss of thermal regulation, perceptual deprivation problems - we've looked into that somewhat - and gastrointestinal motility is reduced. So there's a large scope of changes that we expect to see from bed rest or water immersion or space flight that we need to deal with. And the question, of course, arises regarding exercise, which is our specific charge; which of these are we going to use exercise as a countermeasure for? Certainly, there's different kinds of exercise that can be used for each one individually, and I'm talking here generally. It's possible that exercise might not help many of these.

So, with this background, we want to look at some of the countermeasures that have been used; not just exercise, but others have been used, of course. At the top of that list is exercise: isometric exercise, aerobic training, weight lifting. Pharmaceutical agents have been used, steroids and antidiuretics. In several studies, leotards, elastic leotards, have been used to try to combat this orthostasis problem. Elastic tourniquets have been used to regulate blood flow, venous return, etc. Lower body negative pressure and positive pressure breathing have been used, and that seems to have been effective in part. Also tried are water loading, hyperhydration, electrical stimulation - which we've briefly considered - upper body positive pressure, and there are several more. All of these have been used and have been found effective in one way or another. The question is, do we stick with one method: exercise? From my experience, I cannot say that exercise is a cure-all for everything. I think that sometimes exercise physiologists get into that mode. Certainly, it can be helpful in some areas, but I think we need to think about combinations of treatments using exercise as one component of the total treatment of the subject; in this case, the astronaut.

Areas of concern from my reading are the following: first (I read this once and liked it), too many bricks in the brickyard. A lot of research I came across is just tidbits, fragments here and there, individual areas of concern to the investigators eventually ending up in the literature. Trying to put it into an integrated whole becomes a problem. So what we need is more comprehensive integrated approaches to solving the problem rather than taking one principal area of interest and getting out a piece of information that obviously will be helpful but may not help to answer the question as well as it could. And, of course, to do this comprehensive kind of work, you need better funding, more cooperation, and the kind of things that we're trying to get started here. Second, bed rest and water immersion are not space flight. There are some similarities, some qualitative differences that are similar, but quantitatively, we are not looking at the same thing. Therefore, we need more actual flight data from astronauts, and that's an important ingredient that's lacking. Third, we need to know more about the working energy requirements, and the last couple of presentations have shed a little bit more light on it. (I'll show you something that was initially interesting to me but the interest has waned - not waned - but the interest has not been as much of a concern for me now that I just received more data from a good presentation on extravehicular activity (EVA).) Fourth, what is the countermeasure for? Exercise must be prescriptive and it must be specific. Are we giving exercise for effecting changes during space flight as the suggestion has been made. I'm not convinced. Do we in fact want to prevent these changes that take us to a different homeostatic baseline, if you will, in space flight? I'm not convinced that maintaining high plasma volumes in space flight is the ultimate goal or should be. Certainly, when we come back to Earth, we're working in a one-g environment, where it may be desirable. When we look at exercise as the mode for effecting that change and reconditioning the legs to handle the one-g environment, maybe we should be thinking, at least in long space flight, of implementing exercise training just before reentry. Of course, we need to look at time course, the kinetics of reestablishing the physiology, so that it can handle the one-g environment. So, depending on what the time courses are, maybe we want to get up there, let the body adjust to that environment, work in that environment, and then, just before reentry, enact several measures to bring us back to handle the one-g environment. So that's something that we'll need to talk about in a little more detail.

As to future areas of study, duration of exercise, Vic has suggested that maybe longer duration might be good. We need to look at that. Regarding type of exercise, upper body has been suggested as a key, and I concur with that. It doesn't seem as if the lower body is as important, at least in space flight. Certainly during reentry, the lower body will be a very important factor to be countered with a combination of measures, and I don't mean combinations of exercise. I mean combination of measures such as exercise possibly with some pharmaceutical agent or maybe with lower body positive pressure, or whatever, but combining modalities so that the person isn't constantly in a situation where he is trying to expend calories to maintain the physiology suitable for a one-g environment. So, certainly, these things need to be looked at, and, in the U.S. program, research programs at least, they have not been done very effectively. As a matter of fact, we're just now getting to mixing different types of exercise. Most of the research I looked at just applied to one kind of work, and that was it. Right now, we're getting into combining isotonic, isometric, isokinetic, and so on. But that's not enough. I think we need to look at the other agents, whether mechanical manipulations or pharmaceutical manipulations in addition to exercise.

With regard to intensity of exercise, the data we just received a few minutes ago suggested that the space suits at maximum are engineered to handle 500 kcal/hr. I was only privy to the data from Spacelab. Looking at Skylab information, I very roughly calculated that the work rates reported were steady state for long EVA. I'm suggesting that the data I looked at were for workouts lasting 1 to 2 hours. Intensity came out to about 21 to 30 percent of the predicted VO_2 max. Data they reported are for 75-percent activity, and so I extrapolated from there and calculated that they were working at about 21 to 30 percent of VO_2 max, which seems to be low. I present here a table to explain what has been done. This was the 75-percent value that's reported in the literature. I predicted a max VO_2 value along this line here. So, 2.2 liters, which was 75 percent, predicted a 2.8 VO_2 max, and then, from that value, I calculated calories, calories per hour, and the fraction of the maximum working capacity which the suit allows (which is 500 kcal/hr). I got 60, 42, and 48 percent allowable intensity for the three crewmembers, that's if they work at the maximum capability of the space suit to handle the metabolic heat. On the other hand, the data suggested that at a steady-state average working level, there were around 230 kilocalories expended. Well, I was generous, I guess. Two-hundred fifty kilocalories average per hour came out to 30, 21, and 24 percent, and maybe I'm naive, but I think that those intensity levels are a little low even for arm work. Furthermore, from what I've gathered, in zero g, the external work induces a larger oxygen consumption, so in terms of the absolute amount of work being done, it's less than what we would normally think of for a one-g environment. With that in mind, I think we need to - when we finally get into our groups - try and collectively come up with a solution to the question of how we handle a zero-g environment.

Discussion With Questions and Answers

Ed Bernauer, Ph.D.
Human Performance Laboratory
University of California, Davis
Davis, California

The speakers, starting with Dr. Bill Thornton this morning and Drs. Reggie Edgerton and Gunnar Blomqvist this afternoon, touched on some of the things that I had planned to address. I will take some time to review a report we made in 1976 on a bed-rest study at the NASA Ames Research Center (ARC). The focus of that study was to look at the effects of a 14-day bed rest on orthostatic tolerance (OT), the oxygen uptake capacity (VO_2 max), blood volume, and fluid and electrolyte exchange. First, I'll just have a comment or two to make on the changes in orthostatic tolerance. One of the things that struck me was Dr. Edgerton's comment on the need to focus our attention on physical performance. I think that's really where the emphasis should be, on performance. For some years, I was interested in, and in fact coached, a varsity track team at the university level. I assumed that there was a strong relationship between oxygen (O_2) capacity and endurance performance, but I have found subsequently that this is not necessarily so. I find rather that there are people who perform very well at endurance activities who do not possess extraordinarily high aerobic capacities. Performance is not dependent upon a single physiological dimension such as VO_2 max.

In assessing a specific physical performance or condition, often, there are critical elements that we fail to discern, especially given unique circumstances, in favor of a more conventional and convenient measurement approach. If the ability to perform is the paramount factor, then reliance on such conventional functional measures as aerobic and anaerobic capacities may not be the discriminating variables, but rather some less apparent covariate. Another way of expressing this idea is to state that the performance may not be limited by functional capacities per se but by some covariate that is associated with the physiological conditioning or deconditioning process that produces the functional capacity. There exist, then, standardized quantitative functional measurements, such as VO_2 max, that are conventionally employed as criteria for physical performance under widely dissimilar experiential circumstances. Users of this approach frequently ignore the specificity of the response; that is, specificity in the context of physical and metabolic properties of muscle tissue as commented on by Dr. Edgerton, or, at the systemic level, in the context of systemic integrations which result from the interaction of physical and ambient environmental demands.

For example, in work that we completed for the U.S. Air Force, we were interested in examining the effect of aerobic training on $+G_Z$ tolerance, either as a predictor of or as a means of inducing a positive training adaptation; i.e., an increase in VO_2 max. The prevailing wisdom at that time suggested that aerobic training (i.e., endurance running) was probably the best way of developing a protection against a loss of orthostatic tolerance, if not of actually increasing orthostatic tolerance. After testing a number of people, we found that the VO_2 max, per se, was not highly related to orthostatic tolerance. What we did find, however, was that the volume of running per week was highly related to orthostatic tolerance but in a negative fashion.

Utilizing 70-percent head-up tilt to syncope or 40 minutes to end point, we have dichotomized 30 subjects to date as either fainters or nonfainters. When subjects were categorized on the basis of the volume of their weekly aerobic training, we found the following pattern.

1. Of those who ran >60 miles/week, 9 of 9 were fainters.
2. Of those who ran >45 but <60 miles/week, 3 of 4 were fainters.
3. Of those who ran >20 but <45 miles/week, 3 of 5 were fainters.
4. Of those who ran <20 miles/week, 6 of 12 were fainters.

Thus, it appears from these data that volume of endurance training rather than aerobic capacity is a better predictor of OT. Further, it would seem that the prescription of endurance training would be counterproductive with respect to orthostatic-dependent performance.

We next initiated a pilot study to investigate the effects of specific training regimens on OT. Six subjects engaged in one of two supplemental training programs while continuing their preferred exercise activities; viz, jogging or weight training. The joggers added a prescribed weight training program; the weight trainers, a supplemental jogging program. The results of the pilot study revealed a measurable improvement in the OT of the jogger with added weight training, but no change in the weight trainers with added bicycle endurance training. These results are very preliminary and only suggestive; however, they do raise a number of interesting questions related to appropriate exercise prescription, which is the basic theme of this meeting.

Turning now to the effect of bed rest on VO_2 max and related physiological responses which are thought to affect physical performance, I would like to present results from our 1976 study. The 15-week study was a series of ambulatory control periods followed by 14 days of bed rest; each subject served as his own control, engaging in dynamic and static exercise and abstaining from exercise (control) during the 14 days of bed rest (fig. 1). The purpose of the study was to evaluate the effect of exercise during bed rest in maintaining or diminishing the loss of aerobic capacity - VO_2 max and associated work tolerance. We also analyzed the submaximal VO_2 intakes and the changes in the blood volume. Passive orthostatic tolerance in the $+G_Z$ configuration on a human centrifuge at 2.1, 3.2, and 3.8 $+G_Z$ was also measured and reported in another paper. Subjects exercised twice daily for 30 minutes at either 68 percent VO_2 max dynamically or 25 percent VO_2 max statically on a bicycle ergometer or leg pulley weights, respectively.

The assumption was that the bed rest would result in a general reduction in aerobic capacity, work tolerance, and orthostatic tolerance. The further assumption was that dynamic aerobic exercise is the better type to offset the observed regression in functional capacities and physical performances during the simulated weightless conditions of bed rest. We have already commented that physical performance depends on a complex integration of a number of underlying environmental and physiological stimuli, and a single-dimension exercise approach will probably not result in a broad-spectrum maintenance of the physiological systems necessary to sustain ambulatory levels of physical performance. However, it seemed appropriate to assess the contribution made by two quite distinct types of exercise modalities during bed rest to functional capacities and associated physical performances. Incidentally, these results served as one of the fundamental references to the 30-day bed-rest study currently under way at ARC this summer.

The results of the 1976 integration are summarized in the next three slides. Given the repeated bed-rest design of the study, it was essential to demonstrate that there were not accumulative effects, particularly a progressive loss of function or performance. Table I, taken from reference 1, does not reveal any signs of a regressive loss of function; the one significant difference seen is in bicycle ergometer exercise duration, the increase of which probably was psychologically induced by the knowledge of having completed the study. Further, note the failure of the VO_2 max to comply with the increase in the exercise duration; also note the general increase in exercise tolerance during the course of study.

The next slide shows VO_2 intake and heart rate response to various exercise or resting-control regimens (fig. 2). To our surprise, the static (leg isometric) exercise group experienced the least reduction in their VO_2 max, the bicycle ergometer group was intermediate, and the nonexercise regimen showed the greatest reduction: 4.8, 9.2, and 12.3 percent VO_2 max, respectively. No significant differences

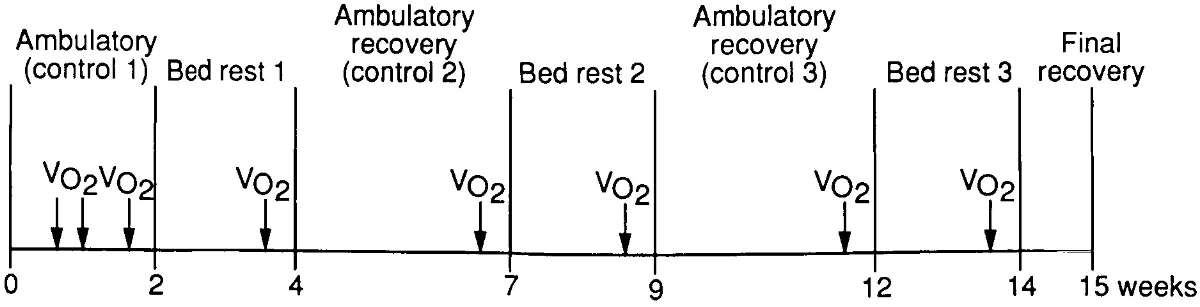


Fig. 1.- Experimental protocol for the 15-week study (from ref. 1).

TABLE I. - MAXIMAL WORK CAPACITY DATA FROM INITIAL CONTROL PERIOD AND END OF TWO 3-WEEK RECOVERY PERIODS

[From ref 1; values are means plus or minus standard error]

Variable	Value for -		
	Control period	Recovery 1	Recovery 2
VO_2 max, liters/min	3.68 ± 0.11	3.86 ± 0.16	3.86 ± 0.19
Max. ${}^{a}VE_{BTPS}$, liters/min	129.7 ± 6.1	141.9 ± 1.8	136.0 ± 5.2
Max. heart rate, beats/min	183 ± 3	187 ± 4	183 ± 3
Test duration, min	12.09 ± 0.75	13.14 ± 0.79	^{b}13.91 ± 0.85

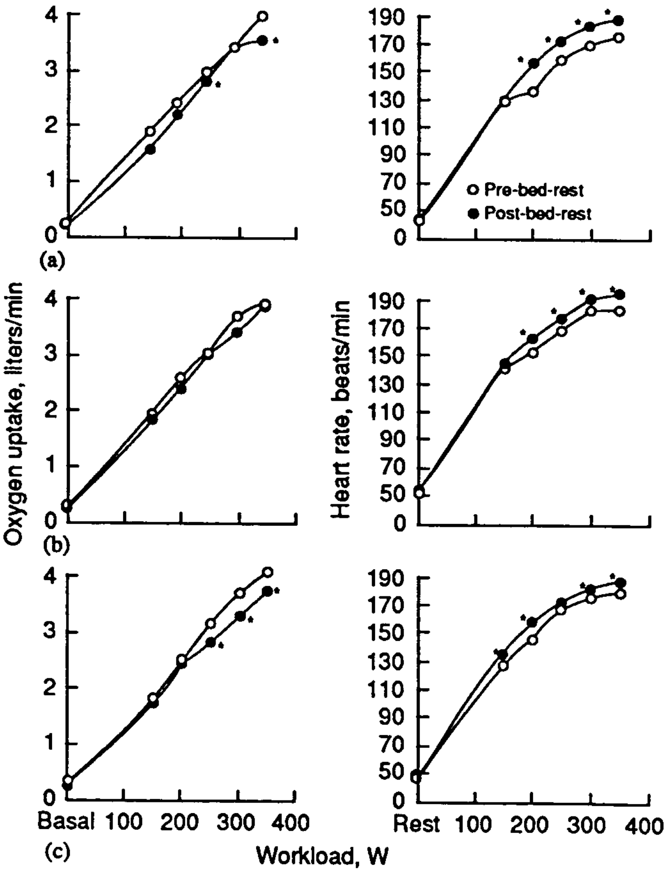
[a] VE = ventilation; BTPS = body temperature and pressure, saturated with water.
[b] Significantly different ($P < 0.05$) from control period.

were seen between the pre- and post-bed-rest O_2-intake curves at any of the exercise intensities in the leg isometric training group. However, significant differences are noted for both the no-exercise and the dynamic (bicycle) exercise groups at both submaximal and maximal levels.

Heart response to exercise reveals a consistent pattern for all three groups for both pre- and post-bed-rest periods. Heart rate is significantly higher both at submaximal and at maximum exercise intensities following bed rest. One can infer that any change in work tolerance, duration, and functional aerobic capacity is not uniformly reflected by the heart rate response (fig. 2).

The last of the result slides presents the changes in blood and plasma volume as the result of 14 days of bed rest for the three physical activity regimens. All three groups show a reduction in blood and plasma volumes; however, the rank order for this parameter differs from that observed for the oxygen intake and exercise tolerance and duration. The greatest loss is seen in the no-exercise regimen, followed by the leg isometric and bicycle dynamic exercise regimens. Further, note that only in the no-exercise group were both blood and plasma significantly reduced. The bicycle regimen resulted in nonsignificant changes for both blood and plasma volume. The isometric groups showed mixed results (table II).

In summary, it appears that specific exercise regimens provide selective and differential protection against the deconditioning seen during 14 days of bed rest. Functional capacities did not always coincide



*P ≤ 0.05 from pre-bed-rest value (two-tailed t-test).

Fig. 2.- Mean oxygen uptake and heart rates at rest and at submaximal and maximal workloads for the three regimens (from ref. 1). (a) No exercise. (b) Static exercise. (c) Dynamic exercise.

TABLE II.- PLASMA VOLUMES AND TOTAL BLOOD VOLUMES
DURING THE RESPECTIVE CONTROL (C) PERIODS AND
FOLLOWING BED-REST (BR) PERIODS

[From ref. 1; values are means plus or minus standard error]

Measurement	Value for -								
	No exercise			Static exercise			Dynamic exercise		
	C	BR	(BR - C), % change	C	BR	(BR - C), % change	C	BR	(BR - C), % change
Plasma volume, ml	3491 ± 205	2966 ± 184	[a]-15.1	3518 ± 247	3161 ± 170	[a]-10.1	3367 ± 205	3111 ± 233	-7.8
Total blood volume, ml	5230 ± 283	4604 ± 265	[a]-13.6	5256 ± 340	4940 ± 237	-6.4	5078 ± 260	4798 ± 341	-5.8

[a] $P \leq 0.05$.

with the observed physiological compensations. Submaximal oxygen intakes which were not expected to change because of bed rest did; however, this may be an artifact of the measurement protocol. Since the oxygen measurement was made between 1 and 2 minutes of each progressive incremental exercise step, it may not have achieved a steady state and may reflect a change in the time constant of the oxygen delivery system. The differential physiological response to the exercise regimens during bed rest were distinct and not necessarily related to the observed changes in performance.

The effects of various durations of bed rest on the VO_2 max and the ameliorating effect of selective exercise regimens during bed rest on VO_2 max changes are summarized in tables III and IV, respectively. The average decrement for VO_2 max was 7.5 ml/kg based on a mix of chair and bed-rest confinement studies ranging from 4 to 20 days. Thus, the magnitude of the hydrostatic pressure reduction and muscle activity is not directly comparable. If you scan the last slide (table IV), you will see a list of studies which incorporated exercise intervention, and one sees a very mixed picture. Bicycle ergometer exercise results in a reduction of about 7.6 percent in one's VO_2 max, whereas, with static exercise, you get about 4.8 percent reduction; the latter comes out of our 1976 study (ref. 1). It's the only such information available related to bed rest, to my knowledge. The results of trampoline exercise are interesting because of the variation, from increasing oxygen capacity to 15.5 percent to a loss of 9.1 percent. This type of exercise needs further investigation.

To summarize these data and observations, with respect to recommending the type of exercise which is best suited to maintaining aerobic capacity and exercise tolerance while in a weightless state for the subsequent return to normal gravity, one is left with the following observations. If the purpose is to maintain aerobic capacity and work tolerance for reentry, then 60 min/day will attenuate the deconditioning observed during bed-rest simulation of the weightless state. A clear choice of exercise modality or protocol for this purpose is not evident at

TABLE III.- MEAN CHANGES IN MAXIMAL OXYGEN UPTAKE DURING DECONDITIONING WITHOUT REMEDIAL PROCEDURES

[From ref. 1]

Source, ref.	N[a]	Sex	Age, yr	Exercise test		VO_2 max			Deconditioning	
				Apparatus	Position	Predeconditioning, liters/min	Postdeconditioning, liters/min	Change, %	Time, days	Method
2	6	M	18-23	TM[b]	UP[c]	2.72	2.51	-7.7	4	Chair rest
2	6	M	18-23	TM	UP	3.07	3.06	-0.3	6	Chair rest
2	5	M	18-23	TM	UP	2.61	2.43	-6.9	8	Chair rest
2	6	M	18-23	TM	UP	2.69	2.95	+9.7	10	Chair rest
3	3	M	21-26	TM	UP	3.66	3.47	-5.2	10	Bed rest
4	4	M	22-25	BE[d]	SUP[e]	3.14	2.87	-8.6	13	Bed rest
5	15	M	19-23	BE	SUP	3.52	3.20	-9.1	14	Bed rest
1	7	M	19-22	BE	SUP	3.83	2.43	-12.3	14	Bed rest
6	4	M	21-24	BE	UP	3.14	3.13	-0.3	15	Bed rest
5	8	F	23-34	BE	SUP	2.06	1.86	-9.7	17	Bed rest
7	4	M	22-24	BE	UP	3.10	2.70	-12.9	20	Bed rest
8	5	M	19-21	BE	SUP	3.30	2.43	-26.4	20	Bed rest
Mean						3.07	2.75	-7.5		

[a]N = number of subjects.
[b]TM = treadmill.
[c]UP = upright.
[d]BE = bicycle ergometer.
[e]SUP = supine.

TABLE IV.- MEAN CHANGES IN MAXIMAL OXYGEN UPTAKE DURING DECONDITIONING WITH VARIOUS REMEDIAL PROCEDURES

[From ref. 1]

Source, ref.	N[a]	Sex	Age, yr	Exercise test		VO_2 max			Bed rest training schedule			
				Appa-ratus	Posi-tion	Predeconditioning, liters/min	Postdeconditioning, liters/min	Change, %	Time, days	Duration, min/day	Stimulus	
											Type	Posi-tion
1	7	M	19-22	BE[b]	SUP[c]	3.80	3.45	-9.2	14	60	BE	SUP
1	7	M	19-22	BE	SUP	3.77	3.59	-4.8	14	60	Static	SUP
6	4	M	22-26	BE	UP[d]	3.19	3.42	+ 7.2	15	30	BE	SUP
6	4	M	21-24	BE	UP	2.96	3.42	+ 15.5	15	30	TR[e]	SUP
9	6	M	18-21	TM[f]	UP	2.91	2.28	-21.6	28	60	BE	SUP
6	4	M	21-25	BE	UP	3.17	2.92	-7.9	30	45	TR	SUP
6	4	M	21-22	BE	UP	3.51	3.19	-9.1	30	15	TR	SUP
Mean						3.33	3.18	-4.3				

[a] N = number of subjects.
[b] BE = bicycle ergometer.
[c] SUP = supine.
[d] UP = upright.
[e] TR = trampoline.
[f] TM = treadmill.

this time. The results to date reflect the mixture of study designs and an arbitrary approach taken to establishing standardized exercise regimens. As seen, dynamic exercise, performed for 30 minutes twice daily, indicated a clear advantage over nonexercise controls based on bed-rest studies. A further complicating factor is the interaction between state variables such as body mass, composition, blood volume affected by the bed-rest confinement, and the state functions such as VO_2, cardiac output, heart rate, to name a few. Further, it must be recognized that the physiological changes associated with various regimens of exercise intervention are not equivalent to the physical performance essential to the success of a mission. Finally, one must address the question of the purpose(s) of the exercise regimens; i.e., to maintain appropriate functional capacities for performance while in space and/or for the stress of reentry and subsequent gravity demands on Earth. In subsequent investigation, these questions must be addressed and more attention must be given to the fundamental aspects of homeostatic mechanisms underlying specific fitness factors; i.e., to focus on the specific system tissues or physical chemical processes underlying the adaptive function.

Q. What was the relative level of activity in bed vs. the ambulatory level of activity?

A. I suspect that some of the variation reported can be attributed to these differences. We made an effort to match the subjects based on their aerobic capacities. We matched subjects and then controlled their daily activity and diets. In the 1976 study (ref. 1), we reduced the dietary intake to adjust for the decrease in their activity during bed rest; this reduction was on the order of 35 to 40 percent. They maintained their weight relatively constant; therefore, one can assume there was about 35 percent reduction in energy requirements, which would be about the reduction in their daily physical activity. We found that there was no significant change in the body weight or the lean body weight of the exercisers. However, there was a significant loss of lean body weight and an increase in the percent of body fat of the control subjects.

Q. What was the protocol for the isometrics?

A. The isometric exercise I emphasized was limited to the legs. The isometric exercise was an isometric leg extension (i.e., a leg press) held for 1 minute interspersed with one-half minute rest for 30 minutes per session twice a day. The load was 25 percent of an individual's one repetition - max (1 - RM). I might add that when the 1976 study was designed and conducted, we were not privy to much of the interesting information I've heard in the last day. It would have been beneficial to have had that information to better design the exercise protocols.

Q. Have you done exercise studies with your arms rather than the legs, and say if you can prevent the plasma loss that's commonly seen?

A. We haven't done arm experiments. We were contemplating doing that in the study currently under way. The design got too complicated. What we're attempting now takes about eight exercising subjects about 8 to 10 hours a day to complete. To add arms to a leg exercise regimen would greatly increase the time required. Sometime in the future, it might be wise to just look at arm mass. I don't know what the stimulus is that is necessary to maintain plasma and/or blood volume, the amount of mass involved, or the metabolic demand.

But, if you come back to exercise specificity, I think all of us can agree, there's restricted activity and reduced metabolic demand in space, so really aren't you somewhat forced to see what your arm movements could or should do to maintain one's blood volume or muscle mass or functional capacity? I'm not denying it's an interesting question. If you plan an experiment on board with astronauts, it would probably be informative to schedule various modes of leg exercises and also designate some of the astronauts to perform arm exercise only. It is a direct way of answering that question.

Q. Are you proposing that we still use the max VO_2 test?

A. No; in fact, I probably wasn't as clear as I should have been. It seems to me that too much emphasis has been placed on max VO_2, which is only one index of the metabolic function and probably not the best one to look at, given the emphasis on routine physical performance as opposed to functional capacity. More attention needs to be given to the changes in meeting the exercise demands at submaximal exercise. I believe that the response of the cardiovascular system to submaximal workload changes with the duration of bed rest; i.e., it takes longer to achieve a steady state, but not necessarily one differing from pre-bed-rest levels in terms of energy requirement. In the current bed-rest study being conducted at ARC, which will be reported later in this meeting, we are doing a submaximal exercise protocol, and once a submaximal state is achieved in approximately 5 to 10 minutes, we measure cardiac output over the next 5 minutes. Work that Paul Mole has done in our laboratory shows that it takes minimally 8 to 10 minutes to achieve a true submaximal baseline, a steady state; that's in terms of oxygen intake and carbon dioxide stores being in equilibrium within the system and respiratory quotient and acid-base ratio stabilizing. After establishing a steady-state baseline, we then measure the corresponding cardiac output under the same conditions. We hope to have a better insight with respect to the effect of exercise on the metabolic and cardiovascular changes due to bed rest by using this submaximal exercise protocol.

Q. I accept what you say, but I'm not so willing to accept the possibility of metabolic profile changes in the tissue which are always predominantly observed on a slow tissue after restricted activity.

A. That's the other problem with a lot of the documented data. There are differences in the duration of the bed rest or chair study. There are differences in how the oxygen intake was measured, whether it was measured in the supine or in the upright position following bed rest; so, it's really apples and oranges and - despite what appears to be a fair amount of data - is really quite confusing and not all equivocal. To repeat, we need to better understand the underlying mechanisms responsible for the bed-rest change. Is it primarily a cardiovascular reflex mechanism or is it an oxygen metabolic capacity change? I don't think we really know yet.

References

1. Stremel, R. W.; Convertino, V. A.; Bernauer, E. M.; and Greenleaf, J. E.: Cardiorespiratory Deconditioning With Static and Dynamic Leg Exercise During Bed Rest. J. Appl. Physiol., vol. 41, no. 6, Dec. 1976, pp. 905-909.

2. Lamb, L. E.; Stevens, P. M.; and Johnson, R. L.: Hypokinesia Secondary to Chair Rest From 4 to 10 Days. Aerospace Med., vol. 36, 1965, pp. 755-763.

3. White, P. D.; Nyberg, J. W.; and White, W. J.: A Comparative Study of the Physiological Effects of Immersion and Recumbency. Proceedings of the Second Annual Biomedical Research Conference, NASA Manned Spacecraft Center (Houston, Tex.), 1966, pp. 117-166.

4. Georgievskii, V. S.; Kakurin, L. I.; Katkovskii, B. S.; and Senkevich, Y. A.: Maximum Oxygen Consumption and Functional State of the Circulation in Simulated Zero Gravity. The Oxygen Regime of the Organism and Its Regulation, N. V. Lauer and A. Z. Kolchinskaya, eds. Naukova Dumka (Kiev), 1966, pp. 181-184.

5. Convertino, V. A.; Stremel, R. W.; Bernauer, E. M.; and Greenleaf, J. E.: Cardiorespiratory Responses to Exercise After Bed Rest in Men and Women. Aerospace Med. Assoc. Preprints, 1975, pp. 238-239.

6. Chase, G. A.; Grave, C.; and Rowell, L. B.: Independence of Changes in Functional and Performance Capacities Attending Prolonged Bed Rest. Aerospace Med., vol. 37, 1966, pp. 1232-1238.

7. Kakurin, L. I.; Akhrem-Akhremovich, R. M.; et al.: The Influence of Restricted Muscular Activity on Man's Endurance of Physical Stress, Accelerations and Orthostatics. Soviet Conference on Space Biology and Medicine, 1966, pp. 110-117.

8. Saltin, B.; Blomqvist, G.; et al.: Response to Exercise After Bed Rest and After Training. Circulation Suppl., vol. 7, 1968, pp. 1-78.

9. Miller, P. B.; Johnson, R. L.; and Lamb, L. E.: Effects of Moderate Physical Exercise During Four Weeks of Bed Rest on Circulatory Functions in Man. Aerospace Med., vol. 36, 1965, pp. 1077-1082.

Comments

Joan Dunellis, Ph.D.
NASA Ames Research Center
Moffett Field, California

Before I get started, I want to make a comment related to the last speaker's discussion. Serendipitous observations sometimes turn out to be the more interesting phase of studies. Twenty days ago, we started our bed-rest project. During the control period, we were doing a variety of tests, one of which was a tilt test. Another investigator was doing performance tests. He usually did his performance tests whenever he could get a subject. I walked onto the floor and saw this subject lying on a gurney head-down. "What on Earth is this guy doing head-down?", I asked. They said , "Well, the investigator wants to eliminate the orthostatic effect on the performance tests." I said, "Yes, that's all very well, but, when we eventually put the subjects head-down in bed rest, we won't see anything or we may not see anything." Nobody has really determined whether you can condition people to going head-down. The closest analogy would be with yoga, I suppose. Investigating this further, we determined that some of the performance tests had been conducted immediately before the tilt test. In looking at the data, it transpired that out of the four ambulatory subjects who had been head-down for 20 minutes before being tilted, three fainted on the tilt test. I am aware of Hordinski and Wegmann's work showing that 2 hours head-down could have that sort of effect on subsequent orthostatic tolerance in a lower body negative pressure test. However, I was a bit surprised that it could happen after just 20 minutes; it is an acute effect and it is very interesting.

We at the NASA Ames Research Center are now in day 14 of bed rest in a study for which quite a few of you have provided planning input of one form or another, at one stage or another. If this study did nothing else but trigger off this meeting or increase the necessity for this get-together, then it has served its purpose. The study was designed to include 7 days of ambulatory control data collection, 30 days of head-down bed rest, and 5 days of recovery. The subjects are 19 males around 37 years of age. They are divided into three groups: five nonexercised controls, seven subjects exercising on a bicycle ergometer, and another seven subjects on an isokinetic device (LIDO). All exercise is done in the horizontal position, twice a day, for a total of 1 hr/day. Ed Bernauer will provide you with the details in his presentation. We are addressing various questions: How are these three conditions affecting orthostatic tilt tolerance, max VO_2? How are arm and leg isokinetic strength altered? What effect do they have in maintaining normal resting and exercise cardiac output?

Dr. S. Arnaud and her colleagues are studying the effects of bed rest on bone and calcium metabolism in these subjects. The risk of stone formation and the impact of exercise on that are also being assessed. Changes of both leg and arm and of L2-3 vertebral bone are being measured, and the endocrine and metabolic regulation of calcium before and after exercise in bed rest is being assessed. The hypothesis is that different people have different rates of bone turnover and that their response to bed rest and to the remedial effects of exercise would be different depending on the initial rates of bone turnover. Should this theory prove to be correct, it could have important implications in the selection of crews for long-duration missions.

Dr. S. Ellis is determining muscle changes using magnetic imaging techniques. Dr. Cohen is assessing posture, the effects of bed rest with and without exercise on posture and gait. These tests are done immediately on resumption of the upright posture at the end of bed rest, as well as after 4 days of recovery. The test involves stepping onto a stationary or moving stabilometer platform with eyes open or eyes shut. This action is followed by a gait test, walking a closed course, and negotiating a turn. The control data have been very impressive, so we hope to get some good information out of this aspect of the study. We are trying to determine how the endocrine, neurohumoral, and circulating volume mechanisms we believe underlie the post-bed-rest orthostatic intolerance are affected by 30 days of bed rest and whether exercise alters the response. Plasma volume is measured before and during bed rest. The endocrine and neurohumoral responses to exercise are being assessed. Resting blood samples are also drawn before and throughout the bed-rest period as well as before and 5 minutes into the tilt.

SECTION 4

SUMMARY AND
RECOMMENDATIONS FOR THE INITIAL EXERCISE PRESCRIPTION

N91-10585

52 8P 526895

Considerations for an Exercise Prescription

Victor A. Convertino, Ph.D.
The Bionetics Corporation
Biomedical Operations and Research Office
Kennedy Space Center, Florida

Introduction

The development of an effective exercise prescription for long-duration space flight depends on the identification and understanding of various characteristics of the physiological response to muscular work in microgravity. We need to establish the optimum combination of intensity, duration, frequency, and mode of exercise that will be required to maintain normal cardiovascular reflexes, fluid-electrolyte balance, and musculoskeletal integrity for one-g as well as weightless environments. This determination will require accurate assessment of the normal prelaunch fitness levels of the astronauts and their specific work requirements for successful performance of operational activities and extravehicular activities (EVA's) during flight as well as those for safe return to Earth.

I should like to use this opportunity to present a number of our past and most recent research findings that describe some of the physiological responses to exercise in man and their relationship with exposure to various gravitational environments. Most of our data pertain to adaptations of the cardiovascular and body fluid systems. It should be kept in mind that our data from studies on microgravity simulation in man include exposures of relatively short duration (5 hours to 14 days). However, I believe that our results may provide important guidelines for the consideration of many variables which are pertinent to the development of exercise prescription for long-duration space flight.

Fitness Requirements for Astronauts

M. A. Berry and associates (ref. 1) have reported that the average aerobic capacity (VO_2 max) of U.S. astronauts is approximately 45 ml/kg/min. This level of aerobic fitness is average for individuals in the astronaut age group (35 to 50 years). There is little documentation of their strength fitness. However, the available data from space-flight and ground-based studies suggest that performance of EVA, the most vigorous, muscular work performance in space, requires significantly greater muscular endurance than maximum contractile strength.

I will start by trying to provide some perspective on the energy requirement for work during EVA. Tom Moore has presented some relevant data on the absolute levels of energy exchange. Although these work levels may appear small based on metabolic measurements, it is important to address the point raised earlier by Reggie Edgerton regarding how much relative work is performed by the specific muscle groups involved during EVA. The mean oxygen uptake (VO_2) over 3 to 6 hours of EVA during various Space Shuttle missions was approximately 0.8 liter/min. However, the VO_2 required for peak work output of short duration (minutes) during nine EVA's (averaged over six missions) was about 1.6 liters/min. Our data from normal individuals and from wheelchair-dependent subjects (i.e., paraplegics and amputees) who use their arms routinely indicate that the VO_2 max of the arms for individuals at similar aerobic fitness levels as the astronauts is approximately 1.8 liters/min (ref. 2). Since muscular work during EVA requires predominantly arm activity, astronauts are functioning for hours at an average exercise intensity of 45 percent VO_2 max with short periods requiring as much as 80 percent of the maximal working capacity of the arm and upper body muscle groups. Based on these data, I suggest that astronauts train both before flight and in flight specifically to maintain high aerobic fitness and endurance of the arms as well as some degree of arm strength.

The requirements of muscle strength for EVA are poorly defined. Although the astronauts have reported fatigue following EVA, this condition may be more representative of poor endurance of arm muscle groups as well as related to strength characteristics. Since objects in space are theoretically "weightless," it appears unlikely that astronauts would require great arm strength to lift and move objects. However, an accurate assessment of muscle strength requirements for working in space awaits measurements of muscle forces produced during specific work tasks.

Concern for High Aerobic Fitness

Since muscular endurance as well as strength seems to be required for successful performance of EVA, the relationship between preflight aerobic fitness level of astronauts and orthostatic intolerance is an important issue that should be addressed. Historically, this issue has become very controversial and should be considered when developing exercise prescriptions for astronauts.

Last week, Don Stewart asked me to prescribe an exercise program for long-duration space flight based on my current knowledge. I emphasized that the beginning fitness level will determine the exercise prescription for space flight. Data from our bed-rest studies indicate that the reduction in work capacity and cardiovascular responsiveness to orthostasis following simulated weightlessness is twice as great in highly fit individuals compared to unfit individuals (refs. 3 to 5). From these and other data, it has been suggested by numerous investigators that unfit individuals should be chosen for space flight. This suggestion does not seem practical based on the endurance requirements for EVA presented earlier. Furthermore, despite greater loss, the VO_2 max and working capacity of trained subjects remains significantly higher than that of untrained subjects following simulated weightlessness (refs. 3 to 5). For this reason, I suggest that we select astronauts for EVA who have high endurance and strength in the arm and upper body musculature. Based on some of our results (ref. 6), I propose that the greater, more rapid reduction in functional "reserve" in athletic subjects exposed to microgravity should not be considered physiologically adverse, but may indicate that these subjects adapt more readily to the weightless environment. However, the tendency for athletes to adapt (decondition) more rapidly in microgravity may indicate that the maintenance of physical work capacity in fit individuals will probably require a greater amount of exercise or other measures during space flight to maintain preflight fitness level. This should be an important operational consideration.

Another potential problem that has been raised is that high aerobic fitness in some studies has been associated with orthostatic intolerance. Furthermore, individuals who are more fit have a greater reduction in orthostatic tolerance than do unfit subjects following simulated weightlessness. These data have been used to suggest that we should not select fit individuals as astronauts.

In an earlier presentation, Mary Anne Frey outlined the results of a number of our most recent studies. We have conducted a number of cross-sectional studies which were designed to examine the relationship among aerobic fitness, strength profiles, and orthostatic tolerance. One of these studies was performed on men and women before and after simulated weightlessness using a head-down bed-rest model (ref. 7). The aerobic fitness of our subjects has ranged between 30 and 70 ml/kg/min, a fitness range well within that of the astronauts. With this series of studies, we have observed no significant relationship among aerobic fitness, leg muscle strength, and orthostatic intolerance (refs. 8 to 10). Therefore, based on our data, I strongly suggest that an individual with moderately high aerobic capacity should be selected for the astronaut corps without concern for predisposition to orthostatic intolerance before or after space flight.

Finally, Gunnar Blomqvist asked if it has been established that aerobic training per se can reduce orthostatic tolerance. From nine longitudinal studies currently reported in the literature, there are no data that demonstrate a reduction in orthostatic tolerance following aerobic exercise training and increased VO_2 max. Of these nine studies, four of them have shown no change and five of them have shown an increase in orthostatic tolerance (ref. 10). In terms of selecting a mode of exercise for prescription during space flight, it is rather interesting that a definite trend has developed: the four studies that showed no change in orthostatic tolerance all used running as the mode of training; four of the five studies that showed an increase in orthostatic tolerance used cycling. Further, increased orthostatic tolerance following exercise training was associated with increased plasma and blood volume (refs. 10 and 11). Therefore, endurance exercise training can be used to increase aerobic capacity and orthostatic tolerance when the mode of training produces a localized resistive component and hypervolemia (refs. 10 and 11).

Preflight Training

Another important factor to consider for the development of exercise prescriptions for long-duration space flight is the preflight training. Most of us appreciate the concept of specificity of training. For example, the South African miners become most successful in their jobs because they have become acclimatized to working in hot, humid environments. Our experience during operational tasks and EVA in space has demonstrated a predominant use of arms and upper body muscles for working and the use of legs for stabilizing the body. It seems that the most effective way to prepare an astronaut for specific requirements of working in space would include a preflight exercise training program which could be performed in a microgravity environment and is specific to increasing the strength and endurance of the arms. Therefore, swimming might be an excellent mode of training for preflight conditioning.

I did not have an appreciation for the potential use of swimming as a mode of preflight training until we completed a study more than a year ago that was conceived by one of my graduate students when I was a faculty member at the University of Arizona. The student was a former competitive swimmer. We were discussing possible thesis projects and he expressed a special interest in aerospace physiology. He made the anecdotal observation that when he was a competitive swimmer, he remembered that during the first week of returning for training for his competition, he was forced to get out of the water frequently to go to the bathroom to urinate. After the first week of training, he recalled that he could stay in the water for the duration of the training session and had no symptoms of diuresis, suggesting that there was an adaptation to exercising in a microgravity environment.

Since I have been interested in examining the mechanisms associated with the diuresis and natriuresis of weightlessness, we decided to perform an immersion study (ref. 6). We compared various renal and hormonal responses during 5 hours of water immersion to the neck in three groups of subjects: a sedentary control group, a group of competitive long-distance runners from the university track team, and a group of swimmers from the university swimming team matched for aerobic fitness with the runners. We also examined alterations in responses of heart rate and blood pressure during a 10-minute cycle exercise at 35 percent of VO_2 max before and after immersion as an index of how the cardiovascular response may have been altered by 5 hours of water immersion. We found that the control group and the runners did show a change that indicated greater cardiovascular stress - they increased their resting and exercise heart rate by 10 bpm, and a number of the subjects had unstable blood pressure indicating some problems with orthostasis. The swimmers showed no change whatsoever in any of their cardiovascular responses, suggesting that training in a microgravity environment might provide some specific protective effect against cardiovascular deconditioning during exposure to weightlessness.

Therefore, one factor we should consider in the development of an exercise prescription for long-duration space flight is to make available to the astronaut corps various preflight training programs that can be performed in water. Specifically, swimming may represent the most effective preflight training mode since it is performed in a buoyant (microgravity) environment, emphasizes training of the arms while the legs are used primarily for stabilizing the body, and appears to provide some protective effect against the cardiovascular deconditioning effects of weightlessness.

In-Flight Training

The assessment of an appropriate in-flight exercise prescription should be centered around the objectives for maintaining in-flight and postflight task performance. One might contend that arm exercise during space flight should be emphasized because of the predominance of the muscle activity of the arms and upper body compared to that of the legs. However, our data and the review of other studies suggest that the functional capacity of the arms is minimally reduced following long-duration simulated weightlessness and that low-intensity exercise can maintain arm strength (ref. 12). This effect may be due to the use of cycle ergometers and the arm exercise associated with stabilizing the upper body. Therefore, appropriate preflight training and normal in-flight activity may be adequate for maintaining the working capacity of arm muscles during long-duration flight.

Leg exercise will be required during long-duration flight to protect astronauts during and after return to the one-g environment, when they will require the muscular and skeletal, as well as cardiovascular, integrity to safely and effectively resume the standing upright posture. Exercise of the leg muscles during space flight is probably most critical since these muscle groups are more likely to lose their functional capacity compared to the arms and upper body (ref. 12). U. C. Luft and coworkers (Lovelace Foundation) demonstrated that high leg (venous) compliance and blood pooling were associated with orthostatic intolerance. In a recent study (ref. 13), we measured leg compliance in 10 men and correlated these measurements with various functional and anthropometric characteristics of muscle associated with fitness. We included measurements of leg cross-sectional area of muscle determined by computer tomography scan. We performed a multivariate regression analysis to explain the variation in the measurement of leg compliance. The only factor that significantly contributed to the prediction of leg compliance was muscle mass; i.e., the cross-sectional area of the muscle in the leg independent of the individual's muscle strength or aerobic fitness level. Thus, from a cardiovascular standpoint, there can be an argument for maintaining the integrity of the leg muscle mass during space flight.

In regard to the question of the need for inflight exercise raised by Mike Bungo, I will reemphasize my "yes" response. Through our experience with long-duration simulated weightlessness (bed rest) studies, we have certainly verified that there are physiological problems in maintaining work capacity and normal orthostatic function following weightlessness. We have further evidence that exercise can ameliorate these problems to some degree. I think the more important question is "How much exercise is required during space flight?" We now have evidence that protection of the cardiovascular reflex responses following long-duration exposure to microgravity may only require one maximal aerobic exercise regimen once every 10 days. In one study (ref. 14), I tested 10 subjects with supine cycle ergometry followed by an upright treadmill test (similar to the test given to the astronaut corps) before and after 10 days in the 6° head-down position (simulated microgravity). The subjects performed maximal exercise during both treadmill and cycle tests. Before the subjects got up from bed rest, they repeated the supine cycle test, and we found a decrease in working capacity of 8 percent, which is very consistent with our previous finding (refs. 3, 5, 6, 15, and 16). Following the supine test, the subjects were allowed to ambulate and drink water ad libitum for 2 hours followed by their maximal treadmill test. Bengt Saltin and coworkers (1968) reported the largest reduction in VO_2 max (26 percent) following bed rest when an upright treadmill test was used. Their subjects probably experienced some adverse orthostatic effects. Based on Saltin's observations, we hypothesized that there should be a greater reduction in VO_2 max during treadmill compared to the cycle test. However, there were no reductions in VO_2 max and no change in blood pressure or heart rate responses before, during, or after the exercise test in the upright position. Our apparent restoration of physiologic response following one bout of maximal exercise was similar to that of John Holloszy and coworkers (Washington University), who reported that one bout of maximal exercise restored insulin receptor sensitivity, which was significantly reduced following 10 days of deconditioning in competitive long-distance runners. Similarly, Howie Green (University of Toronto) demonstrated that the increase in plasma volume with training could occur in 3 days, the same 12-percent increase we observed after 8 days (ref. 17). The major difference in training regimen was that they used maximal exercise and we used 65-percent VO_2 max. Based on these data, I propose that one bout of maximal exercise performed 7 to 10 days in flight may provide an optimal stimulus to restore or maintain normal responses of cardiovascular function as well as some metabolic and fluid-electrolyte systems at preflight levels. From an operational standpoint, this proposal has important implications with regard to minimizing the amount of exercise time that might be required to protect the cardiovascular and fluid-electrolyte systems, and could also become a basis for more emphasis being placed on the development of specific exercise prescriptions to protect against deterioration of muscle and bone.

Boening and Stegemann (West Germany) compared orthostatic responses in trained and untrained subjects before and after 6 to 8 hours of water immersion. They proposed that trained individuals are less suited for space flight since they tended to faint following immersion, whereas the untrained subjects did not have a significant orthostatic problem. When the trained subjects repeated water immersion a second time, but performed maximal swimming exercise 1 hour before they got out of the tank, syncopal episodes were eliminated. These data reinforce my hypothesis that maximal stimulation of cardiovascular and fluid control systems by high-intensity exercise is adequate in reversing fluid-electrolyte and cardiovascular alterations associated with exposure to microgravity.

Postflight Training

Although physiological limitations to muscular work and orthostasis immediately after reentry are a concern, it is also necessary to consider the effects of a long-term recovery rate as a factor limiting the resumption of normal physical activity following flight as well as the return to subsequent missions. The bed-rest study of Saltin and coworkers (1968) is often cited as evidence favoring the use of exercise conditioning programs as an effective technique for enhancing the recovery from the deleterious effect of microgravity on exercise performance. We found that reductions in VO_2 max and exercise capacity following 14 days of bed rest were returned to pre-bed-rest levels after 3 weeks of recovery using 30 minutes of daily exercise at 50-percent VO_2 max (ref. 18). Furthermore, this complete recovery of functional work capacity was similar following repeated exposures to bed rest (ref. 18).

However, in a study of 12 middle-aged men (45 to 55 years) who had been at bed rest for 10 days (ref. 19), we randomly assigned six subjects to perform individually prescribed physical exercise daily for 60 days after bed rest (exercise group), and six simply resumed their customary activities (control group). Despite a significantly greater increase in VO_2 max in the exercise group at 60 days compared to the control group, VO_2 max and physical work capacity in both groups returned to pre-bed-rest levels by 30 days after bed rest. We concluded that simple resumption of usual physical activities after bed rest was as effective as formal exercise conditioning in restoring the functional capacity. These results are further supported by our more recent data demonstrating that pre-bed-rest VO_2 max values were restored by 14 days of recovery from repeated 10-day bed-rest periods in nine healthy middle-aged men (35 to 50 years) who merely resumed normal daily activities with no daily exercise (ref. 3).

Therefore, recovery from exposure to weightlessness can be supplemented with a formal exercise prescription if desired. However, with regard to exercise metabolism and functional work capacity and endurance, 2 weeks of minimal daily activity are adequate for complete recovery from the deconditioning effects of microgravity, and repeated missions should be safely tolerated.

Summary

We have a formidable task in determining the optimum exercise prescription for long-duration space flight. From an operational standpoint, we need to consider a program which will minimize the time required on an exercise device, yet will enhance Space Station crews to work most effectively in space and be returned to Earth in a healthy, functional condition, as close as possible to that which they enjoyed prior to their mission. With regard to cabin space, we need to consider the least amount of and smallest exercise equipment which will facilitate aerobic and cardiopulmonary conditioning and provide maintenance of full body strength and size of muscles and bones as well as protect against the adverse effects of alterations in body fluids and cardiovascular function.

I have presented the results from several of our experiments which have allowed us an opportunity to examine the interrelationships among exercise training, physical fitness, functional working capacity, and orthostatic intolerance before and after simulated weightlessness in man. Although our observations are limited to exposure in microgravity for relatively short duration, I propose that our data can be used for formulating the following considerations for exercise prescriptions during long-duration space flight.

1. Relatively high aerobic fitness and strength, especially of the upper body musculature, should be a criterion for selection of astronauts who will be involved in EVA, since endurance and strength appear to be predominant characteristics for work performance.
2. Some degree of upper body strength will probably be required for effective performance of EVA. However, the endurance and strength required by the upper body for EVA can probably be obtained through preflight exercise prescription which involves swimming. In addition, preflight swim training is attractive since it may provide protection against some of the cardiovascular deconditioning induced by weightlessness.
3. Although some degree of arm exercise may be required to maintain preflight endurance and strength, I propose that regular EVA will probably be sufficient to maintain the endurance and strength required to effectively perform work tasks during space flight. An emphasis for in-flight exercise should be placed on the use of the larger leg musculature. Specifically, cycle ergometry may represent one of the most effective modes of training since it can provide aerobic and resistive components for maintenance of muscle endurance and strength.
4. A minimum of one maximal aerobic exercise every 7 to 10 days during space flight may be all that is necessary for maintenance of normal cardiovascular responsiveness and replacement of body fluids for reentry following prolonged space flight. Therefore, a smaller portion of the exercise prescription in flight may be required for these systems and a larger portion can be committed to maintaining the integrity of muscle and bone.
5. At the NASA John F. Kennedy Space Center, we are currently studying the efficacy of electromyostimulation (EMS) as a potential countermeasure against muscle atrophy effects of microgravity. The possible reduction in the amount of exercise required for maintenance of cardiovascular system and body fluids in combination with the use of EMS or methods other than conventional exercise for

maintaining size and strength of muscles and bones needs great consideration for further research. These approaches represent a potential solution to the problem of compromising valuable time for exercise that is needed for daily operations.

References

1. Berry, M. A.; Squires, W. G.; and Jackson, A. S.: Fitness Variables and the Lipid Profile in United States Astronauts. Aviation, Space & Environ. Med., vol. 51, no. 11, Nov. 1980, pp. 1222-1226.
2. Kinzer, S. M.; Sather, T. M.; and Convertino, V. A.: Role of the Leg Vasculature in the Cardiovascular Response to Arm Work. Fed. Proc., vol. 44, 1985, p. 817.
3. Convertino, V. A.; Karst, G. M.; et al.: Exercise Capacity Following Simulated Weightlessness in Trained and Untrained Subjects. Aviation, Space & Environ. Med., vol. 56, 1985, p. 489.
4. Convertino, V. A.; Goldwater, D. J.; and Sandler, H.: Bedrest-Induced Peak VO_2 Reduction Associated With Age, Gender and Aerobic Capacity. Aviation, Space & Environ. Med., vol. 57, 1986, pp. 17-22.
5. Convertino, V. A.: Exercise Responses After Inactivity. Inactivity: The Physiology of Bedrest, ch. 7, H. Sandler and J. Vernikos-Danellis, eds. Academic Press, Inc. (New York), 1986, pp. 149-191.
6. Convertino, V. A.; Rogan, R. B.; Hale, D.; and Smith; L.: Diuresis, Natriuresis, and Cardiovascular Responses to Water Immersion in Trained Runners and Swimmers. The Physiologist, vol. 28, 1985, p. 345.
7. Ludwig, D. A.; Convertino, V. A.; Goldwater, D. J.; and Sandler, H.: A Logistic Risk Model for the Unique Effects of Aerobic Fitness on $+G_z$ Tolerance Before and After Simulated Weightlessness. Aviation, Space & Environ. Med., 1987 (in press).
8. Convertino, V. A.; Sather, T. M.; Goldwater, D. J.; and Alford, W. R.: Aerobic Fitness Does Not Contribute to Prediction of Orthostatic Intolerance. Med. Sci. Sports Exer., vol. 18, 1986, pp. 551-556.
9. Convertino, V. A.; Lightfoot, J. T.; et al.: Orthostatic Responses in Men With Varying Profiles of Strength and Aerobic Fitness. J. Appl. Physiol., 1987 (in review).
10. Convertino, V. A.: Endurance Training and Orthostatic Intolerance. Exercise and Sport Sciences Reviews, K. B. Pandolf, ed. Macmillan Publ. Co. (New York), vol. 15, 1987, pp. 223-259.
11. Convertino, V. A.; Montgomery, L. D.; and Greenleaf, J. E.: Cardiovascular Responses During Orthostasis: Effect of an Increase in VO_2 max. Aviation, Space & Environ. Med., vol. 55, 1984, pp. 702-708.
12. Greenleaf, J. E.; Van Beaumont, W.; Convertino, V. A.; and Starr, J. C.: Handgrip and General Muscular Strength and Endurance During Prolonged Bedrest With Isometric and Isotonic Leg Exercise Training. Aviation, Space & Environ. Med., vol. 54, 1983, pp. 696-700.
13. Convertino, V. A.; Doerr, D. F.; et al.: Leg Size and Muscle Functions Associated With Leg Compliance. J. Appl. Physiol., 1987 (in press).
14. Convertino, V. A.: Potential Benefits of Maximal Exercise Just Prior to Return From Weightlessness. Aviation, Space & Environ. Med., 1987 (in press).
15. Convertino, V. A.; Kirby, C. R.; Karst, G. M.; and Goldwater, D. J.: Response to Muscular Exercise Following Repeated Simulated Weightlessness. Aviation, Space & Environ. Med., vol. 56, 1985, pp. 540-546.

16. Convertino, V. A.; Karst, G. M.; Kirby, C. R.; and Goldwater, D. J.: Effect of Simulated Weightlessness on Exercise-Induced Anaerobic Threshold. Aviation, Space & Environ. Med., vol. 57, 1986, pp. 325-331.

17. Convertino, V. A.; Brock, P. J.; et al.: Exercise Training-Induced Hypervolemia: Role of Plasma Albumin, Renin, and Vasopressin. J. Appl. Physiol., vol. 48, 1980, pp. 665-669.

18. Stremel, R. W.; Convertino, V. A.; Bernauer, E. M.; and Greenleaf, J. E.: Cardiorespiratory Deconditioning With Static and Dynamic Leg Exercise During Bed Rest. J. Appl. Physiol., vol. 41, no. 6, Dec. 1976, pp. 905-909.

19. DeBusk, R. F.; Convertino, V. A.; Hung, J.; and Goldwater, D.: Exercise Conditioning in Middle-Aged Men After 10 Days of Bed Rest. Circulation, vol. 68, 1983, pp. 245-250.

13

N91-10586

526896

10p

Work, Exercise and Space Flight

II. Modification of Adaptation by Exercise (Exercise Prescription)

William Thornton, M.D.
Scientist Astronaut

While the rudiments of physical training have been understood for the history of mankind, it was only in the last century that a quantitative approach was made to human work and exercise and their effects. All too often it is still treated as a misunderstood art rather than a science. This has delayed progress in solving a number of problems in space as well as on earth.

If our available knowledge and experience of exercise physiology on earth and in space is properly used, the approach to exercise can be scientific and direct. Even where questions still remain, there appears to be sufficient knowledge to proceed efficiently to obtain needed answers. At the risk of boring some of you, I am going to briefly review the essential principles of the problem beginning with Wolff's law, the specificity of exercise, and magnitudes of quantities involved in work and exercise on earth. Work is defined here as any physical activity that is imposed or required by our usual life, while exercise is physical activity deliberately engaged in beyond that.

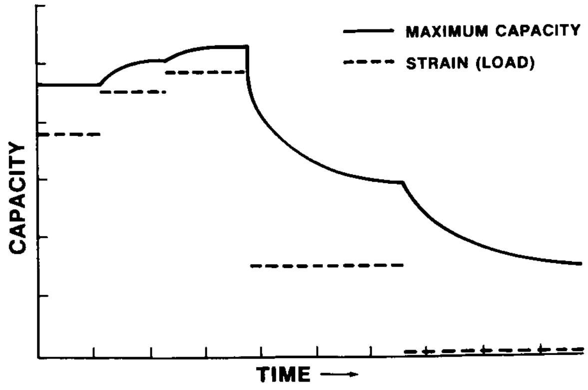


Fig. 1.- Generalized response curve of Wolff's 'law' for any tissue or system. The basic response seems to be an exponential function of time and consists of an increase or decrease in system capacity with increases or decreases in load. Response time is an individual function and may range from minutes to months or more. Capacity is well above average *maximum* stresses that are normally seen. If the load is increased, the difference between load and capacity. If this increase in load is continued, a limit will be reached. In the same way if load is decreased, capacity will decrease but never disappear, e.g. bone and muscle remain in long-term paraplegia.

Nature and Effects of Exercise: - Wolff's 'law' postulates that bone will increase or decrease its capacity in response to loads (1). This 'law' can be usefully and safely extended to postulate that in general a biological tissue's or system's capacity is determined by the maximum stress usually imposed. Within limits, if the load is increased, the capacity to bear that load is increased and vice versa. In muscle, for example, if the maximum force loads are increased, muscle mass and strength are increased. The rate of change of this capacity, the time constant, is a function of the tissue involved, e.g. weeks for muscle and months for bone. Response curves of the general shape shown in Fig. 1 seems to be valid for many tissues and systems. There are several pertinent characteristics of this curve. Capacity is greater than the usual maximum stress or loads. As loads are changed, the capacity responds in an exponential fashion; however, the reserve capacity usually decreases as individual limits are approached. There are definite upper and lower limits of capacity; train forever, and few people are going to surpass world records—put the person at bed rest forever and neither bone nor muscle will completely disappear. The time to approach limiting performance is increased above that in the mid range.

Specificity of exercise is even more frequently misunderstood. A German physiologist in the 19th century appears to have first pointed out that muscle strength and mass in rats were increased by increased treadmill speed[a], not duration. We now understand the fundamental differences in muscle fibre types and their plasticity (2, 3, 4) which enables the muscle to greatly increase strength and mass with relatively few repetitions at large loads (5 through 27). Conversely, continued repetitions at decreased weights result in possibly reduced muscle mass with increased vascularity and metabolic capacity (28 through 41) and endurance. Strength and endurance are different

---

[a] Increased running speed increases muscle force generated.

characteristics of muscle, and while many forms of exercise may produce overlap, pure forms of endurance exercise produces endurance, not strength, and vice versa.

A secondary effect of continued exercise with large muscle masses, e.g. running, produces large metabolic loads which must be supplied by increased cardiorespiratory capacity [Fig. 2]. The heart and pulmonary muscles (34) increase their capacity, blood volume increases, metabolic efficiency is increased, and other changes occur which are characteristic of the trained individual. However, an impressive stress test with high O_2 uptake cannot be used as a complete evaluation of a subject's musculoskeletal capacities.

There was a time recently when the role of force in formation and maintenance of bone was seriously questioned. While it is unfortunate that it took at least 85 years to recognize what Wolff postulated, the evidence is now overwhelming and generally recognized as true by workers current in the area. At the same time, there is no evidence for any other significant cause of bone loss in normals during bed rest and weightlessness beyond the removal of usual forces; hence, it no longer seems necessary to defend these mechanisms.

There is still a general misunderstanding of the source and magnitude of forces on the skeleton. This is exemplified by the term 'weight bearing' bones. Weight is not the major force on bones of the locomotor system, nor frequently for any other bones. This was recognized by some observers during the polio epidemics in which weight bearing was imposed by braces and other mechanisms in an unsuccessful attempt to prevent bone loss. Only when some minimum muscle mass was left could bone loss be prevented (42, 43, 44). The same was true in Dr. Schneider's bed rest studies. The reason becomes obvious with inspection of the biomechanics involved. When one is standing symmetrically, 1/2 of the body's weight (BW) is on each leg and its bones [Fig 3]. Fig. 4 is a bicycle force curve for comparison. Walking

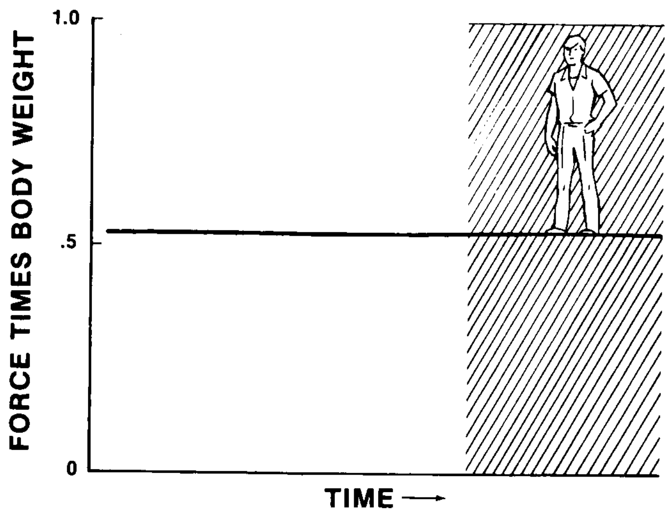
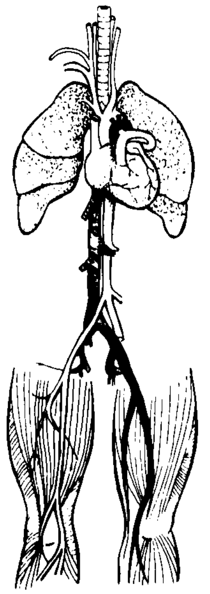


Fig. 3.- Foot force on one leg of man standing in 1-g. When balanced, it is 1/2 body weight (BW) but this may vary throughout the shaded region to a maximum of 1.0 BW

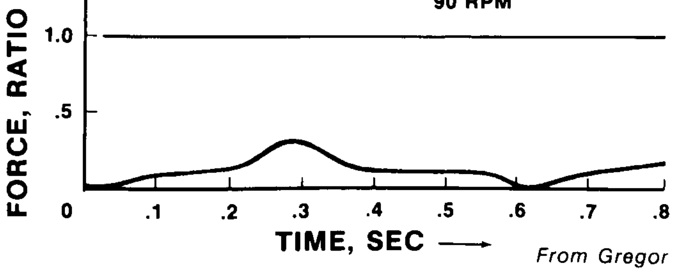


METABOLIC LOADS			
EARTH		SPACE	
Rest	Max	Max(est)*	
4-6	30+	10-15	C.O.-L/min
15-20	100-130	50	Min Vol-L/min
0.25	4-5	1-2	$\dot{V}_{O_2}$-L/min
3-4	50-60+	20-25	$\dot{V}_{O_2}$-ml/kg/min
—	180-250	70	Ext. Work Watt/min
60	170-190+	110-130	Heart Rate bpm

Duration 70-80% of max. for 1 hr or more

Duration in minutes
*Does not include E.V.A.

Fig. 2.- Locomotor activity usually produces the maximum metabolic stress in most individuals. Some typical maximum and minimum loads are shown here.



From Gregor

Fig. 4.- Measured foot force from a professional cyclist. Typical bicycle ergometry is much less, usually below 50 pounds. The prolonged, low forces result in high *metabolic* loads just as do the brief but higher impulsive forces of locomotion.

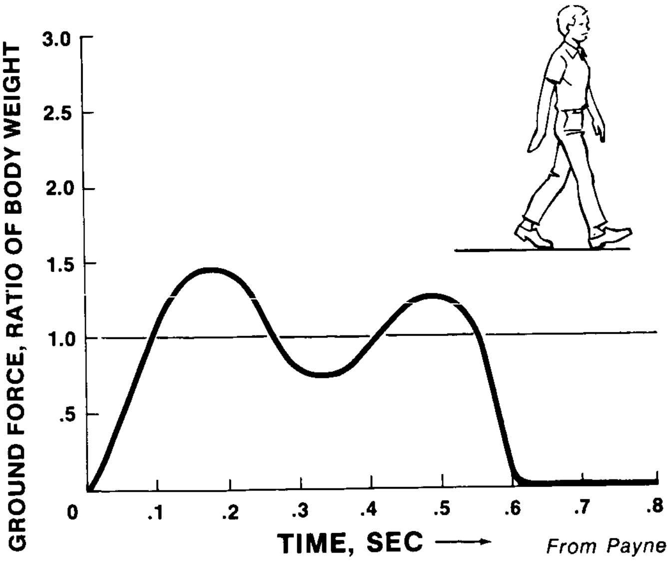


Fig. 5.- Typical foot force curve for one leg in walking. The increase above BW is caused by decelerating and accelerating the body's mass, i.e. inertial forces plus weight.

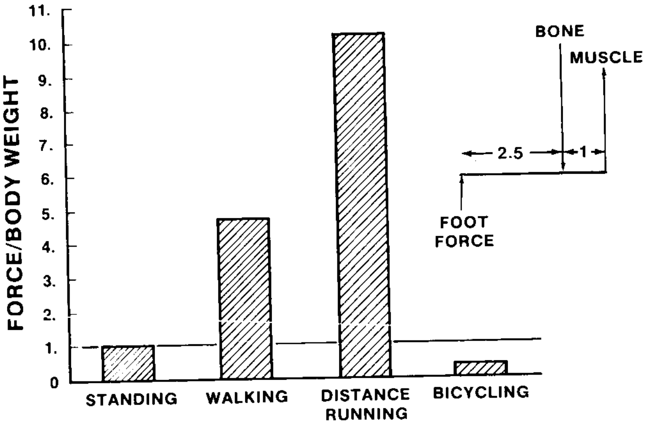
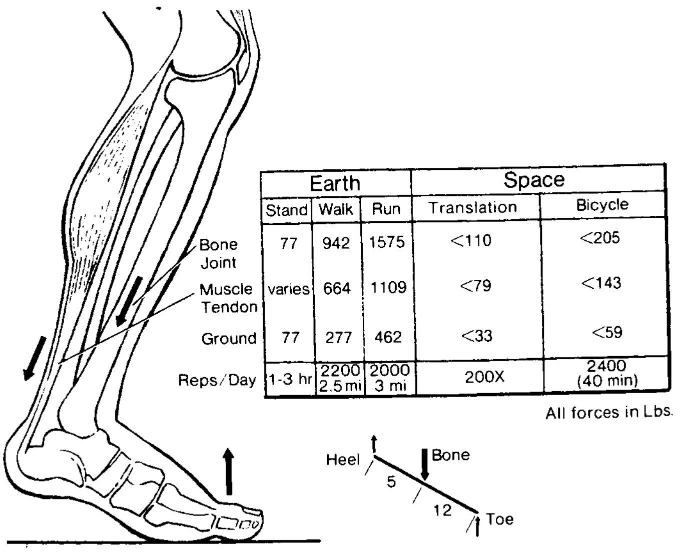


Fig. 7.- Typical forces on the tibia in various activities. Note that this amounts to more than a ton in a 200-pound man while jogging.

increases this force to say 1.8 BW on heel strike and 1.3 BW on toe off [Fig. 5][a]. But these are only foot/ground forces, not muscle and bone. Using Dr. Cavanaugh's model, on toe off, this force is increased 2.5 X at the achilles tendon, i.e. 3.25 BW [Fig. 6]. The ankle is the fulcrum and sees a total force of 4.5 BW versus .5 BW standing, a nine-fold increase. In running, the ground forces increase to 3 B.W. and tibial force in a 200 lb man are thus more than a ton! [Fig. 7]. It should be obvious why the small forces in the bed rest studies and in space did not prevent bone loss. Fig. 8 is a composite comparison of forces from various activities. These forces are real, not abberations of a physics model and similar forces are seen by other bones of the leg, especially femur and hip. A few investigators are beginning to measure such forces in vivo and their results support this simple analysis.

It is hard to believe how useless and unused legs generally are in space. They are used for 'perching' by hooking a foot or toe under a structure or temporary clasping but never for exertion of their extensor force capacity. Conversely, arms become even more used than on earth albeit at lower than usual 1-g loads, unless one is doing EVA work. The American Skylab program was our first opportunity to examine the effects of long term space flight. Initially there were



	Earth			Space	
	Stand	Walk	Run	Translation	Bicycle
Bone Joint	77	942	1575	<110	<205
Muscle Tendon	varies	664	1109	<79	<143
Ground	77	277	462	<33	<59
Reps/Day	1-3 hr	2200 2.5 mi	2000 3 mi	200X	2400 (40 min)

All forces in Lbs.

Fig. 6.- Magnification of muscle and bone forces by anatomical arrangement of foot. Some typical values and repetitions are given.

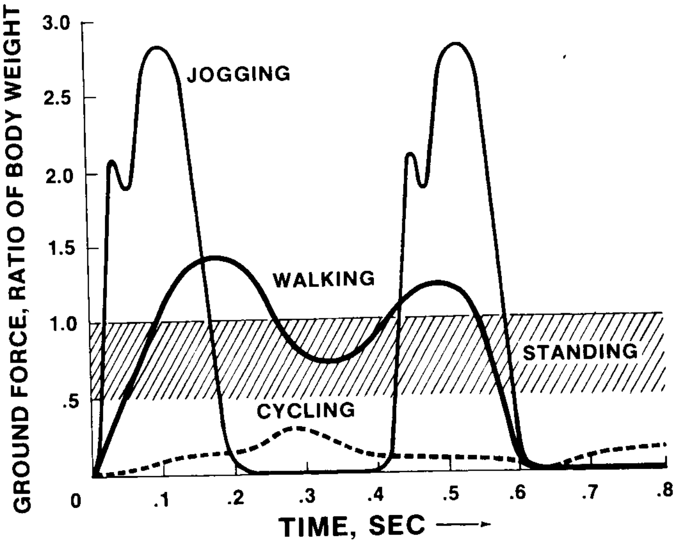


Fig. 8.- Comparison of various foot/ground forces, one leg.

---

[a] Force is a function of speed.

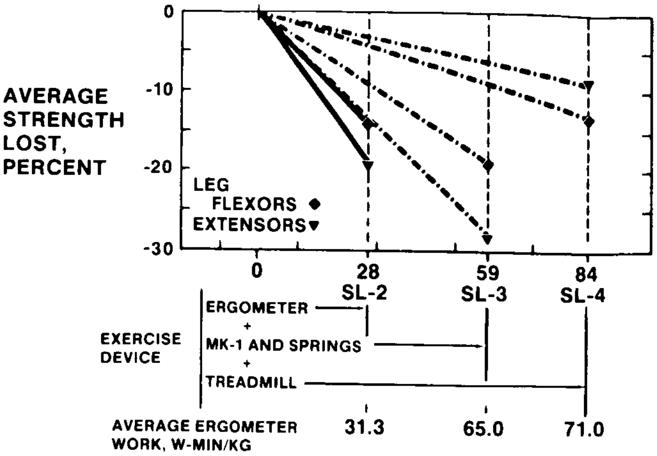


Fig. 9.- Mean of peak forces from 10 repetitions of isokinetic (45° sec.$^{-1}$) dominant leg flexion and extension for each crew on Skylab missions. This was primarily hip motion. Only bicycle exercise was available on SL-2 and SL-3 with a form of locomotor exercise on SL-4. Postflight measurements were made on day of recovery for SL-3 and 4, and on R+4 for SL-2.

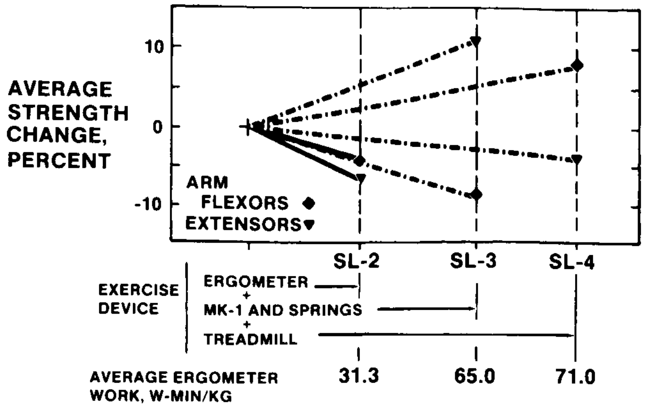


Fig. 10.- Mean of peak forces from 10 repetitions of isokinetic (45° sec.$^{-1}$) dominant elbow flexion and extension for each crew on Spacelab missions. Arm exercise was available on SL-3 and SL-4. The sharp rise in extensor strength on SL-3 was the result of a great increase in extensor strength in one crewman whose 1-g exercise was restricted to running.

no plans to study muscle, only bone, and bicycle ergometry was the only countermeasure. While it was not possible to get adequate exercise aboard prior to flight, it was possible to do an *ad hoc* isokinetic elbow and leg strength measurement pre and post flight. The angular rate was 45° sec.$^{-1}$ and at least ten repetitions were made (45).

The first flight lasted 26 days, and the crew returned with 20% extensor leg losses and 5% arm losses [Fig. 9, 10] with urgent request that better exercise facilities be added. For the 56-day flight, bicycle ergometry time was doubled. Such arm and trunk exercise devices as could be gotten ready between missions were added. They were extension springs with handles and a rope and handle with approximation of adjustable, constant velocity load (45). On this flight there was little change in rate of loss of leg strength but a sharp reduction in loss of arm extensor strength. On the last 84-day mission, a crude locomotor exercise apparatus was flown (see Fig. 9, Sect. I) consisting of harness and elastic bungees to provide forces equivalent to body weight and a teflon pad on which the feet would slip. It was equivalent to trying to climb an icy hill and provided an estimated force of 1.3-1.5 BW but could be maintained for only 10 minutes per day. Arm exercises were also intensively used. Not only did the crew return in apparently better condition but both muscle mass [Fig. 11] and strength loss of the legs were sharply reduced. While this exercise was far from optimum, the results are consistent with theory, i.e. forces equivalent to those which will be required of the muscles must be used. While the bicycle ergometer's low prolonged forces provide a high metabolic load and adequate cardiorespiratory maintenance, such low forces cannot maintain strength of the legs nor prevent Ca^{++} loss from their bones. Russian results from their long-duration flights are not available; however, a Russian bed rest study (46) produced results comparable to those from Skylab and an earlier American bed rest study (47) [Fig. 12].

Countermeasures - This then brings us to what is required of exercise in space and the first question to be answered is one of policy: do we let the body adapt to weightlessness and then protect it, i.e. carry the crewmen off the spacecraft and then give them time to readapt; or do we prevent adaptation to weightlessness? Prevention of adaptation is costly in

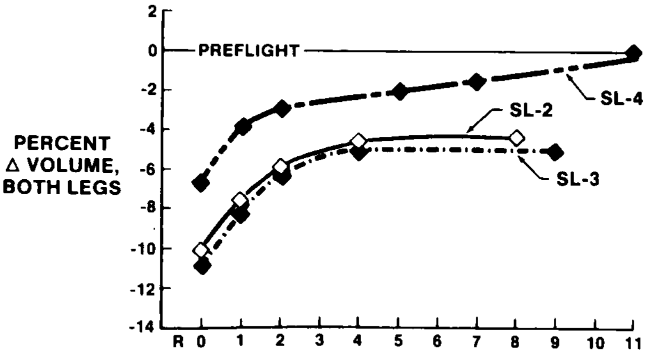


Fig. 11.- Mean postflight change in leg volume of Skylab crews. The rapid increase in volume for the first three days is presumed to be fluid shift. Durations of flights were: SL-2, 28 days, SL-3, 59 days, SL-4, 84 days.

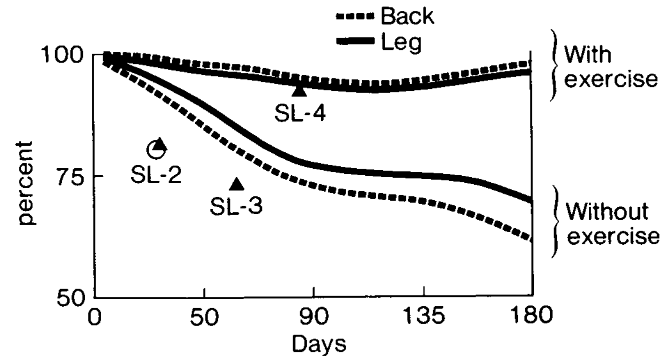


Fig. 12.- Mean changes in isotonic strength of back and legs in Russian bed rest study with and without exercise consisting of electrostimulation, horizontal locomotor activity, and other exercises. Triangles are measured results from Skylab missions and the circle at SL-2 are from a cast restrained bed rest study (47).

terms of on-orbit time but our office has never been willing to allow the alternative if it can be prevented. Other factors to consider are emergency egress in case of entry problems and irreversible trabecular bone changes. Even temporarily incapacitated crewmen are undesirable from a safety standpoint. On-orbit EVA operations must also be considered. At this point, no one is willing to consider not using countermeasure in space so the effects and means of preventing them must be considered.

Countermeaures

Loss of Locomotor Function	• Replace Locomotor Capability.
Reduced Arm Force Loads	• Individually selected arm exercises.
Hydrostatic Pressure	• Preload fluid. • Shift fluid with LBNP or other means. • Stimulate neuro-mechanisms.
Altered Neurosensory Inputs	• 'Normal' stimuli will accrue from exercise.

The above general proposal is adequate for days of controversy, but there are other issues to consider. The question of artificial gravity will not go away. Individuals in both flight operations and life science feel that artificial G will be required for long flights. There are liabilities both in providing such forces and in some of their effects on the body. While I disagree with the need for such, the question can only be definitely answered with experience. Conversely, there is one aspect of artificial G that should be answered by existing knowledge, the level of gravity required, e.g. 1/6 or 1/3 or what. If one simply lives in it, then from Wolff's law the effects will be commensurate with the level used and 1-G will be required to maintain condition for normal life on earth. Why not simply add mass to the body and arms and legs until the weight is equivalent to earth weight? While this is possible with the arms, Margaria points out that nothing is gained for the legs and they are our primary concern.

Another issue which seems obvious is the question of a standard vs. individual exercise protocol. It speaks for itself. Would you feed everyone the same type and quantity of food? Does anyone think that the same type and level of exercise required by a 200 lb male can even be accomplished by a 100 lb female (or male)?

Fitness Level - What is the level of fitness which must be maintained? At this time it is not practical to maintain extremes of capacity, e.g. the ability to run marathons or do competitive weight lifting. It will simply be too costly in time and equipment. Some individuals are going to have significant deconditioning as regards their former 1-G capacity, and all are going to have some. One is not going to run marathons or compete in athletics soon after return from long space flights.

What then are reasonable levels of performance? The following are my estimates.

Arm strength and endurance

Commensurate with emergency egress and escape on landing (possibly aided).

Commensurate with EVA activity on orbit.

Locomotor capacity

Performance — Unless limited by orthostasis, the subject should be able to perform emergency and normal egress and be able to walk, as required, for essential post-flight functions.

Bone Loss — Some Ca^{++} loss will probably be inevitable but the goal should be no detectable loss of bone density or structural change.

Cardiorespiratory Capacity — After correction of fluid losses and allowance is made for any anemia present, the level should not be significantly reduced except in those individuals with unusually high pre-flight levels.

Exercise Protocol - The word exercise prescription has become popular and some useful analogies can be drawn. First, one must know what changes are desired in the body. Second, one must know what the countermeasure can do, and finally, the dosages must be known. Giving endurance exercise to maintain strength is as useless as giving Penicillin for Herpes. Also prescribing because the patient likes the taste or because you like the detail man's pitch or the package will almost certainly lead to failure. The first issue to be resolved then is what lost function we replace. There should be little doubt that muscle strength, mass, and bone density in the locomotor apparatus will suffer most in space. Probably next in importance is maintenance of cardiorespiratory capacity. Arms, hands, and shoulders will be individually determined concerns as will flexibility and coordination.

Looking at the first priority, there is currently only one way to overcome the loss of locomotor function which requires strength, endurance, coordination, and produces large metabolic load. The function should be replaced as completely as possible, i.e. walking, jogging, and running under 1-g equivalent loads. If this is done, priority two will also be covered. If only cardiorespiratory maintenance should be desired for research or for supplement, then other modes of exercise can be used, e.g. bicycle ergometry.

The exercise for upper body, arms, shoulders, torso, etc., are almost endlessly varied, hence it becomes a question of choosing several standard forms of 1-g exercise and reproducing it, e.g. weight equivalent, etc.

This leads us to exercise devices which are too often chosen on an emotional, political, or other basis with insufficient knowledge of what they actually do. First, one must know what they can do. Their forces, both nature and magnitude, and their kinesiology must be measured in terms of physics. Then and only then can one begin to logically replace exercise on earth. This must also be known in terms of physical quantities.

If there is another way to perform locomotor activity other than with a treadmill, please let me know, for I have attempted to replace it with several alternatives—running in place, step climbing devices, etc., but nothing else comes close. It alone produces the high force and metabolic loads required for strength and endurance.

If one wants to produce metabolic loading, there are too many ways to mention. A classic favorite of the researcher is the bicycle, for only the legs are involved and electrodes and other devices can be placed on a relatively stable upper body. Maximum O_2 uptake approaches that of the treadmill. A currently popular device is the rowing machine, and from a biomechanical view, it does have advantages of using portions of legs, back, and arms. Maximum leg forces are not high enough to replace even walking. Conversely, they are higher than the bicycle. Back and arm forces are high, probably near maximum for repeated motion, and the energy required is large; thus it is very attractive as an ancillary exercise device but not adequate to replace locomotor exercise.

Simply having a form of exercise or device does not automatically assure it is usable in flight. The next section explores the problem of exercise devices in flight.

We now come to the quantity in the prescription itself. An overriding operational concern is crew time on orbit. Resources allocated to exercise is considered by many in NASA an overhead item. While it is agreed that sleep, food, etc., are essentials, time for exercise is given grudgingly and the first thing cancelled on short missions. The Russians spend up to two hours per day and at one time were considering shorter durations on orbit in an effort to reduce this overhead. To maintain a person in orbit, one must know first what his usual activity on earth is. There is surprisingly little such data and we are in the process of trying to obtain such. Considering only the locomotor apparatus:

If we are going to replace the crewman's 1-g activity with the exercise we must know the individual's normal activity. We are in the process of devising ways to measure that. A typical person spends most of his time sitting and standing, some walking, and a bit in high level activity, i.e. jogging, running, etc. We feel that by reducing or limiting the time spent in walking and other low level activities and maintaining or increasing high level time, we can effectively replace usual activities by a much shorter protocol. We don't know that this is possible but shortly hope to find out with bed rest studies in which we measure the subject's usual activity and his locomotor capacities, i.e. strength, endurance, metabolic capacities, bone density, size, etc.

We will then attempt to substitute shorter periods of more intense exercise for his usual lower intensity work and exercise. As for upper extremity exercise, we will again measure his usual activity and resulting capacity and replace them, if required and desired. As noted, a good deal of work is done with arms on orbit so that in some individuals little or no added work will be required. At this point in time, I feel that we can select the type of exercise required for the prescription but not the amount. This can be determined with proper studies. Well prior to Space Station we should be able to prescribe the quantity.

While we can select the general types of exercise equipment, it will be a great waste to freeze the details. We should have sufficient flexibility to take advantage of the advances which are sure to come, especially in monitoring.

The question of crew motivation for exercise on orbit has received a great deal, possibly an inordinate amount, of attention and resources. There are an infinite number of scenes and schemes which can be programmed for presentation to the crewman as he exercises, e.g. scenes of the countryside which pass according to the effort on jogging or riding an ergometer. The first question is whether they are needed. It will be hard to find a group of people who are less likely to need titillation to do a job than the astronauts. A good set of instrumentation with display means of current and previous performance will be more useful.

The final question is how to monitor the subject's condition. Monitoring may have three operational purposes which should not be confused, although they may aid each other. This is for routine operations, not research. First, there should be the individual's personal record which allows him to tabulate what he has done. WARNING - This should not be turned into a time keeping, mandatory task. This can be an automatically recorded personal record on appropriate media capable of rapid personal review. Second, there should be a shared personal and medical performance test. In the case of locomotor activity, simply put the subject on a treadmill with 1-g equivalent loads and see how far he can walk or jog, how fast he can run. For strength, put him in an appropriate machine and look at strength or endurance. Finally, there is medical monitoring which should allow evaluation of physiology and follow trends before they are functionally significant, e.g. O_2 uptake. The temptation to do research in guise of operational requirements must be avoided and only those items of proven value should be used, and as infrequently as possible. This data should also be available to the crewman involved. An ancillary question sure to arise is how cardiovascular function fits here. Should orthostasis be a consideration in these tests?

In summary - The fundamentals of exercise theory on earth must be rigorously understood and applied to prevent adaptation to long periods of weightlessness. Locomotor activity, not weight, determines the capacity or condition of the largest muscles and bones in the body and usually also determines cardiorespiratory capacity. Absence of this activity results in rapid atrophy of muscle, bone, and cardiorespiratory capacity. Upper body muscle and bone are less affected depending upon the individual's usual, or 1-g, activities. Methodology is available to prevent these changes but space operations demand that it be done in the most efficient fashion, i.e. shortest time. At this point in time we can reasonably select the type of exercise and methods of obtaining it but additional work in 1-g will be required to optimize the time.

Bibliography

1. Wolff, J., Das Gesatz des Transformation der Knochen, Berlin, A. Hirschwald, 1892.
2. Goldspink, G., K.F. Howells, and P.S. Ward, Effect of Exercise on Muscle Fibre Size, Med. and Sport *9*, Advances in Exercise Physiology, 102-113, Karger, Switz., 1976.
3. Hall-Craggs, E.C.B., The Significance of Longitudinal Fibre Division in Skeletal Muscle, J. Neurol, Sci. *15*, 27-33, 1972.
4. Sola, D.M., D.L. Christensen, and A.W. Morten, Hypertrophy and Hyperplasia of Adult Chicken Lat. Dorsi Muscles Following Stretch With and Without Denervation, Exper. Neurlogy *41*, 76-100, 1973.
5. DeLorme, T. L., Restoration of Muscle Power by Heavy Resistance Exercises, J. Bone & Joint Surg. *27A*, 645-667, 1945.
6. Clarke, H.H., Ch. V, Muscular Strength and Endurance in Man, Prentice Hall, USA, 1966.
7. Petow, H., and W. Siebert, Z. Klin Med. *102*, 427, 1925.
8. Eyster, J.A.E., Trans. Assoc. Am. Physiol. *62*, 15, 1927.
9. Siebert W., Klin Med. *109*, 350, 1928.
10. Hettinger, T., Ch III, Muscle Training, Physiology of Strength, Chas. Thomas, 1961.
11. De Vries, Herbert A., Ch. 18, Physiology of Strength, Physiology of Exercise, 2nd Ed., W. C. Brown, USA, 1971.
12. Hosler, W. W., Electromyographic and Girth Considerations Relative to Strength Training, Perceptual and Motor Skills *44*, 293-294, 1977.
13. DeLorme, T.L., and A.L. Watkins, Progressive Resistance Exercise, Appleton, Century, Crafts, USA, 1951.
14. DeLorme, T.L., and A.L. Watkins, Technic of Progressive Resistance Exercise, Arch. Phys. Med. *29*, 263-273, 1948.
15. Barney, V.S., and B.L. Bangerter, Comparison of Three Programs of Progressive Resistance Exercise, Res. Quarterly *32*, 138-146, 1961.
16. Clark, H.H., Development of Muscular Strength and Endurance, Physical Fitness Res. Digest, January 1974.
17. Hellegrandt, F.S., and S.J. Hontz, Mechanisms of Muscle Training in Man: Experimental Demonstration of the Overload Principle, Phys. Therapy Rev. *36*, 371, 1956.
18. Zinovieff, A.N., Heavy Resistance Exercises: The Oxford Technique, British Jour. of Physical Med. *14*, 129, June 1951.
19. McGovern, R.E., and H.B. Luscome, Useful Modifications of Resistive Exercise Technique, Arch. Phys. Med. and Rehab. *34*, 475-477, 1953.
20. Morris, R.O., and E.C. Elkins, A Study of Production and Evaluation of Muscular Hypertrophy, Arch. Phys. Med. and Rehab. *35*, 420-426, 1954.
21. Stull, G.A., and D.H. Clarke, High-Resistance, Low-Repetition Training as a Determiner of Strength and Fatigability, Res. Quarterly *41*, No. 2, 189, May 1970.
22. Berger, R.A., Application of Research Findings in Progressive Resistance Exercise to Physical Therapy, Jour. of Assoc. for Phys. and Mental Rehab. *19*, No. 6, 200-204, November-December 1965.
23. Berger, R.A., Effect of Varied Weight Training Programs on Strength, Res. Quarterly *33*, No. 2, 168, May 1962.
24. Berger, R.A., and B. Hardage, Effect of Maximum Loads for Each of Ten Repetitions on Strength Improvement, Res. Quarterly *38*, No. 4, 715, December 1967.
25. Berger, R.A., and M.W. Harris, Effects of Various Repetitive Rates in Weight Training on Improvement in Strength and Endurance, Jour. of Assoc. for Phys. and Mental Rehab. *20*, No. 6, 205, November-December 1966.
26. Goldberg, A.L., et al, Mechanism of Work Induced Hypertrophy of Skeletal Muscle, Med. & Science in Sports *7*, 248-261, 1975.
27. Goldspink, G., and K.F., Howells, Work Induced Hypertrophy in Exercised Normal Muscles of Different Ages and the Reversibility of Hypertrophy After Cessation of Exercise, J. Physiology *239*, 179-193, 1974.
28. Astrand, P.O., and K. Rodahl, Ch. IV, Textbook of Work Physiology, McGraw-Hill, USA, 1970.
29. Clark, D.H., and G. Alan Stull, Endurance Training as a Determinant of Strength and Fatigability, Res. Quarterly *41*, 19-26.

30. Stull, G.A., and D.H. Clark, High-Resistance, Low-Repetition Training as a Determiner of Strength and Fatigability, Res. Quarterly *42*, 189-193.

31. Shaver, L.G., The Relationship Between Maximum Isometric Strength and Relative Isotonic Endurance of Athletes with Various Degrees of Strength, Jour. Sports Med. *13*, 321-337, 1973.

32. Clarke, H.H., Physical Fitness Res. Digest Series 4, No. 1, January 1974.

33. Heyward, V., Relationship Between Static Muscle Strength and Endurance - An Interpretatiave Review, Amer. Corr. Ther. Jour. *29*, 67-72, 1975.

34. Leith, D.E., and M. Bradley, Ventilatory Muscle Strength and Endurance Training, Jour. Appl. Physiol. *41*, 508-516, 1976.

35. Vannotti, A. and H. Pfister, Untersuchungen zum Studium des Trainiertseins, Arbeitsphysiol. *7*, 127, 1934.

36. Vannotti A., and M. Magrday, Untersuchungen zum Studium des Trainiertseins, Arbeitsphysiol. *7*, 615, 1934.

37. Petren, T., T. Sjostran, and B. Syven, Des Einfluss des Trainings auf du Heufigkat der Capillaren in Herz - und Skelettmuskulatur, Arbeitsphysiol. *9*, 376, 1936.

38. Holloszy, J.O., Adaptation of Muscular Tissue to Training, Prog. in Cardiovasc. Dis. *18*, 445-458, 1976.

39. Brown, M.D., et al, The Effect of Long Term Stimulation of Fast Muscles on Their Ability to Withstand Fatigue, J. Physiol. *238* London, 478-488, 1973.

40. Hudlick, O., et al, The Effect of Long Term Stimulation of Fast Muscles on Their Blood Flow, Metabolism and Ability to Withstand Fatigue, Pflugers Archiv. *369*, 141-149, 1977.

41. Anderson, P., and J. Hendrikson, Training Induced Changes in the Subgroups of Human Type II Skeletal Muscle Fibres, Acta. Physiol. Scand. *99*, 123-125, 1977.

42. Abramson, A.S., and E.F. DeLongi, Influences of Weight Bearing and Muscle Contraction of Disuse Osteoporosis, Arch. Phys. Med. and Rehab. *42*, 147-151, 1961.

43. Hodkinson, H.M., and A.T. Brain, Unilateral Osteoporosis in Longstanding Hemiplegia in the Elderly, J. Am. Geriatrics Soc. *15*, 59-64, 1967.

44. Walton, J.N., and C.K. Warrick, Osseous Changes in Myopathy, Brit. J. Radiol. *27*, 1-15, 1954.

45. Thornton, W., and J. Rummel, Muscular Deconditioning and its Prevention in Space Flight, pp. 191-197, Biomedical Results from Skylab NASA SP 377, 1977.

46. Fishler, V.A., et al, Study of Mass-Inertia Characteristics of Human Body Segments During 6 months Hypolinesia by the Gamma Scanning Method, Kosmicheskaya Biologiya I Aviakosmicheskaya Meditsina, USSR Report Space Biology & Aerospace Medicine *15*, 52-59, 1981, JPRS 77513, NTIS Springfield, VA 22161.

47. Dietrick, J.E., G.D. Whedon, and E. Shorr, Effects of Immobilization Upon Various Metabolic and Physiological Functions of Normal Men, Am. J. Med *4*, 3-36 1948.

N91-10587

N4

5-26899

8P

Cardiovascular Group

Gunnar Blomqvist, M.D.
Division of Cardiology
University of Texas Health Science Center
Dallas, Texas

As a starting point, the group defined a primary goal of maintaining in flight a level of systemic oxygen transport capacity comparable to each individual's preflight upright baseline. We did not consider it appropriate to require any specific preflight level of fitness. Medical standards for crewmembers are adequately addressed in many other ways. However, we felt that it is essential to establish measurement procedures for quantitation of preflight fitness levels in all crewmembers. Such procedures should include measurement of maximal oxygen uptake VO_2. Ideally, there should be at least three data points over a period of several months before flight to document the habitual level of fitness for each individual which then defines the level that should be maintained in flight. We realize that a goal of maintaining the preflight level can be achieved in a variety of ways with different exercise regimens. Assuming that one can transpose ground-based methodology (i.e., there are some reasons to believe that one can, including the Skylab data), a minimal regimen included four sessions per week for 30 minutes at an intensity level of 70 to 80 percent of preflight maximal VO_2.

The goal of maintaining capacity at preflight levels would seem to be a reasonable objective for several different reasons, including the maintenance of good health in general and the preservation of sufficient cardiovascular reserve capacity to meet operational demands. It is also important not to introduce confounding variables in whatever other physiological studies are being performed. A change in the level of fitness is likely to be a significant confounding variable in the study of many organ systems.

The principal component of the in-flight cardiovascular exercise program should be large-muscle activity such as treadmill exercise. We realize that other exercise regimens that may have been designed to achieve maintenance of the musculoskeletal system may partly or completely satisfy also the requirements for the cardiovascular system. Furthermore, routine work such as extravehicular activity may replace all or some of the scheduled activity that is required to maintain cardiovascular fitness. It is desirable that at least one session per week be monitored to assure maintenance of proper functional levels and to provide guidance for any adjustments of the exercise prescription. Appropriate measurements include evaluation of the heart-rate/workload or the heart-rate/oxygen-uptake relationship. Respiratory gas analysis is helpful by providing better opportunities to document relative workload levels from analysis of the interrelationships among VO_2, VCO_2, and ventilation.

We considered in addition what should be done to prevent readaptation problems on return to normal gravity. The committee felt that there is no clear evidence that any particular in-flight exercise regimen is protective against orthostatic hypotension during the early readaptation phase. Some group members suggested that maintenance of the lower body muscle mass and muscle tone may be helpful. There is also evidence that late in-flight interventions to reexpand blood volume to preflight levels are helpful in preventing or minimizing postflight orthostatic hypotension. Progress toward this goal can probably be achieved by means of a variety of in-flight interventions that may help in maintaining a normal blood volume; e.g., late fluid loading, administration of vasodilators, exercise combined with thermal loads, or intermittent redistribution of fluid by lower body negative pressure or by combinations of these interventions. All of these and other alternatives should be explored in the future.

Whatever recommendations regarding an exercise prescription are adopted, the first set will be an approximation that will need to be modified appropriately after evaluation of flight data. It is therefore an absolute necessity to begin with an effective system for collection and evaluation of the physiologic characteristics and effects of any exercise program. The individual responses and the benefits that are being derived from the program must be documented. An essential part of that task is quantitation of the preflight state. Bear in mind that this committee has only addressed the minimal cardiovascular measurement set. There are many other measurements that should be part of a standard physiological measurement set, including cardiac imaging.

With regard to exercise devices, the modified micro-g treadmill is generally an excellent choice for maintenance of cardiovascular fitness. However, it is important to realize that there are various ways of producing the desired effects. Multiple programs may initially be defined to benefit different organ systems. Regimens will eventually be consolidated and devices will be selected that make it possible to achieve in an efficient manner the specific objectives for all systems that are being targeted.

Muscle Group

Reggie Edgerton, Ph.D.
Department of Kinesiology
University of California
Los Angeles, California

Two different exercise programs are recommended by the muscle group. The first one is intended to maximize performance and extravehicular activity (EVA) and, therefore, focuses on exercise for the upper body. The second exercise program is oriented toward muscles of the leg.

Extravehicular activity demands considerable time and effort and may well be the most dangerous aspect of the early missions on the Space Station (SS). These missions will be characterized by frequent EVA's in order to assemble the various SS components. Therefore, we believe that exercise prescriptions should be designed to train for optimal productivity with an acceptable safety margin for human error. It may be advisable to train the upper body before flight, because of the high demands of the upper body musculature in EVA. Given the specific types of activity that seem to be required during EVA, and considering the minimal experience that we've had characterizing these movements, considerable time and thought was given the topic of training crewmembers in a pressurized suit in the range of 7 to 8 psi. It appears that considerable use of the hands may be required, perhaps for prolonged periods of time, during EVA. Fortunately, in this particular case, we may be able to create a reasonable underwater simulation of EVA for many movements. However, all movements must be analyzed with respect to both displacement and the forces required for the distal digits (fingers) and for other more proximal joints (elbow and shoulder). This analysis can be done by proper instrumentation of the space suits in a way so that movements can be quantified meaningfully. Such instrumentation should help to optimize the exercise training required. This apparatus could be used in practicing movement precision and for endurance training. A general feature of every exercise apparatus should be that it has the capability to record continuously force, displacement, and electromyography. In this way, crewmember movement training can be individualized.

Feedback to the crewmembers on movement precision may increase compliance with the training program as well as optimize the effects of the training sessions for the crewmembers. It is estimated that a crewmember may need to train for a maximum of several hours a day under some circumstances. However, perhaps as little as 30 minutes or less, every other day, may be sufficient. Even though EVA may last for as long as 6 to 8 hours, it is unlikely that the same muscle groups will or could be used safely for 6 to 8 hours. Perhaps one task could be performed for 1 hour and then alternate with tasks that require different muscle groups. It would appear that endurance and the strength capabilities of the upper arm could be maintained with less than an hour a day, and perhaps 30 minutes per day, three to four times a week. Ground-based experiments will be important in addressing this issue. These details can be defined more precisely in ground-based experiments before the Space Station initial operating capability (IOC).

There should be a means for the individuals to maintain their training capability in flight. Preflight training could be extensive in cases for which considerable EVA is required early in a 90-day mission. It should be noted that the exercise apparatus should accommodate the muscles of the shoulder girdle as well as the more distal segments of the arm.

Another exercise-related issue is how to minimize muscle atrophy. This seems to be an issue with respect to the lower body only. Is it important to totally prevent muscle atrophy? One approach would be to ignore it and accept the recovery period required upon return to one g. The general consensus is that we should minimize but not necessarily prevent muscle atrophy. Some tradeoffs between muscle maintenance and work productivity in space may be desirable. For example, suppose 15 min/day is required to maintain muscle function within 90 percent of normal, whereas 2 hours would be necessary to maintain muscle mass at the 100-percent level. All muscles do not atrophy similarly in microgravity. Based on the evidence from Cosmos and NASA flights, most atrophy occurs in the extensor muscles. This category probably includes muscles of the neck, the back, and the legs. How do we minimize this atrophy? We are suggesting several exercise apparatuses. One recommendation is to use a treadmill similar to what Dr. Bill Thornton has demonstrated, particularly if the treadmill can be configured for use so that impact forces are imposed. The U.S.S.R. seems to have a very effective treadmill in this regard. Secondly, a rowing machine would probably be a useful apparatus. Both of these apparatuses require muscular effort of the back, the hips, the knees, and the ankles.

A more specific approach is to exercise one joint at a time. Obviously, this approach is inefficient with respect to the training time required. A rowing machine or a treadmill would seem to be the most suitable apparatus. Furthermore, the more complex exercises would probably result in greater user compliance than would single-joint exercise machines. It is also suggested that an apparatus be devised for jumping. For example, a platform with bungee cords may be effective and feasible. The force/time curves could be recorded from such an apparatus. A jumping apparatus could be an effective way to produce the higher power efforts that would require recruitment of the higher threshold motor units.

Lastly, we recommend apparatuses which can be used to test and, if desired, to train specific joints; for instance, a mechanism whereby muscle lengthening and shortening velocities and torques can be controlled and recorded. Such an apparatus would allow each individual to monitor force-velocity capabilities over time for specific muscle groups before, during, and after flights.

What research is needed to further define these apparatuses? Bed-rest studies are considered to be an important resource. In addition to anthropometric, strength, physiological, and biochemical data from bed-rest and other ground-based studies, data from muscle biopsies are needed. Analyses of muscle biopsies will be needed to test the working hypotheses which underlie the recommendations being made. How selective is muscle atrophy? How severe is the atrophy, and how rapidly does it develop? These issues can be addressed effectively using a combination of ground-based models and the short-duration flights that will take place between now and IOC.

Skeletal Group

Dr. Peter Cavanagh
Director, Center for Locomotion Studies
Pennsylvania State University
University Park, Pennsylvania

We addressed five key questions within our group. The first one was - Can exercise prevent bone demineralization in flight? The second one, regardless of the answer to the first one, is - Are the skeletal losses sufficient to warrant countermeasures? If so, what countermeasures would we add? What devices would be recommended? The answer to the last question is, of course, interrelated with the countermeasures. And finally, the question we actually could answer: What issues need to be researched further?

The answer to the first question - Can exercise prevent demineralization? - got general support as a concept with the following reservations. The animal data are much stronger than are the human data in providing an answer. There is a lack of prospective studies; therefore, cause and effect relationships cannot truly be established. The mechanisms are not truly known. The best studies, the bed-rest studies, have been varied in their protocols, and they don't provide the conclusive evidence that we need to refer to a flight situation. Secondly, the density measurements that have been taken on the calcaneus are inadequate to give us a global picture of what's happening to the calcium in the body as a whole. So in answer to the question, "Can exercise prevent demineralization?", it is our strong feeling that it can, but that opinion is based on animal studies and human studies which need to be refined.

Turning to the question, "Is it important during a 90- to 180-day space flight to reverse the observed changes?", the answer was an almost unanimous "yes." There was a strong consensus that something should be done despite the fact that it may possibly be ignored without detriment to in-flight performance on a 90-day flight. However, it was pointed out by a number of committee members that the Space Station should be treated as a test for longer interplanetary missions. Therefore, we have a chance to address the problem now, and it should be solved as a prelude to future long-term activity. There is the feeling that if 180 days is the requirement now, that's definitely going to be extended in the future. Concern was voiced that the changes that occur beyond 180 days are not presently known. There was also concern regarding the secondary effects of calcium excretion. In particular, renal status and other potential problems related increased mobilization of calcium. The feeling was voiced that, although calcium loss is not a life-threatening problem, it certainly is sufficient to demand investigation, not just as a solution to the present problem but as a problem that needs solving in longer duration missions. The statement was made by one committee member that a 15-percent loss in the calcaneus may not be worrisome to anybody, but a 15-percent loss in the vertebrae would certainly be cause for concern. Another major reason for concern is that we don't understand the recovery profile. And if it were to be discovered, for example, that the calcaneus recovered quickly, the spine recovered slowly, and the long bones recovered hardly at all over a long period, then that in itself would be cause for concern. So the answer to question 2, "Is it important to prevent calcium loss in a 90- to 180-day flight?", was an almost unanimous "yes."

The third and fourth questions regarding countermeasures and exercise devices, respectively, are obviously interrelated. The general feeling is that countermeasures should be designed to substitute for what has been taken away. And what has been taken away are principally two things. They are the force/time profiles that are input to the lower extremity repeatedly in locomotion-type activities, and they are vigorous eccentric muscle action. Both of these things are absent relative to their normal occurrence in a one-g environment. Therefore, the countermeasure suggested by our group would be mechanisms which involve applying loads to various parts of the human body which would require eccentric muscle action to overcome. Nobody recommended simple passive impacts or passive loads. Other possible modalities include devices that apply bending stresses to bones and muscle stimulation.

With regard to a frequency for application of a bone countermeasure, it was felt that the requirement for this kind of input to the lower extremity should be there on a daily basis. Several people suggested at least twice a day periods of locomotor-type activity. As far as what devices would be recommended if at this time anything should be fixed, it is that the device should have the flexibility to change. And there was a general feeling that, at this point, to specify the device without possibility for change would be premature. However, the almost unanimous recommendation of the group is that the treadmill should be included as the primary exercise device to apply locomotor forces to the lower extremity with the following reservations. The current configuration of the treadmill may need modification. It may need to be an active treadmill with a longer tread. The harness may need review, and the subjects may require training so that it simulates typical one-g impacts. The point was made that the harness for the treadmill could be used for other types of jumping activities where the legs would be subjected to large eccentric actions not possible without the body being harnessed down. Other types of devices that were suggested included the possibility of a trampoline with variable tension.

We spent time discussing the issue of whether the exercise should be voluntary and whether it should be standardized or individualized. And I think that even though there was no consensus on this, it was generally acknowledged that the rates of calcium flux are different in different individuals and this, therefore, raises the possibility that the exercise protocols should be individually tailored. Most people felt the exercise should be compulsory rather than left to individual choice. It should be variable in duration and in magnitude, but compulsory in the fact that it should be done by all crewmembers.

Finally, with respect to the issue of what research needs to be done, there were three issues that deserve emphasis. The first I want to mention is the lack of baseline information on the preflight status of the astronaut corps. Everybody felt that it was indefensible that we do not have epidemiological data on the astronauts from day 1 of their acceptance into the program all the way through their training, through space flight, and through postflight recovery. Various people on our committee had made similar recommendations years ago that this information should be kept. It was perhaps the strongest consensus in our committee that you cannot plan experiments without having good baseline data on the individuals for planning purposes. In our particular point of view, there was the feeling that this must include total-body calcium, which, as was pointed out, takes only 1 hour to measure and results in minimal radioactive exposure. Among the data that should be collected are information on bone density and on individual rates of bone loss, sensitivity to calcium changes, a family history of osteoporosis, presence of lactose intolerance, or limited calcium intake. It was felt that these kinds of things are so basic that it's surprising these data do not exist.

Secondly, we felt that the most important thing that needs to be done is more research to confirm the effects of exercise on bone changes. Concern was expressed over the difference in exercise modes across the various bed-rest studies and the interaction of the exercise posture with the type of exercise. Studies need to be done in a very specific manner; they need to be refined to identify exactly what the various exercise effects and dose relationships are. Some suggestions were made, including an interest in the use of the water exercise as a possible alternative model to bed-rest exercise. It was felt that the uncertainties in the interaction of all these factors affecting the loss or retention of calcium have to be identified. It was also felt that we have to determine the effect of different types of forces on the various parameters in calcium kinetics. We must know the difference between brief-duration forces and prolonged forces. We must know the difference between voluntary muscle forces and electrically stimulated forces. Because there is so much uncertainty as to what types of forces are involved in the maintenance of skeletal mass, the decisions of what to do at the moment are based on educated guesses. It was felt that studies must be done on individuals at both extremes of bone turnover rates in order to maximize the success of the experiments. Preselection of experimental subjects based on their rate of loss may resolve some of the variance in previous results. Individuals with high rates and individuals with low rates of bone turnover should be studied in order to determine whether the members of the astronaut corps lose at the same rate.

It was suggested that we should study the exercise profiles of individuals who are going either into the bed-rest studies or into a zero-g environment so that the history of force application to their lower extremities can be recorded and evaluated. It is thought that possibly an "equivalent" effort can be compacted into a shorter exercise period. We felt that, in light of planned long-term space flight, we must have long-term research and that the duration of any of the simulated studies must be at least as long as the planned duration of the space flight. Furthermore, there is a strong feeling that the recovery kinetics need to be examined. For example, if complete restoration of preflight levels occurs in all locations in 3 months, then perhaps this problem can be given a lower priority. If, however, there is not complete restoration, then one has to worry about repeated flights by the same individuals, and whether there are any long-term cumulative effects.

It was also stated that a lot of the previous data on calcium changes and on bone demineralization were obtained using methods that may now be outmoded, and that there must be an attempt to use the latest techniques and, equally important, to study many different regions of the body. We cannot simply determine the changes in the calcaneus and extrapolate from those data to all regions of the body. The point was made that, clinically, many different interventions have specific effects. More must be known about the differences in losses between cortical and trabecular bone.

We realized all through this deliberation that we couldn't consider bone in isolation, and, at this point, we allowed our focus to broaden. In particular, we must try to consider the various effects on bone and muscle as a single unit where possible. There was some dispute in the group on whether biopsies of bone would be acceptable or not, with support expressed for both sides. The question was raised as to whether or not head-down position accelerates the bone resorption, and even though this was said to be a very heretical point of view, it was thought that because the head-down position per se affects so many other physiological systems, it is worth investigating. In a similar vein, lower body positive pressure protocols should be studied as a potential model. It was felt that hormonal studies are needed, both in flight and during bed rest, because that could be the full extent of the problem. There was general skepticism on the point, but it needs to be disproved because of its possible strong effect. The possibility of pharmacological intervention, such as the use of disphosphonates, was mentioned and deserves some further research. And finally, a rather novel suggestion was made of putting a nonexercising deconditioned person in space as a control to learn what happens to the calcium kinetics of that individual.

This rather lengthy account reflects the fact that our group didn't seem to have the same degree of certainty that some other groups demonstrated. We are in general agreement that there is a problem and that the problem needs to be attacked. We feel that it should be attacked in flight with weight-bearing exercise such as treadmill locomotor or possibly jumping exercise to generate large eccentric muscle actions. Furthermore, we feel that there is a substantial amount of research that needs to be done in order to make us feel stronger in the recommendations we have made.

52 6900
8/

N91-10588

/
75

Summary and Recommendations for Initial Exercise Prescription

Bernard A. Harris, Jr., M.D.
Space Biomedical Research Institute
NASA Lyndon B. Johnson Space Center
Houston, Texas

and

Donald F. Stewart, M.D.
NASA Lyndon B. Johnson Space Center
Houston, Texas

Introduction

Designing the exercise countermeasure facility for use on board the U.S. Space Station will be a challenging task for NASA life sciences personnel and the outside community. During the next decade, there will be a transition within the U.S. space program to longer duration space flight. The role of exercise countermeasures in supporting men and women in this operational environment will become exceedingly important and complex. Although most concede that an exercise program of some fashion will be necessary, there is no clear consensus on the type, frequency, duration, or intensity of exercise, nor has the in-flight equipment to be used been accurately identified.

The responsibility for the design of the Space Station exercise countermeasure facility and for the operational objectives resides with NASA physicians and scientists. The exercise countermeasure facility is one of the three subsystems of the crew health care subsystem (CHECS), which additionally includes the health maintenance facility and the environmental health subsystem. The CHECS is designed to provide on-board preventive and medical care for the Space Station crew.

The purpose of the 1986 conference, "Exercise Prescription for Long-Duration Space Flight," was to assemble both NASA scientists and members of the academic community to discuss the development of an exercise prescription and the exercise modalities for use on the Space Station. It is anticipated that the results of this conference could contribute to the preliminary formulation of the Space Station exercise prescription. This prescription will be modified as indicated by future discussion, by ground-based research activities, and, ultimately, by the results of an in-flight effort to validate the operational prescription.

The rationale for the development of an exercise prescription for long-duration space flight is based on operational and medical requirements designed to adequately address health concerns of the crew. The following operational requirements for exercise countermeasures were established.

- Preserve the appropriate level of aerobic capacity and muscular strength/endurance to facilitate crewmembers' ability to perform demanding physical work required on board Space Station, such as repetitive extravehicular activities (EVA's).
- Maintain the integrity of the musculoskeletal system to prevent or minimize risk of injuries resulting from atrophy of bones, tendons, or ligaments.
- Maintain general physical fitness as it benefits the individual's health and sense of well-being.
- Sustain the ability to accomplish an end-of-mission unaided egress.
- Minimize the time required for postmission reconditioning.

Medical requirements for exercise countermeasures were as follows.

- Prevent muscle atrophy, reduction in muscle volume, loss of strength, and decline in functional capacity.
- Prevent cardiovascular deconditioning, decrease in fluid volume, increase of vascular compliance, and orthostatic intolerance.
- Prevent or retard bone demineralization, loss of bone integrity and strength, and the development of hypercalciuria, renal stones, and hypercalcemia.

Formulation of an Exercise Prescription

The design of an exercise prescription for space flight must follow certain parameters for development; i.e., specificity, mode, duration, intensity, frequency, and progression of physical activity (ref. 1). In addition, to meet the operational and medical requirements, there are other significant factors which must be addressed. First, the basic physiology of exercise in respect to one g and the adaptation to zero g must be delineated. The prescription must adequately address the physiologic adaptations to microgravity. Second, the nature of Space Station crew activities must be defined, and the exercise protocols and prescriptions must be incorporated within these activities. Current understanding of these activities is that at least two crewmembers will need to exercise during the same time period. Third, periodic evaluation of the crewmembers' physical condition will need to be conducted in flight to assess effectiveness of the prescriptions. Last, functional in-flight hardware for exercising must be developed.

Summary of Comments and Recommendations by Working Groups

To facilitate discussion on the design of an exercise prescription at the conference, all participants were assigned to a working group. The following is a summary of the conclusions of each group and their overall recommendation.

A. Cardiovascular Working Group

- As a primary goal, the group recommended that the exercise protocols be capable of maintaining a level of systemic oxygen transport which is comparable to an individual's preflight, upright baseline.
- Preflight fitness level should be quantified by measurement of maximal oxygen uptake on at least three occasions over several months in the preflight period.
- The minimum time dedicated to cardiorespiratory fitness is four sessions per week at an intensity level of 70 to 80 percent of preflight maximum oxygen uptake VO_2 max.
- At least one exercise session per week, including measurements such as the heart-rate/workload or heart-rate/oxygen-uptake relationship, should be monitored. Respiratory gas analysis was recommended.
- It was strongly recommended that the exercise system "start out with an effective system for collection and evaluation of the physiologic characteristics and effects of any exercise program."
- The principal component of the in-flight cardiovascular exercise program should be a large-muscle activity exercise such as a treadmill.

B. Muscle Working Group

- Two different components for an exercise program were identified, one intended to target individuals tasked with performing EVA's, and a second component designed to target the antigravitational muscles, to be performed by all crewmembers.
  - To maintain the strength and endurance of the upper arms, a minimum of 30 to 40 minutes per session, three to four times per week, was recommended.
  - Specific recommendations were not given with regard to an amount of time allotted for prevention of muscle atrophy of the antigravitational musculature.
- It was recommended that the exercise prescription be designed to train individuals for optimal in-flight productivity, with an acceptable safety margin for human error.
- Recommendations specific to EVA were as follows.
  - A space suit should be instrumented so as to analyze movements with respect to displacement/forces for both hand movements and movements of the elbow and the shoulder.
  - An instrumented suit could be used for practice of specific movements and for endurance training.
  - Preflight training of the upper body musculature should be conducted for missions with frequent EVA's.
- General consensus of the group was that atrophy of the muscles should be minimized, but that complete maintenance of muscle mass may not be required. It was recommended that an analysis of the tradeoff between time required and maintenance of muscle function be accomplished.
- Several exercise modalities were suggested.
  - For maintenance of general anti-gravitational musculature, a treadmill and a rowing machine were endorsed.
  - For training of specific joints, a device capable of controlling and recording muscle shortening and lengthening velocities and forces was recommended.

- A jumping apparatus was mentioned as a way to produce higher power efforts with concomitant recruitment of motor units with higher thresholds.

- With regard to research required to further define exercise modalities for maintenance of muscle function, bed-rest studies were recommended as an important resource, and analysis of muscle biopsies are needed to test the hypotheses supporting the various recommendations.

C. Skeletal Working Group

- It was recommended that a countermeasure be employed to prevent and/or minimize the previously observed changes in the skeletal system during flights of 90 to 180 days.
- It was recommended that Space Station be used as an operational testbed for longer interplanetary missions planned for the future.
- With regard to a specific countermeasure for treatment of bone loss, it was recommended that the measure employed be capable of replacing the locomotor activity absent in the microgravity environment. Critical activities in this regard include the force/time profiles seen in the lower extremity and vigorous eccentric muscle action.
- It was the recommendation of the group that a treadmill could be used as the primary device to provide locomotor forces to the lower extremity.
- It was suggested that an exercise program should be compulsory for all crewmembers, and that the prescription should be individualized.
- A strong recommendation was made that NASA collect and maintain an epidemiological data base on members of the astronaut corps from time of selection onward.
- A number of recommendations were made regarding the need for research activities to support design of a bone countermeasure, including the following.
    - Additional studies need to be done to identify potential effects of increased calcium mobilization.
    - Studies to elucidate the effects of various types of exercise activities during bed rest need to be accomplished, and the dose/response of the exercise should be established.
    - The effects of different types of forces on various parameters in calcium kinetics need to be demonstrated.
    - Studies should be done on individuals at both extremes of calcium turnover in order to maximize the success of various experiments.
    - Recovery kinetics of bone loss need to be characterized.
    - Various areas of bone need to be evaluated with densitometry rather than measuring the changes only in the calcaneus and extrapolating.
- A specific recommendation was not made with regard to the amount of time needed for a bone countermeasure. It was recommended that this activity be done on a daily basis.

Conclusion

The recommendations summarized herein constitute a basis on which an initial exercise prescription can be formulated. It is noteworthy that any exercise program designed currently would be an approximation. Examination of the existing spaceflight data reveals a scarcity of in-flight data on which to rigorously design an exercise program. The relevant experience within the U.S. space program (with regard to long-duration space flight) is limited to the Skylab Program. Lessons learned from Skylab are relevant to the design of a Space Station exercise program, especially with regard to the total length of exercise time required, cardiovascular (CV) deconditioning/reconditioning, and bone loss. Certain observations of the U.S.S.R. exercise activities can also contribute to the formulation of an exercise prescription for Space Station (ref. 2). Reportedly, the U.S.S.R. uses both a bicycle ergometer and a treadmill device on long-duration missions with some degree of success. Using the third crew of Salyut 6, which was a 175-day stay, as a representative mission, the typical time dedicated to exercise varies from 2 to 3 hours per day. In addition, the cosmonauts wear an elasticized suit, called a penguin suit, for time periods ranging from 12 to 16 hours per day. This device provides a load across the axial skeleton against which the wearer must exert himself. Despite these extensive countermeasures, the effects of adaptation are not totally prevented.

Proposed Exercise Prescription

The following proposed prescription is intended to incorporate the recommendations of the exercise conference working groups and the operational and medical requirements. Table I is the proposed exercise prescription, which reflects the difference between the EVA crewmember and the non-EVA crewmember. Additionally, figure 1 indicates how the proposed prescription could be scheduled to accommodate two exercising crewmembers. It is recognized that the following provides only a structure upon which individualization of crewmember protocols could be developed.

Discussion

The prescription as outlined incorporates the general recommendations put forth by the participants of this meeting. There are still many questions on the intensity, the duration, and the specificity of exercise which must be addressed during the years preceding permanent manned presence (PMP) of the Space Station.

TABLE I.- PROPOSED EXERCISE PRESCRIPTION

Day	Exercise prescription for -			
	EVA crewmember		Non-EVA crewmember	
	Mode and apparatus (a)	Duration, min	Mode and apparatus (a)	Duration, min
1	M1[b]	30	M1	20
	TM	30	TM	30
	BE	20	R/BE	(c)
2	M2[d]	30	M2	20
	TM	30	TM	30
	R	20	R/BE	20
3	M1	30	M1	20
	TM	30	TM	30
	BE	20	R/BE	(c)
4	M2	30	M2	20
	TM	30	TM	30
	R	20	R/BE	20
5	M1	30	M1	20
	TM	30	TM	30
	BE	20	R/BE	(c)
6	M2	30	M2	20
	TM	30	TM	30
	R	20	R/BE	20
7	(c)	(c)	(c)	(c)

[a] Treadmill (TM), bicycle ergometer (BE), and rower (R) exercise performed at approximately 75 percent of preflight maximum oxygen uptake.

[b] M1 = upper body muscle training.

[c] Optional.

[d] M2 = lower body muscle training.

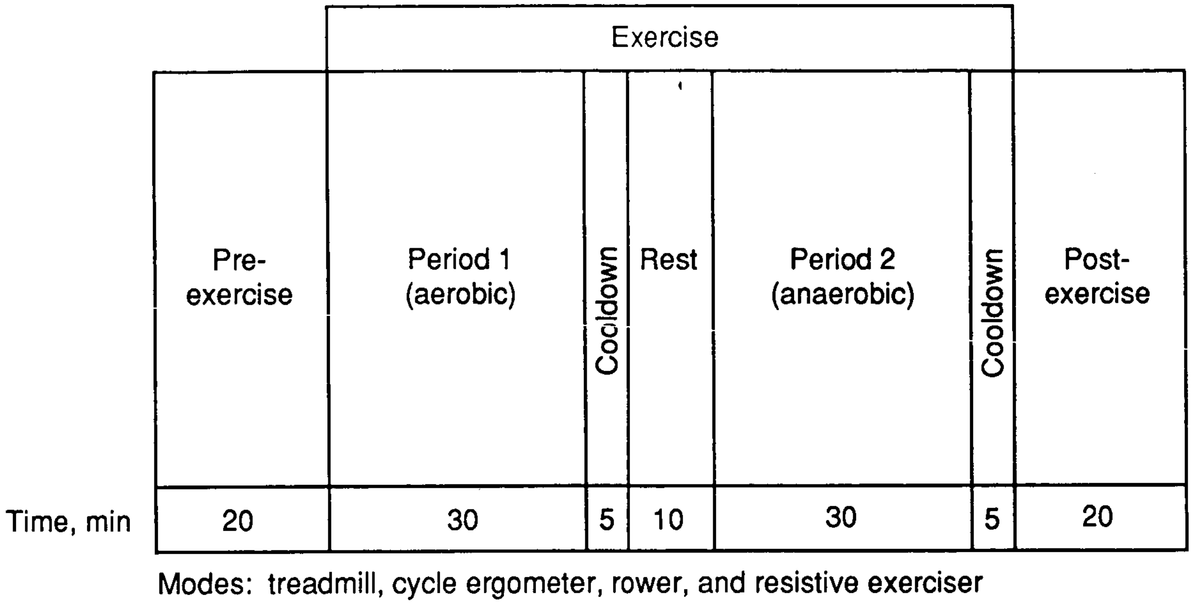


Fig. 1.- Proposed exercise regimen.

The development of any exercise prescription must include consideration of the exercise habits and the in-flight duties of each individual crewmember. The basic goal for any exercise countermeasure program will be to maintain preflight levels of function. The emphasis will be on maintaining a degree of overall fitness and musculoskeletal conditioning which is compatible with both in-flight and postflight operational and medical objectives.

The formulation of a separate exercise prescription for designated EVA crewmembers as suggested was based on the following considerations. As suggested by both Convertino and Moore, EVA tends to be more of an activity requiring sustained submaximal aerobic performance than one requiring frequent use of peak aerobic power. A reasonable characterization would be that of sustained low-level work with infrequent short periods of nearly maximal (aerobic) effort. Therefore, the operationally driven requirement for aerobic fitness in EVA crewmembers would be primarily for endurance rather than sustained peak aerobic performance. The suggested EVA crewmember exercise protocol would require between 45 and 60 minutes per day of aerobic exercise, an adequate amount of time to maintain cardiorespiratory fitness in individuals with a VO_2 max of 40 to 60 ml/kg/min. The requirement for the non-EVA crewmember is 30 minutes per day, which is adequate to maintain the levels of aerobic fitness typically seen in the astronaut corps. (Average VO_2 max for the astronaut corps is around 45 ml/kg/min.) These times are based on the assumption that maximal aerobic capability can be maintained in the microgravity environment with "one-g equivalent" times, which has not yet been proven.

A second requirement unique to designated EVA crewmembers pertains to muscle strength and endurance. Although detailed studies to elucidate the biomechanical nature of EVA have not been documented, the activity has been generally characterized as one requiring primarily upper body fitness. Most of the tasks accomplished during EVA require extensive use of the upper extremities, which in effect requires the crewmember to perform simultaneously his specific task as well as those needed for position stabilization and for counteracting the tendency of the pressure suit to assume a neutral position at the joints. Time has been allotted in the EVA crewmembers' exercise prescription to allow for additional upper extremity training and an emphasis on total-body exercise.

It is anticipated that the nature of the proposed exercise prescription should become more accurate as the subsequent research activities are conducted prior to PMP. As made apparent by comments during the meeting, there is considerable variation across discipline areas with regard to the amount of data available to support design of a particular protocol. The recommendations offered by the CV and muscle groups were more concrete than those put forth by the skeletal group. The general lack of knowledge regarding the nature of force profiles needed to maintain bone integrity (both in one g and in microgravity) may necessitate a more empiric approach to the design of the bone countermeasure for Space Station. Optimally, well-designed scientific studies will adequately address these concerns before Space Station is assembled on orbit. This exercise workshop has set the foundation from which further ground-based and in-flight studies will validate the individualized Space Station exercise prescriptions.

References

1. American College of Sports Medicine: Guidelines for Exercise Testing and Prescription. Lea and Febiger (Philadelphia), 1986.

2. Yegorov, A. D.: Results of Medical Investigations During the 175-Day Flight of the Third Prime Crew on Space Station Salyut-6/Soyuz. O. G. Gazenko and A. M. Genin, eds. (Moscow), 1980.

NASA
National Aeronautics and
Space Administration

REPORT DOCUMENTATION PAGE

1. Report No.
NASA CP-3051

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle
Workshop on Exercise Prescription for Long-Duration Space Flight

5. Report Date
October 1989

6. Performing Organization Code

7. Author(s)
Bernard A. Harris, Jr., M.D., and Donald F. Stewart, M.D., editors

8. Performing Organization Report No.
S-597

9. Performing Organization Name and Address
Lyndon B. Johnson Space Center
Houston, Texas 77058

10. Work Unit No.
073-36-00-00-72

11. Contract or Grant No.

12. Sponsoring Agency Name and Address
National Aeronautics and Space Administration
Washington, D.C. 20546

13. Type of Report and Period Covered
Conference Publication

14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract
The National Aeronautics and Space Administration has a dedicated history of ensuring human safety and productivity in flight. Working and living in space long term represents the challenge of the future. Our concerns are no longer getting a man into space but in determining the effects on the human body of living in space. Space flight provides a powerful stimulus for adaptation, such as cardiovascular and musculoskeletal deconditioning. Extended-duration space flight will influence a great many systems in the human body. We must understand the process by which this adaptation occurs. The NASA is agressively involved in developing programs which will act as a foundation for this new field of "space medicine." The hallmark of these programs deals with prevention of deconditioning, currently referred to as "countermeasures to zero g." Exercise appears to be most effective in preventing the cardiovascular and musculoskeletal degradation of microgravity. This document is a culmination of discussions from an exercise workshop held at the NASA Johnson Space Center. The proceedings from this session provide a comprehensive review of the physiology of exercise and recommendations on the use of exercise as a countermeasure for adaptation to a microgravity environment.

17. Key Words (Suggested by Author(s))
Bone demineralization
Weightlessness
Orthostatic tolerance
Musculoskeletal system
Cardiovascular system
Locomotion
Physical fitness
Maximal oxygen uptake

18. Distribution Statement
Unclassified-Unlimited

Subject Category: 52

19. Security Classification (of this report)
Unclassified

20 Security Classification (of this page)
Unclassified

21. No. of pages
132

22. Price
A07

For sale by the National Technical Information Service, Springfield, VA 22161-2171

NASA-Langley, 1989