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Work, Exercise and Space Flight

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II. Modification of Adaptation by Exercise (Exercise Prescription)

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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.

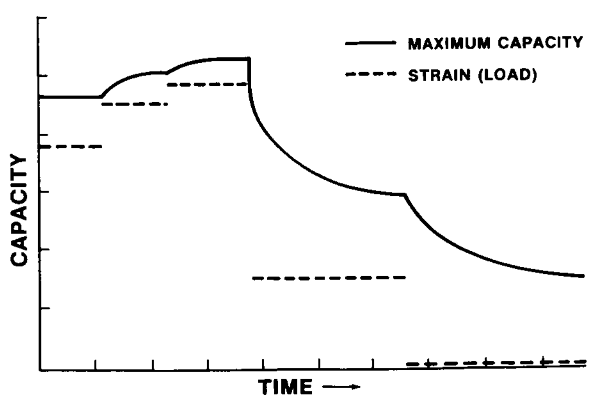

Fig. 1.- Generalized response curve of Wolff's 'law' for any tissue or system. The basic response seems to be an exponential function of time and consists of an increase or decrease in system capacity with increases or decreases in load. Response time is an individual function and may range from minutes 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.

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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

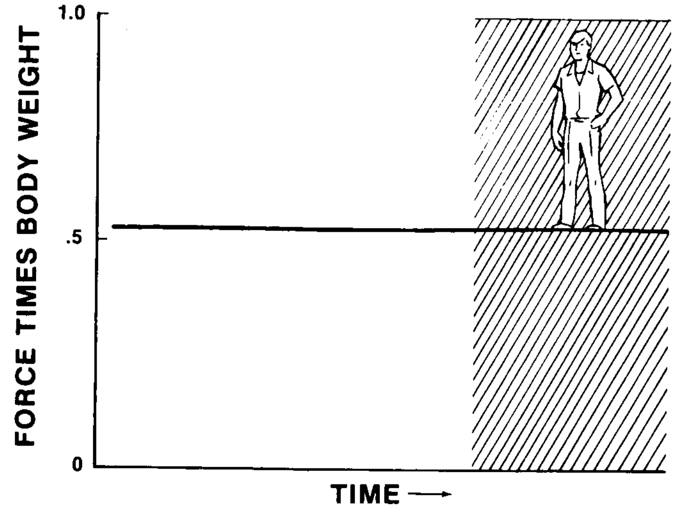
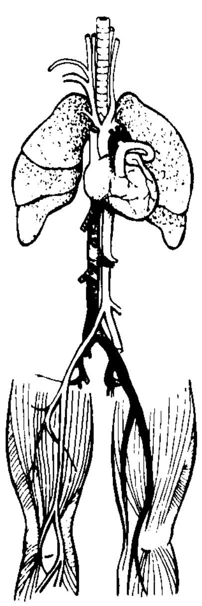


Fig. 3.- Foot force on one leg of man standing in 1-g. When balanced, it is 1/2 body weight (BW) but this may vary throughout the shaded region to a maximum of 1.0 BW



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.

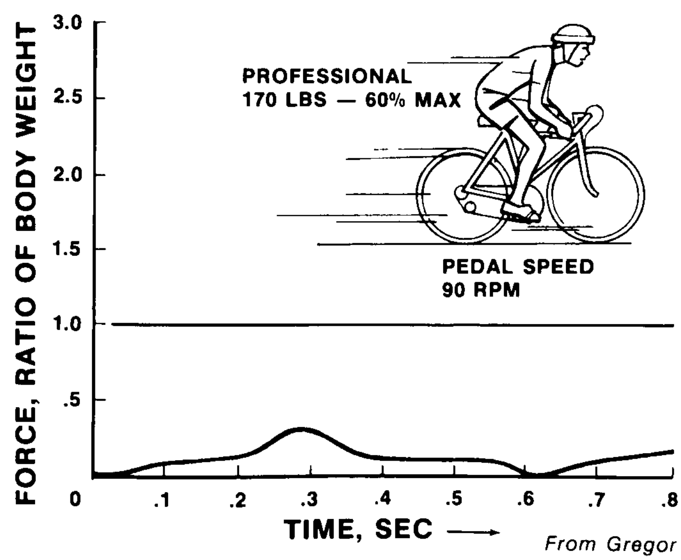


Fig. 4.- Measured foot force from a professional cyclist. Typical bicycle ergometry is much less, usually below 50 pounds. The prolonged, low forces result in high *metabolic* loads just as do the brief but higher impulsive forces of locomotion.

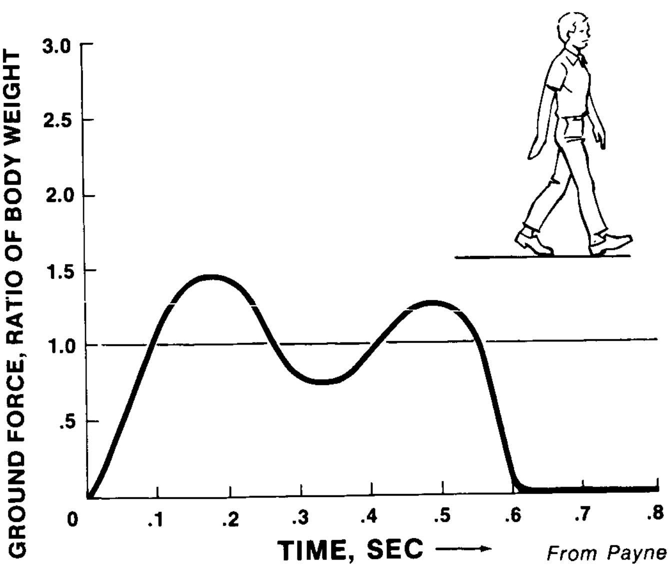


Fig. 5.- Typical foot force curve for one leg in walking. The increase above BW is caused by decelerating and accelerating the body's mass, i.e. inertial forces plus weight.

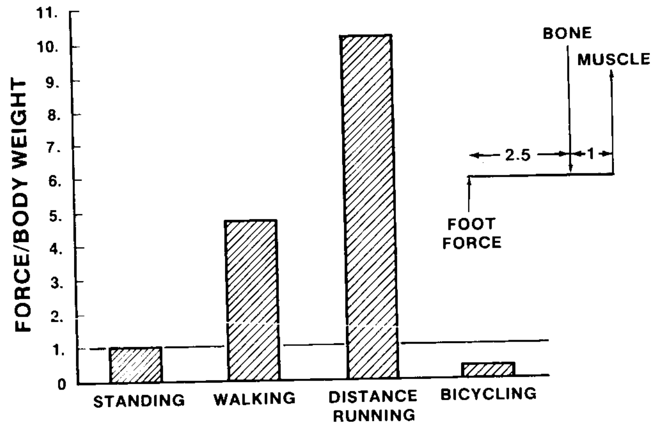
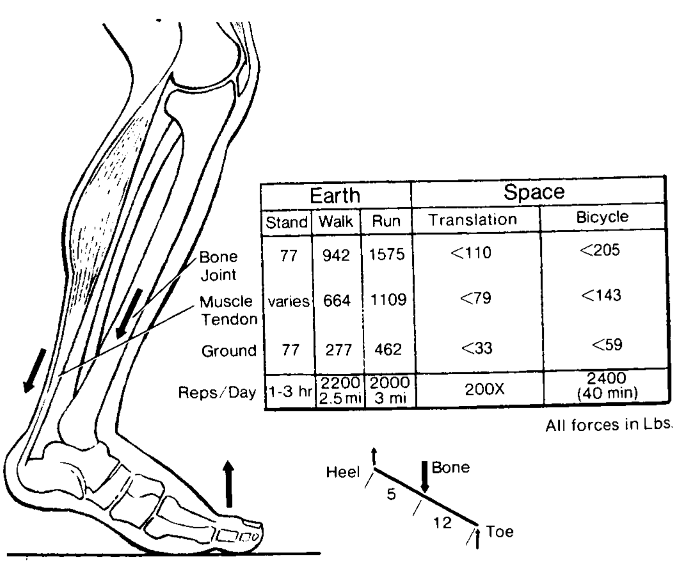


Fig. 7.- Typical forces on the tibia in various activities. Note that this amounts to more than a ton in a 200-pound man while jogging.

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

[a]Force is a function of speed.



	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)

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

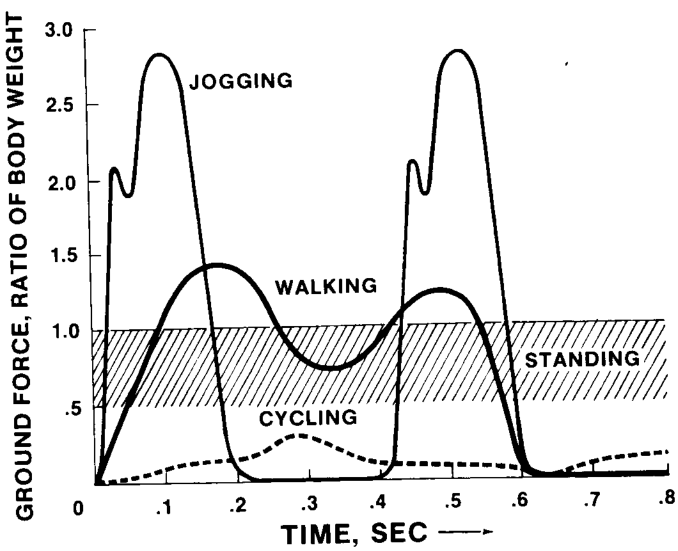


Fig. 8.- Comparison of various foot/ground forces, one leg.

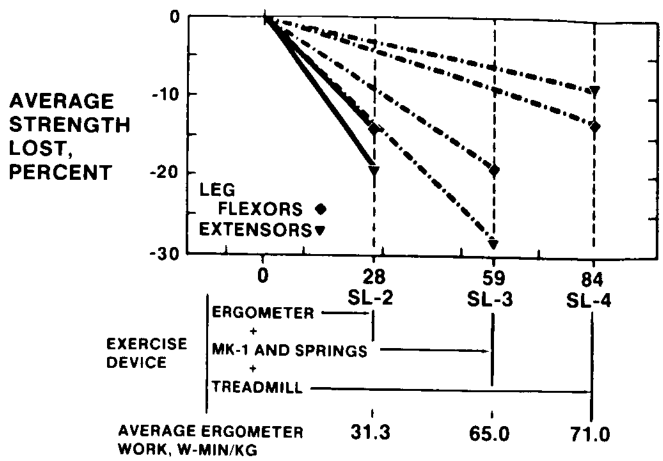


Fig. 9.- Mean of peak forces from 10 repetitions of isokinetic (45° sec.$^{-1}$) dominant leg flexion and extension for each crew on Skylab missions. This was primarily hip motion. Only bicycle exercise was available on SL-2 and SL-3 with a form of locomotor exercise on SL-4. Postflight measurements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

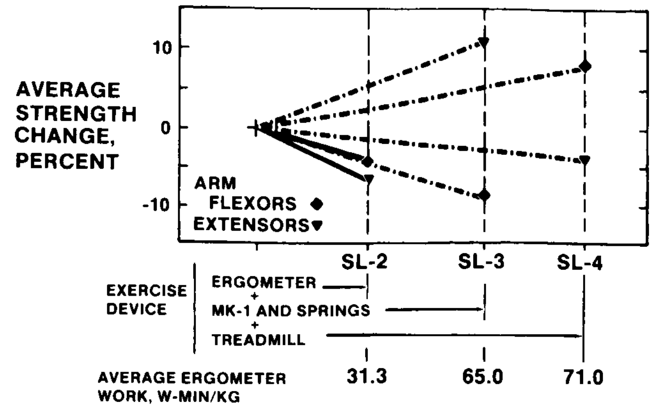


Fig. 10.- Mean of peak forces from 10 repetitions of isokinetic (45° sec.$^{-1}$) dominant elbow flexion and extension for each crew on Spacelab missions. Arm exercise was available on SL-3 and SL-4. The sharp rise in extensor strength on SL-3 was the result of a great increase in extensor strength in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

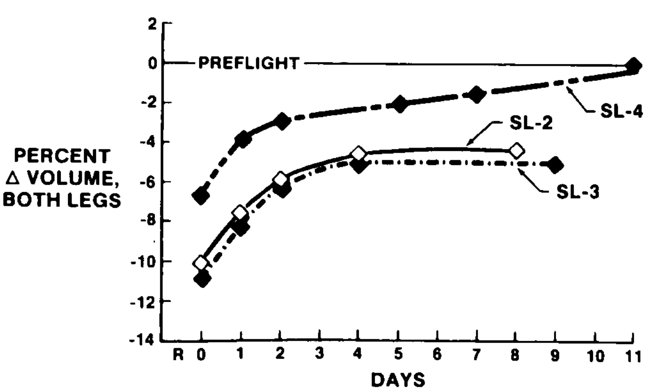


Fig. 11.- Mean postflight change in leg volume of Skylab crews. The rapid increase in volume for the first three days is presumed to be fluid shift. Durations of flights were: SL-2, 28 days, SL-3, 59 days, SL-4, 84 days.

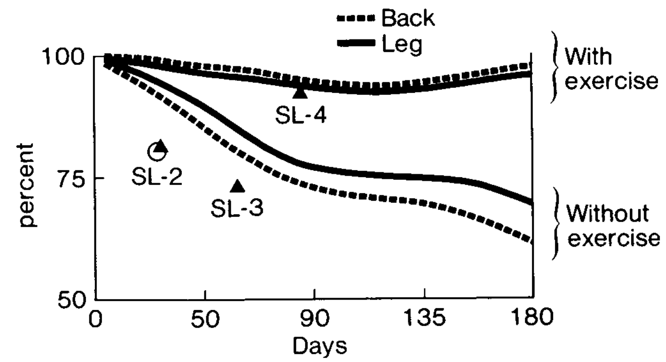


Fig. 12.- Mean changes in isotonic strength of back and legs in Russian bed rest study with and without exercise consisting of electrostimulation, horizontal locomotor activity, and other exercises. Triangles are measured results from Skylab missions and the circle at SL-2 are from a cast restrained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

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