REPRINTED FROM THE PROCEEDING

OF THE SKYLAB LIFE SCIENCES SYMPOSIUM

AUGUST 27 - 29, 1974

LYNDON B. JOHNSON SPACE CENTER

Muscular Deconditioning and its Prevention
in Space Flight

403-416

MUSCULAR DECONDITIONING AND ITS PREVENTION IN SPACE FLIGHT

William E. Thorton, M. D. and J. A. Rummel, Ph. D.
National Aeronautics and Space Administration
Lyndon B. Johnson Space Center
Houston, Texas

ABSTRACT

Under weightlessness without countermeasures, a rapid disuse atrophy of weight-bearing muscular groups appears to occur. For the Skylab Program, such losses were measured with a constant speed (isokinetic) dynamometer. Ten maximum-effort, full-range flexion/extensions of the elbow and hip/knee at 45 degrees/second were recorded and evaluated for each crewman before and after flight. Anthropometric measurements allowed computation of volume changes of limb segments.

During the Skylab 2 mission (28 days), a bicycle ergometer and an isometric device were used for exercise. Losses of strength and of muscle mass, especially in leg antigravity groups, were such that additional exercise devices were launched and exercise time was sharply increased on the Skylab 3 mission (59 days). Good arm exercises and acceptable trunk exercises were provided, but loads and types of leg exercise were limited. This imbalance was reflected after flight by the lack of measurable loss in arm function. Leg function and muscle mass had improved relatively over the Skylab 2 mission, but large decreases continued to be apparent. In addition to the other devices, a simulated treadmill consisting of a Teflon® walking surface, a harness, and elastic bungees to provide 170 pounds equivalent weight was used daily throughout the Skylab 4 mission (84 days). This flight crew returned in unexpectedly good condition; slight losses in muscle functions of arms or legs were measured.

Although weightlessness could cause rapid atrophy of many major muscle groups and disability on return to normal gravity could result after long missions, it has been demonstrated that such deconditioning can be prevented relatively easily through use of familiar exercise techniques. Future research efforts should focus on optimum methods of exercise with respect to crew time and crew acceptance, interrelationship of musculoskeletal fitness with cardiovascular fitness, and design of practical, efficient, total body exercisers.

INTRODUCTION

A major portion of man's musculoskeletal system is dedicated to supporting and moving his body against Earth's gravity. This mass of muscle places heavy requirements for support on other body systems. For example, maximum capacity of the cardiovascular and respiratory systems, and to a large measure their condition, is a function of demands from the body's musculature. It is a common experience that removal of muscle stresses under one-g, that is, lack of suitable exercise, results in atrophy of both muscle and its supporting systems. It could be confidently predicted that atrophy would occur rapidly under weightlessness unless suitable exercise was provided.

The time taken for such atrophy to occur allowed short missions such as Apollo to proceed without significant problems. But it was no longer possible to consider a long mission like Skylab without

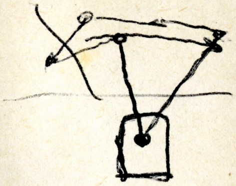
- some method of evaluating muscle condition, and
- suitable in-flight exercise.

On Skylab, we instituted first a minimum impact muscle function test, and as the mission demanded, added exercise and exercise devices and expanded the testing. The result was a different exercise environment on each flight, such that we had three experiments, with the results of each flight affecting the next. The flights will be described chronologically. This report will, insofar as possible, address only aspects of skeletal muscle since the cardiovascular aspects of conditioning and use of the bicycle ergometer are covered in another experiment.

PROCEDURE

Evaluation of the right arm and leg was done preflight and postflight on all missions with the Cybex Isokinetic Dynamometer. This dynamometer may be rotated in either direction without resistance until an adjustable limit speed is reached. Speed cannot be increased above this limit by forces of any magnitude, that is, the constant speed-maximum force of isokinesis is achieved. Input or muscle forces are continuously recorded. Various arms, handles, and the like may be attached to the dynamometer to couple any desired segment of the body to the machine.

The arrangement used on Skylab is shown in figure 1. A crewman, after thorough warm up, made 10 maximum effort full flexions and extensions of the arm at the elbow and of the hip and knee at an angular rate of 45 degrees per second.



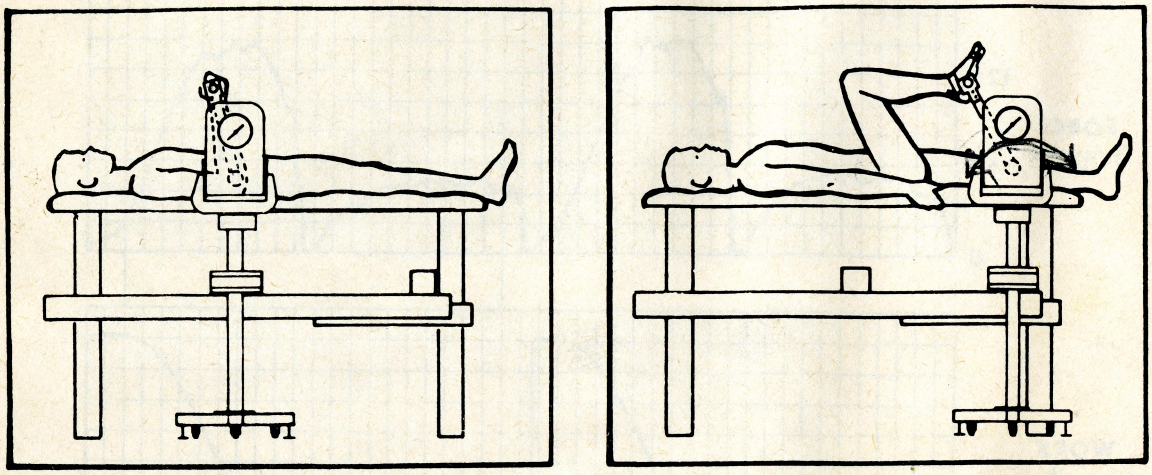


Figure 1. Test arrangement, Cybex Isokinetic Dynamometer.

A continuous force record was made of each repetition at a rate of 25 millimeters per second and the integral of force, or under these conditions, work is recorded on a second channel (fig. 2).

Machine errors are small, two to three percent or less. The test gives a measurement of strength comparable to the more commonly used isometric testing, but has the great advantage of recording this force throughout the whole range of motion as well as allowing a number of repetitions for statistical purposes. It is sensitive enough to show small changes in performance which may occur in days.

A great deal of information is contained in the recordings made, but only one quantity will be used here - the peak force of each repetition at the same point in the cycle. Use of a single point on the tension curve to represent the entire curve may be open to criticism, especially in the leg where a number of muscles are involved. However, for the purposes here, I feel this is a valid measure of strength of the muscles tested.

A plot of such peak points from a preflight and postflight curve is shown in figure 3. The strength for a given movement is taken as the average of 10 repetitions. As you can see, a fatigue decrement is present and may vary. It is included in the strength figure by virtue of averaging the 10 repetitions.

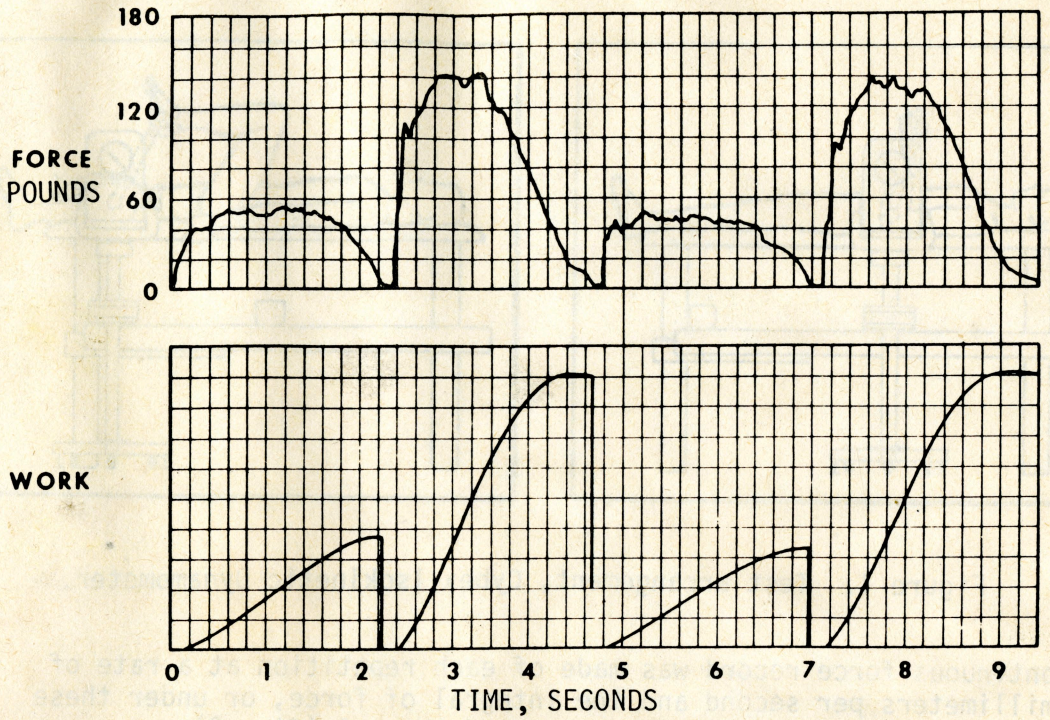


Figure 2. Recording of muscle forces, right leg, Skylab 3 Backup Pilot.

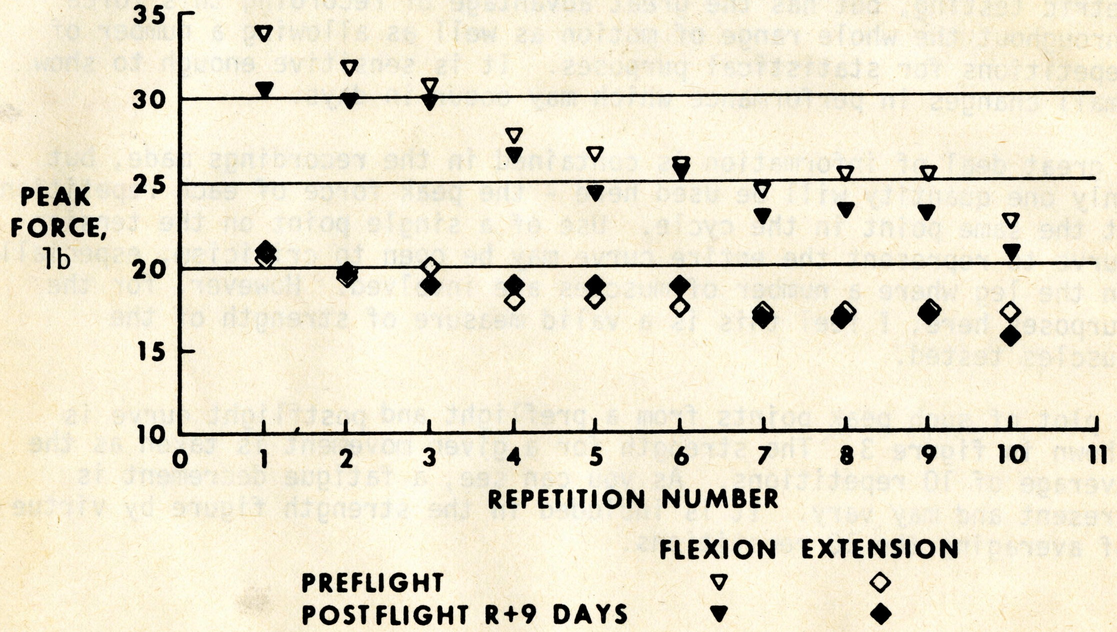


Figure 3. Peak arm forces preflight and postflight, Skylab 3 Commander.

On Skylab 2 only the bicycle ergometer was used for in-flight exercise. Pete Conrad used it in the normal fashion and was the only person on Skylab to use it in the hand-pedal mode and also the only person on this crew to exercise at rates comparable to those of later missions.

On Skylab 3, testing was performed 18 days before launch and five days postflight. It was recognized that this was too far removed from the flight, but this was the best that could be done under schedule constraints.

By the time muscle testing was done on day 5, there had been a significant recovery in function; however, a marked decrement remained. Results from Skylab 2 will be shown in a moment in conjunction with the results from Skylab 3. The decrement in leg extensor strength approached 25 percent, while the arms had suffered less but also had marked losses. The Commander's arm extensors had no loss, since he used these muscles in hand-pedalling the bicycle. This illustrates a crucial point in muscle conditioning: to maintain the strength of a muscle, it must be stressed to or near the level at which it will have to function. Leg extensor muscles which support us in standing and propel us in walking must develop forces of hundreds-of-pounds, while the arm extensor forces are measured in tens-of-pounds. Forces developed in pedalling the bicycle ergometer are typically tens-of-pounds and are totally incapable of maintaining leg strength. The bicycle ergometer is an excellent machine for aerobic exercise and cardiovascular conditioning, but it simply cannot develop either the type or level of forces to maintain strength for walking under one-g.

Immediately after Skylab 2, work was started on devices to provide adequate exercise to arms, trunk, and legs. A mass-produced commercial device, called Mini Gym, was extensively modified and designated "MK I". A centrifugal brake arrangement approximated isokinetic action on this device.

Only exercises which primarily benefitted arms and trunk were available as shown in figure 4. Forces transmitted to the legs were higher than those from the ergometer, but they were still limited to an inadequate level, since this level could not exceed the maximum strength of the arms which is a fraction of leg strength.

A second device, designated "MK II", consisted of a pair of handles between which up to five extension springs could be attached, allowing maximum forces of 25 pounds per foot of extension to be developed.

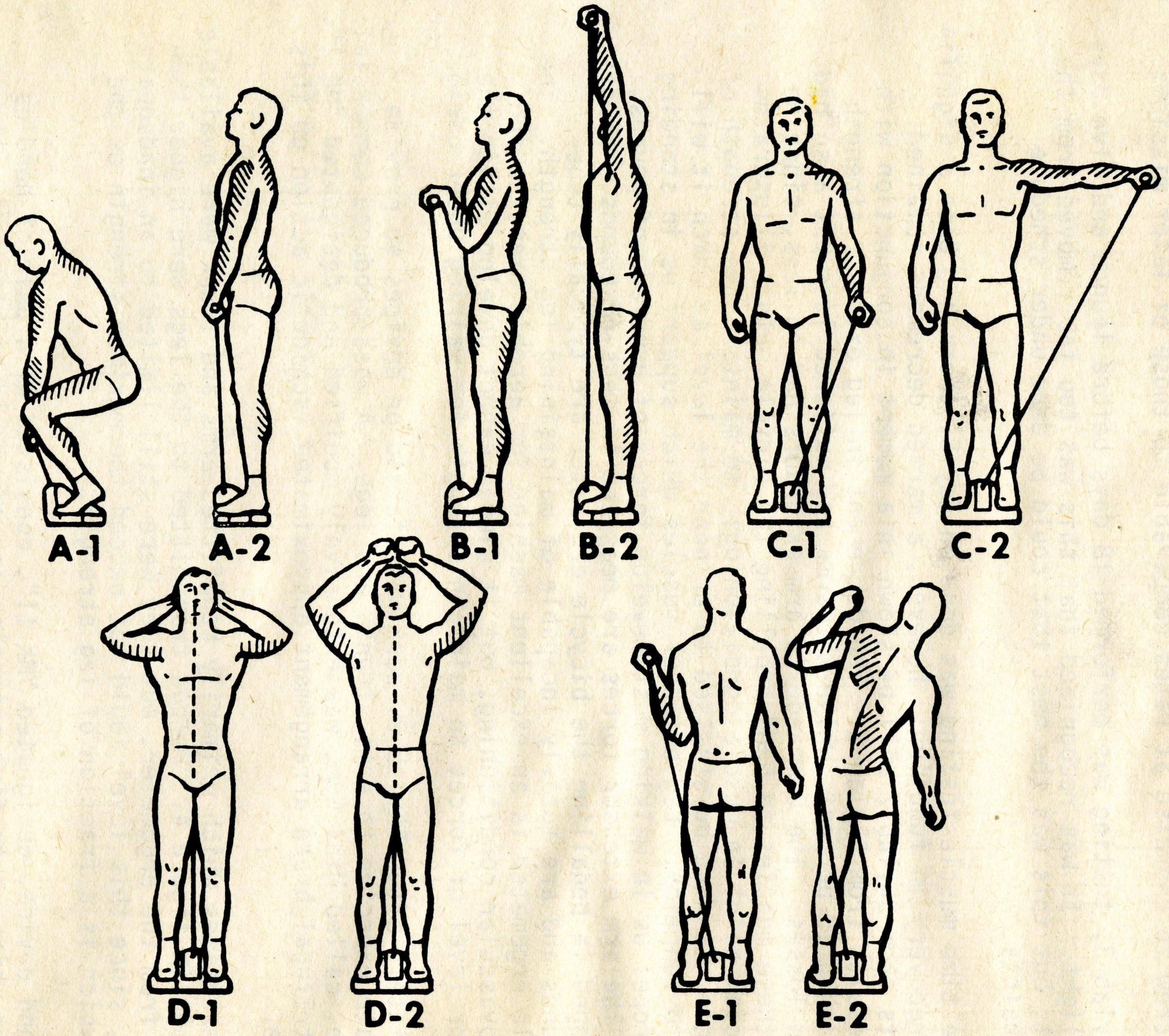


Figure 4. MK I exerciser positions.

These two devices were flown on Skylab 3, and food and time for exercise was increased in-flight. The crew performed many repetitions per day of their favorite maneuvers on the "MK I" and to a lesser extent, the "MK II". Also, the average amount of work done on the bicycle ergometer was more than doubled on Skylab 3 with all crewmen participating actively.

Results of muscle testing of Skylab 3 crewmen demonstrated marked differences from the Skylab 2 crew.

Looking at changes in arm forces on Skylab 3, one sees complete preservation of flexor function in contrast to Skylab 2 (fig. 5). The Scientist Pilot showed a marked gain in arm strength. This is the result of putting a good distance runner, which Owen is, on the equivalent of a weightlifting program.

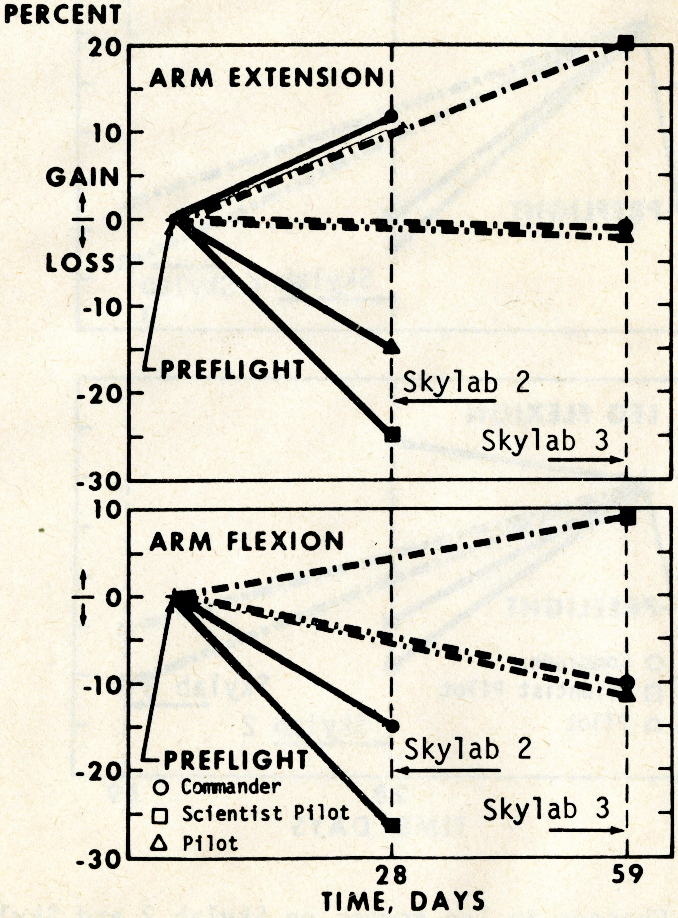


Figure 5. Changes in arm forces on Skylab 2 and Skylab 3.

Looking now at leg function in figure 6, we see a different picture. Only two Skylab 3 crewmen are shown since the Commander suffered a recurrence of a back strain from a lurch resulting from a roll of the recovery ship - possibly another demonstration of the hazard of muscle deconditioning.

Although there is a relative improvement or less loss over Skylab 2, there nevertheless remains a significant reduction in muscle strength. It seems rather obvious that the "MK I" and "MK II" exercise devices did a good job in arm preservation but were still inadequate to maintain leg function.

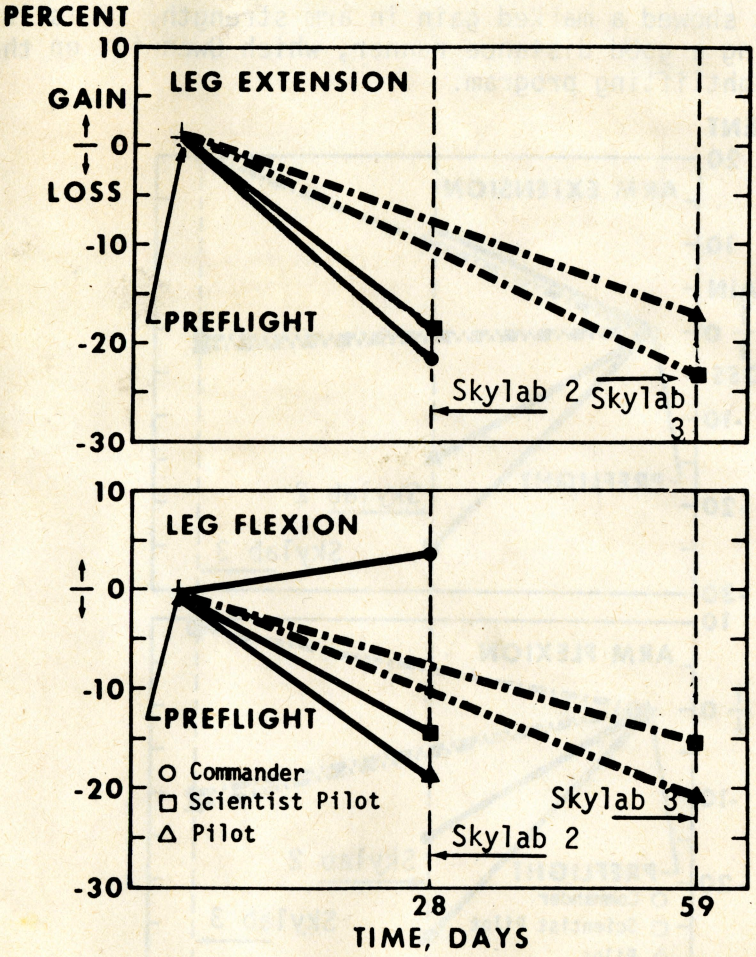


Figure 6. Changes in leg forces on Skylab 2 and Skylab 3.

Some device which allowed walking and running under forces equivalent to gravity appeared to be the ideal answer to this problem. This had long been recognized and immediately after Skylab 2, work was started on a treadmill for Skylab 4. As the mission progressed, launch weight of Skylab 4 became crucial such that the final design was simulation of a treadmill in response to the weight constraints. The final weight for the device was 3-1/2 pounds.

The treadmill, shown in figure 7, consisted of an aluminum Teflon® walking surface attached to the iso-grid floor. Four rubber bungees providing an equivalent weight of 175 pounds (80 kg) were attached to a shoulder and waist harness. By angling the bungees, an equivalent to a slippery hill is presented to the subject who must climb it. High loads were placed on some leg muscles, especially in the calf, and fatigue was rapid such that the device could not be used for significant aerobic work.

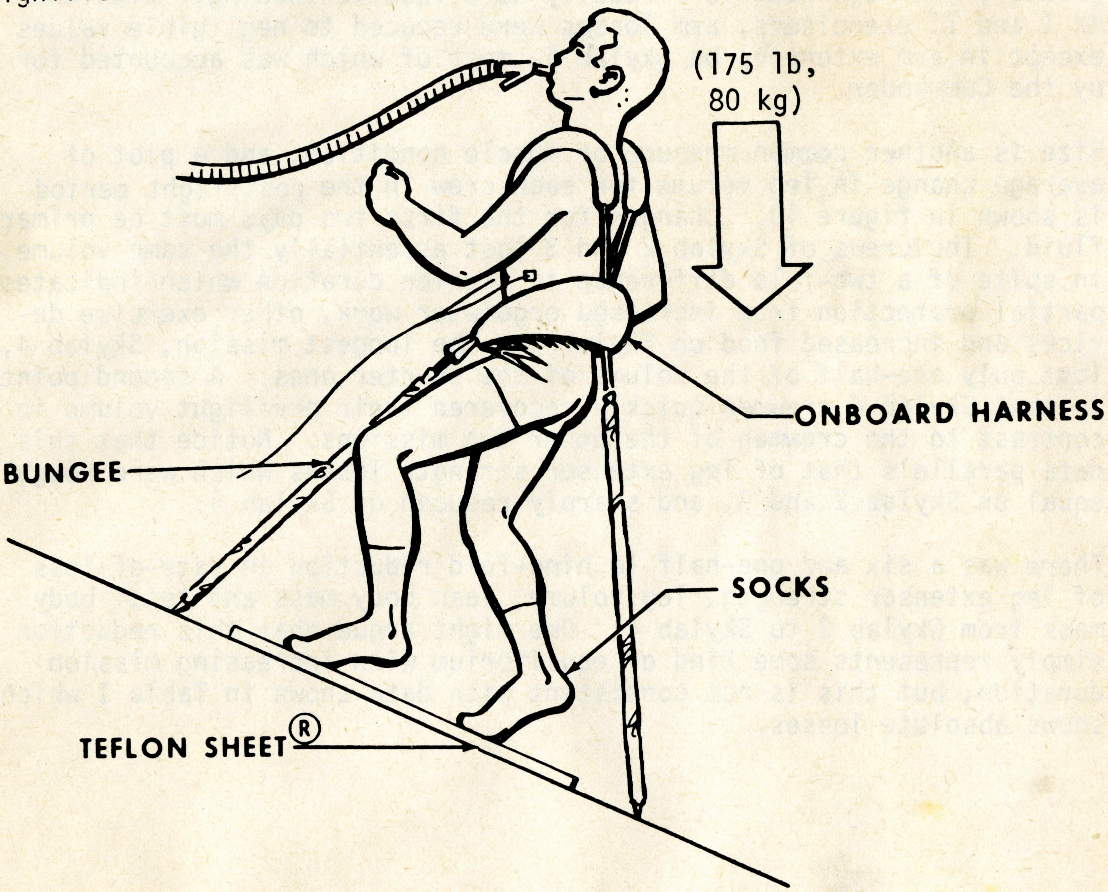


Figure 7. Treadmill arrangement.

On Skylab 4, the crew used the bicycle ergometer at essentially the same rate as Skylab 3, and the MK I and II exercisers. In addition, they typically performed ten minutes per day of walking, jumping, and jogging on the treadmill. Food intake had again been increased.

Even prior to muscle testing, it was obvious that the Skylab 4 crew was in surprisingly good condition. They stood and walked for long periods without apparent difficulty on the day after recovery in contrast to the earlier missions. Results of the testing confirmed a surprisingly small loss in leg strength after almost three months in weightlessness. A summary of the exercise and strength testing shown in averaged values for the three missions is depicted in figures 8 and 9. One point to be noted is the relatively small losses in arms as compared to legs in all missions. This is reasonable for in space ordinary work provides loads for the arms that are relatively much greater; the legs receive virtually no effective loading. With the MK I and II exercisers, arm losses were reduced to negligible values except in arm extensors on Skylab 4, most of which was accounted for by the Commander.

Size is another common measure of muscle condition, and a plot of average change in leg volume for each crew in the postflight period is shown in figure 10. Changes for the first two days must be primarily fluid. The crews of Skylab 2 and 3 lost essentially the same volume in spite of a two-fold difference in mission duration which indicates partial protection from increased ergometer work, other exercise devices and increased food on Skylab 3. The longest mission, Skylab 4, lost only one-half of the volume of the shorter ones. A second point is that Skylab 4 crewmen quickly recovered their preflight volume in contrast to the crewmen of the other two missions. Notice that this data parallels that of leg extensor strength losses which were roughly equal on Skylab 2 and 3, and sharply reduced on Skylab 4.

There was a six and one-half to nine-fold reduction in rate-of-loss of leg extensor strength, leg volume, lean body mass and total body mass from Skylab 2 to Skylab 4. One might argue that this reduction simply represents some kind of equilibrium with increasing mission duration, but this is not consistent with data shown in Table I which shows absolute losses.

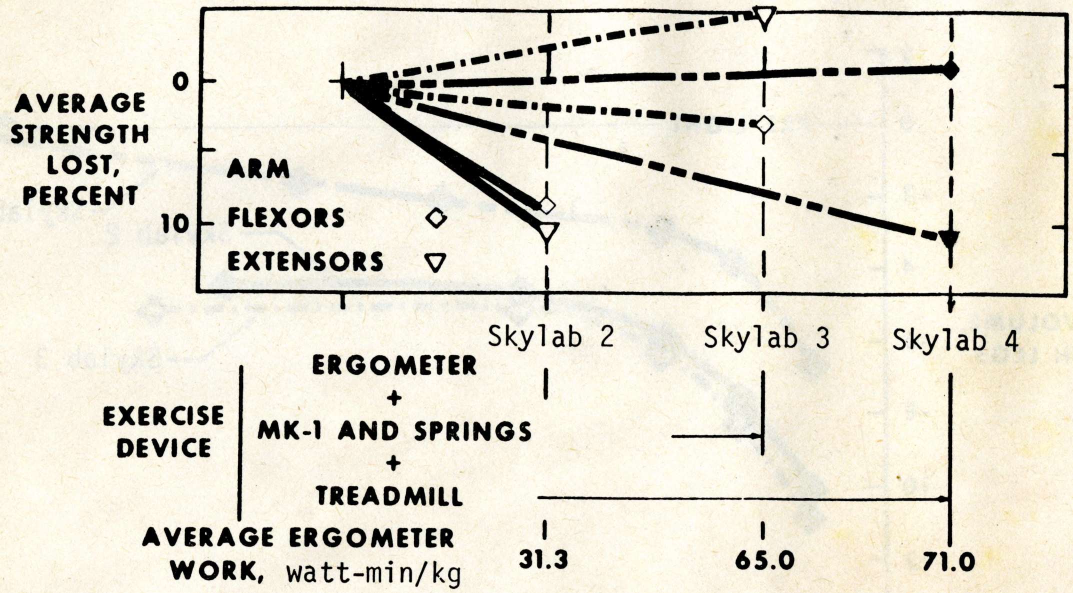


Figure 8. Average strength changes, arm.

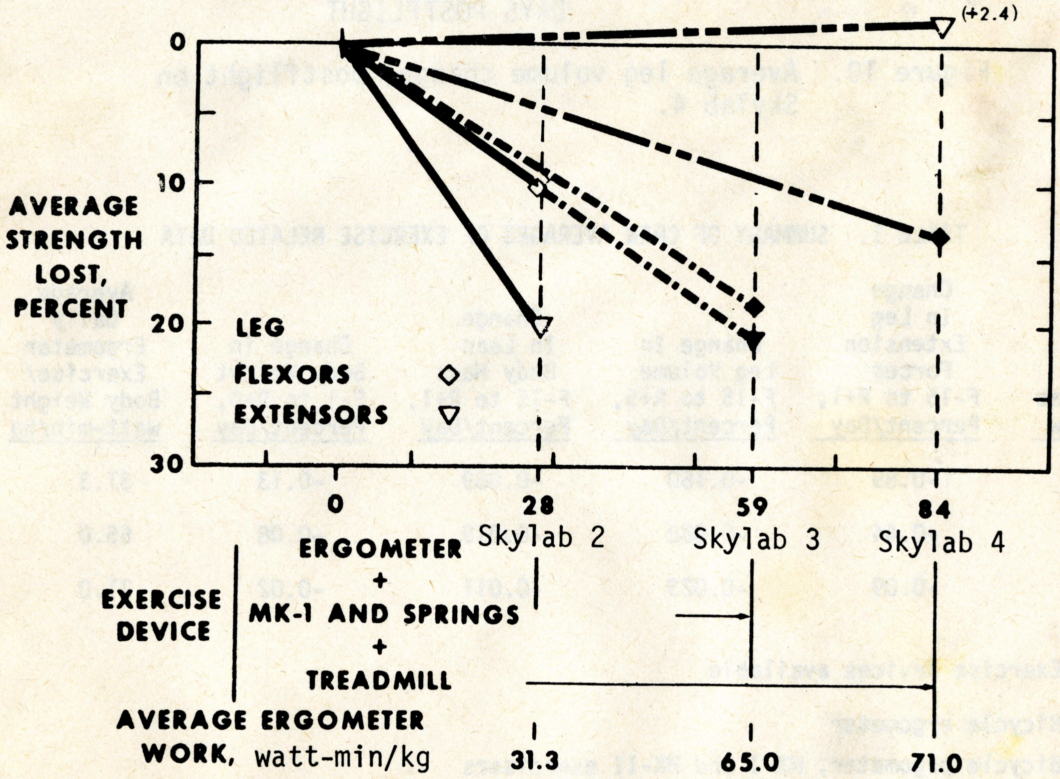


Figure 9. Average strength changes, leg.

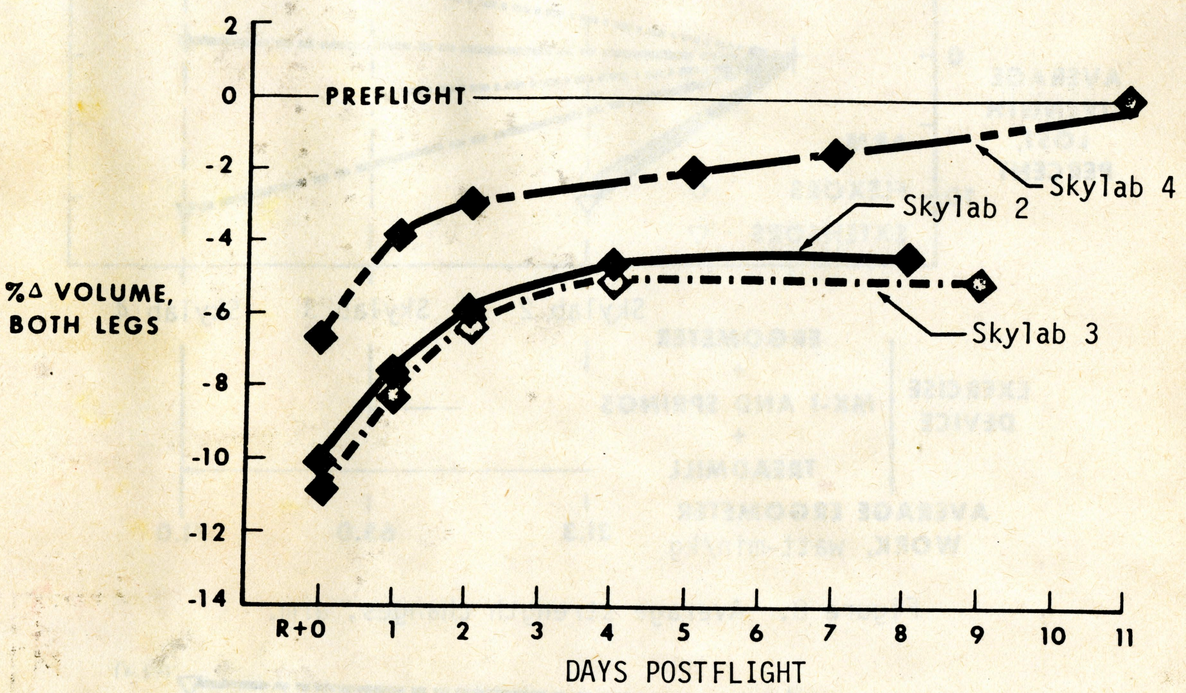


Figure 10. Average leg volume change, postflight on Skylab 4.

TABLE I. SUMMARY OF CREW AVERAGES OF EXERCISE RELATED DATA

Skylab Crew	Change In Leg Extension Forces F-15 to R+1, Percent/Day	Change In Leg Volume F-15 to R+5, Percent/Day	Change In Lean Body Mass F-15 to R+1, Percent/Day	Change in Body Weight F-1 to R+0, Percent/Day	Average Daily Ergometer Exercise/ Body Weight watt-min/kg
*2	-0.89	-0.160	-0.089	-0.13	31.3
†3	-0.44	-0.088	-0.019	-0.08	65.0
‡4	-0.09	-0.023	-0.011	-0.02	71.0

Exercise devices available

*Bicycle ergometer

†Bicycle ergometer, MK-I and MK-II exercisers

‡Bicycle ergometer, MK-I and MK-II exercisers, treadmill

As shown in figure 11, Skylab 4 shows again a marked improvement as regards weight, leg strength and leg volume. I think I am correct in attributing these reductions in loss of muscle strength and bulk to the exercise devices and exercise time that were added. There can be little doubt that adding the MK I and II improved the arm performance of the crewmen on Skylab 2 and 3; and equally little doubt that the treadmill sharply reduced loss of leg strength and mass, since there was negligible increase in leg exercise with other devices on Skylab 4.

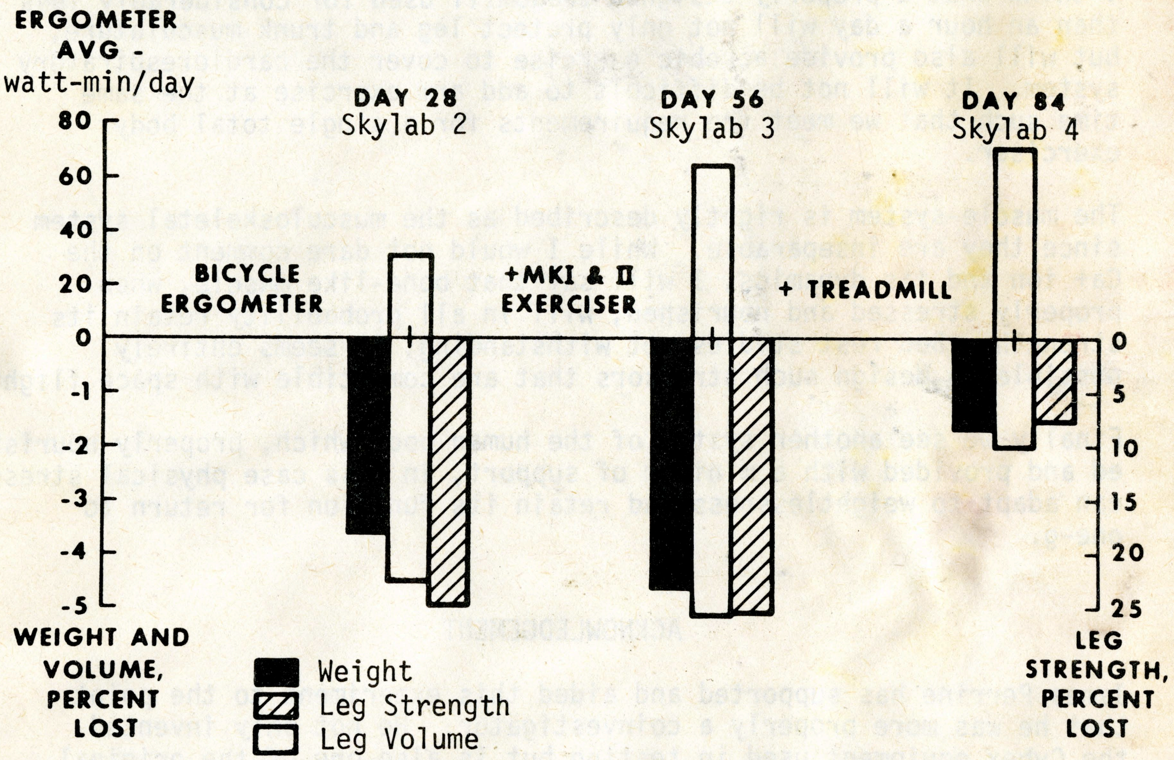


Figure 11. Exercise related quantities on Skylab missions.

However, it must be recognized that another variable was present - food. Virtually all the nutritionists that I know recognize that metabolic losses in normal subjects are mixed, *i.e.*, both fat and muscle are lost. Vanderveen and Allen[1] deliberately reduced caloric intake during a one-g chamber test simulation of space flight conditions using subjects chosen to be as equivalent as possible to the astronaut population. They found an almost pure muscle loss.

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[1]Vanderveen, J. E. and T. H. Allen. 1972. Energy Requirements of Man Living In a Weightless Environment. COSPAR, Life Sciences and Space Research X - AKADEMIE-VERLAG-BERLIN.

At this time, I cannot escape the conclusion that muscle in space is no different from muscle on Earth, if it is properly nourished and exercised at reasonable load levels, it will maintain its function.

I think that a properly designed treadmill used for considerably less than an hour a day will not only protect leg and trunk musculature, but will also provide aerobic exercise to cover the cardiorespiratory system. It will not be difficult to add arm exercise at the same time such that we meet the requirements for a single total body exerciser.

The muscle-system is rightly described as the musculoskeletal system since they are inseparable. While I would not dare comment on the Ca+ ion and its dynamics, I will say that bone-like muscle, when properly stressed and nourished, will in all probability retain its strength. Bed rest studies not withstanding, it seems entirely possible to design such stressors that are compatible with space flight.

Finally we see another system of the human body which, properly nourished and provided with a minimum of support, in this case physical stress, can adapt to weightlessness and retain its function for return to one-g.

ACKNOWLEDGEMENT

James Perrine has supported and aided this experiment to the point that he was more properly a coinvestigator. He not only invented the Cybex equipment used in testing but is also one of the original thinkers in muscle physiology and testing. Roger Nelson provided the original equipment for testing and his brother, Arthur, gave much useful aid in development of electromyography testing to be used in conjuction with the muscle test. The latter effort was aborted by unfortunate events. Jim Evans constructed the integrator and aided in instrumentation work. C. A. Samaniego aided in the testing process and Dave Hilaray of Lumex provided outstanding technical support of the Cybex gear.

Development of the treadmill was a combined effort with Bill Huber and his group and was aided by support of John Stonesifer, and the Skylab 4 crew, especially Bill Pogue.