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MEASUREMENT AND PREVENTION OF MUSCLE DECONDITIONING ON SKYLAB

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Man's body is adapted to living under the constant large forces of gravity such that a major portion of it is dedicated to locomotion under and counteraction of these forces. The majority of the body's voluntary muscle as some of its supporting systems are dedicated to this function. Muscle requirements are the driving forces for the cardiovascular and respiratory system and determine their capacity and condition. Under weightlessness the requirements for much of the body's 1-G capacity and function simply disappears. Such reduction in muscle function reduces cardiovascular requirements. The net result is disuse of much of the body's musculoskeletal system and cardio-respiratory capacity such that atrophy must occur. At this point in time, this same body when returned to Earth must not only be capable of immediately withstanding gravitational forces but is also scrutinized medically on the basis of a preflight physical condition which is normally the best which the individual could achieve.

Thus a major aspect of any comprehensive medical investigation of the effects of weightlessness must include examination of changes in muscle size and function. Further, if the crew is expected to function under 1-G after a long stay in weightlessness, then suitable exercise in flight must assume the same level of importance as diet and other primary life support considerations.

On relatively short missions, say 10-15 days, the effects of deconditioning can be accepted and this was done until Skylab. No direct measurements of muscle function were made on Mercury, Gemini, or Apollo except for a static force measurement of hand grip[1]. In-flight exercise devices were limited to isometrics and a bungee with handles on Gemini[2], and a commercial rope and capstan arrangement on Apollo, but neither were extensively used nor was the effectiveness of their usage in prevention of muscle deconditioning documented.

The Russians are reported to have made extensive preflight and postflight muscle functions measurements and to have performed extensive in-flight exercise on Soyuz,[3] but results are unknown to this author.

A minimum impact, preflight and postflight, muscle function test was implemented for Skylab. Additional corollary information on muscle status was derived from anthropometric measurements and from isotopic body[4] compartment measurements. As a result of these and other studies and of crew inputs, exercise devices and time for exercise were added to Skylab 3 and Skylab 4.

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[1]

[2]Dietlein, L. F., Gemini Midprogram Conference, NASA SP-121, pp. 393.

[3]Kakurin, L. I., Medical Research Performed on the Flight Program of the Soyuz Type Spacecraft, NASA TTF-14, 026.

[4]

Muscle function measurements were obtained by an isokinetic dynamometer[5] at a rate of 45°/sec. Ten maximum effort full flexions and extensions of the dominant arm (elbow) and leg (knee/hip), see figure 1, were made and the resulting forces continuously recorded on one channel of a Brush ink-writing oscillograph. An integral of the force[6] was derived and recorded on the second channel (see figure 2). Care was taken to insure that elbow and shoulder remained on the table to prevent additional forces from shoulder rotation. The machine arm length was adjusted to equal the subject's arm (elbow to palm) length. In the flexions and extensions of the right hip and knee, machine arm length was set such that the lower leg was at right angles to the thigh when the thigh was in a vertical position. Thorough warm-up was made prior to all testing.

Preflight and postflight calibration was added to each crew record by placing known weights on the handle and allowing them to fall, under gravity, from top to bottom dead center using the same rate and arm length as used for the crew record. All forces are recorded in terms of the calibration force, i.e., the force applied to the dynamometer handle or "shoe".

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[5]Cybex I on Skylab 2 and Cybex II on Skylab 3-4, mfg. by Lumex Corp., Long Island, NY.

[6]At a constant speed this integral of force is work.

These measurements were made at the times shown in table 1.

Prime Crew	Preflight	Postflight
SL-2	F-18	R+5
SL-3	F-31 F-21	R+1 9
SL-4	F-35 21 10	R+1 5 31

This method seems to be the best strength measurement available. At the speeds used it is comparable[7] to the widely used static strength testing found in the literature[8,9] while still allowing the maximum forces to be measured over the full range of motion in a few seconds

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[7]Instantaneous forces of a slowly moving limb are a few percent higher than the maximum isometric force at the same limb angles (muscle length). There is a widely held misconception based on studies of excised muscle tissue, and until recently shared by the author, that maximum forces were an inverse function of the speed of the muscle contraction. In fact, maximum forces, as recorded are virtually constant over the whole range of the contraction until some limiting velocity is reached after which the force is an inverse function.

[8]Clarke, H. H., Muscular Strength and Endurance in Man, Prentice Hall, 1966.

[9]Physical Fitness Research Digest, Series 4 No. 1, Jan. 1974. President's Council on Physical Fitness and Sports.

Also, fatigue decrements in muscle strength can be measured after a few cycles rather than after many cycles when conventional, fixed, submaximal load dynamometers are used. Further, repetitive maximum efforts help insure that a valid sampling has been made.

A large number of calibration and control records were made to characterize performance of the machine and further demonstrate the validity of the test itself. The following statements summarize the results derived from these tests. Linearity of machine response was usually within a few percent over the calibrated range and any deviation was further reduced by using the calibration figure nearest the measurement of interest. Speed control was constant within a few percent. No asymmetry in accuracy of measurement during rotation vs. counter rotation, e.g., flexion vs. extension, could be detected. Machine response speed was much higher than any measurement of interest.

While machine errors were probably plus or minus two to three percent, there were many potentially large errors from the nature of the measurement. Since this method is absolutely dependent upon voluntary effort, the first and primary question concerns the integrity of this effort. In the Skylab crews, integrity of effort is probably as high as can be obtained. In cases where fear of exacerbating an old injury or some similar cause prevents such maximum effort, the disability is usually reported and always obvious from the total record. Such runs are eliminated or run on the opposite side of the body, if possible.

There is a tendency to think of muscle strength and endurance as something static or slowly changing in response to marked changes in exercise or work habits. This proves not to be the case. This measurement is very sensitive to changes in muscular performance which may occur in days.

For example, when one attempts to examine the repeatability of this test by performing it daily, there is a rapid and significant training effect from the test itself unless the subject is already maximally trained. It cannot be overemphasized that we are not measuring isolated muscle forces here, but rather the resultant forces from a complex servomechanism with very large amounts of negative feedback (inhibition) from the autonomic nervous system.

After the results of Skylab 2 there was a continuing effort to improve the effectiveness of exercise available in flight. These changes had profound effects on the test results and must be considered in their analysis.

Skylab 1/2 had only the bicycle ergometer (theoretically capable of loads to 300 watt min and equipped with a hand crank option) and "Exergenies" (a rope and capstan arrangement capable of providing high forces though unpopular to use). Except in the case of the CDR, who exercised for appreciable lengths of time, both the amount and type of exercise was inadequate on Skylab 1/2.

On Skylab 3, two additional exercise devices were added. One was an extensively modified mass-produced commercial device[10] designated MK I (figure 4). It consisted of a rope and a pulley with a rewind mechanism coupled to a centrifugal brake assembly which produced large resisting forces once a variable limiting speed was reached, i.e., a rough approximation of isokinetics. The other device was the MK II, a set of extensor springs and handles (figure 5). All of the crewmen exercised vigorously on the ergometer and with added arm exercises, primarily with the MK I exercise device.

An approximation of a treadmill was added to Skylab 4 (figure 6). It consisted of a Teflon "walking" surace and a waist belt and shoulder harness which, coupled to elastic bungees, provided an equivalent downward force weight of approximately 175 pounds.

The crew on Skylab 4 used the bicycle ergometer and arm exercisers at about the same level as the Skylab 3 crew but added the treadmill each day to the fatigue limit, typically 10 or 11 minutes.

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[10]Mini-Gym, Inc., Ind., MO

Amounts of in-flight exercise are shown in table II & III.

Table II (See figures 4 & 5 for legend)

Average Number of Repetitions Per Day

	MK I Exerciser					MK II Exerciser						
	A	B	C	D	E	A	B	C	D	E	F	G
SL 1/3 C*	12.9	4.0	3.9	3.9	---	3.1	1.7	1.4	.3	0	.8	3.5
*Performed an additional 6.6 mins/day on exercises												
SL 1/3 S	43.2	35.3	25.3	0	0	0	0	0	0	0	0	0
SL 1/2 P	35.8	14.1	0	13.7	0	0	0	0	0	0	0	0
SL 1/4 C	30.5	15.3	0	14.3	15.8	0	0	14.5	14.4	7.4	14.4	0
Sl 1/4 S	7.4	67.1	57.6	.4	2.1	0	2.4	2.4	0	0	0	0
SL 1/4 P	38.8	38.7	0	38.1	38.7	0	18.8	18.8	18.8	18.8	18.8	18.8

Analysis and Interpretation

The quantity of data contained in the records plus the number obtained make anything more than preliminary cursory analysis impossible at this time.

Peak force of each flexion and extension cycle is taken as representative of forces throughout the cycle. There is a good theoretical basis for this with the arm muscle recordings which are primarily forces of the biceps and triceps brachii. Some question might be raised over the validity of doing this with the leg where a number of muscles participate in the action measured; however, cursory examination of the records shows the peak force to be representative of all forces throughout the range of motion. A plot of such maximum forces for a preflight and postflight study from the Skylab 3 mission is shown in figure 3. The average of the 10 peaks is taken as the "strength" for that test. These figures of strength in terms of the peak force in pounds applied to the handle or shoe are then plotted for each function in figures 7 and 8. It is impossible to interpret the results of these tests without a knowledge of the types and amount of exercise performed and equally important, the habits and habitus of the individual must be known.

On Skylab 2 the CDR lost some 30 pounds in preflight conditioning and launched in excellent condition and continued a moderately vigorous use of the bicycle ergometer in flight, including using the hand pedal mode. In addition, he consumed large quantities of "free calories"[11] and conserved weight. In spite of this he suffered large losses in leg mass and strength, especially extensor (see figures 7 and 8). His arm extensor functions were protected by hand pedalling the ergometer. His crewmates launched in good condition but exercised much less and ate relatively less and lost more weight. Postflight there was marked loss in strength in all segments except the CDR's arm extensors used in hand pedalling the ergometer.

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[11]Foods without other nutritional value which were allowed in addition to the basal diet.

Exercise time was increased and exercises added for Skylab 3. The CDR was in good condition, and the SPT and PLT in excellent condition[12]. Exercise time and variety was greatly increased by all crewmen, but the exercises were still recognized as being inadequate for trunk and legs. This was reflected postflight by the excellent preservation of arm function with reduced rate loss of leg muscle mass and strength but with a deficit on the order of 20 percent. Shortly after recovery the CDR suffered a severe low back strain from a lurch of the ship and thereby prevented leg measurements but probably demonstrated a hazard of loss of back muscle function.

The Skylab 4 CDR was in good condition preflight while the PLT had lost some 30+ pounds and was in excellent condition. The SPT, an excellent athelete, elected not to reach his peak prior to launch but was in good to excellent condition. In flight all crewmen worked as hard as the previous crew on the existing exercises as well as spending 10-11 minutes/day on the treadmill in heavily loaded leg exercises. This was immediately obvious postflight in the crew's ability to walk and stand as well as from strength measurements.

A summary of the three missions is made in figure 9 in which the averages for all crewmen are plotted. A glance at the charts shows the relative losses between arm and leg. This is not surprising since maximum forces developed by the arm are (1) much less and (2) the arms

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[12]Excellent condition implies at level of trained distance runner with minimal body fat.

are used far more in flight not only for manipulation but also for body positioning and locomotion. Effects of adding the arm exercise devices to Skylab 3 and 4 are clearly shown (losses in arm extensor force on Skylab 4 was largely in one man). In short, the loss of arm forces is slight, of relatively little significance, and can be easily prevented. Conversely, the loss of large masses and forces from the legs cannot be tolerated. Also, it cannot be prevented by large amounts of exercise at low force levels. Relatively short durations of heavy loading can prevent losses as shown by Skylab 4.

Another source of ancillary data is the various anthropometric measurements. There has not been time to analyze these data comprehensively. The calculated cross section area of midcalf derived from M-092 measurements is shown in table III, together with the amounts and type of exercise and leg extensor strength decrements. These calf area measurements are complicated by the metabolic losses suffered by all crews since the great majority of authorities in the field recognize that metabolic losses are mixed, i.e., both fat and muscle are lost.

Also tabulated in table III are daily average amounts of ergometry exercise and daily average weight loss. Although these "averages" are based on samples much too small for statistical validity, they nevertheless correlate well with the strength observations.

Both leg and arm strength, and midcalf cross section area[13] losses were large in Skylab 1/2. On Skylab 3 there was a sharp drop in arm losses with appreciable losses in strength and cross section remaining. The improvement in arm performance can be reasonably attributed to the added arm exercise devices used while the decreased rate of leg atrophy could be decreased fat or muscle loss, but these losses are, in Skylab 3, proportionally less than observed weight losses. Increased exercise time and some loading of legs by the arm exercises performed undoubtedly made the difference in strength and probably also in atrophy. On Skylab 4 arm losses are little changed, but both the atrophy and the strength losses of the leg are sharply reduced; the reasonable explanation is the protection afforded by the treadmill.

The muscle studies on Skylab corroborated what has been fairly well established by previous Earth based studies: namely,

- Disuse atrophy occurs rapidly and results not only in loss of strength and endurance but also loss of muscle tissue.

- Muscles require stresses near or at their maximum tension levels to be able to maintain their level of strength and muscle mass, i.e., many repetitions at a fraction of the maximum forces will not maintain muscle strength and mass.

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[13]Measured at R+5 days to allow for complete body fluid redistributions.

• Relatively few repetitions near the muscle's maximum strength are required to maintain its condition.

• No one aspect of body conditioning can be emphasized without cost to the body's overall function, i.e., cardiovascular conditioning must be accompanied by general muscular conditioning and conversely, if ability to function under one-g is to be retained after return from zero-g.

• Joint and skeletal functions are intimately related to muscle tone and condition.

To plan a logical course for the future, the main effort should be directed toward further investigations. Some of the priority areas of concern are:

• To determine losses of muscle mass and muscle function under conditions of weightlessness and the relationship of this skeletal muscle loss to cardiovascular condition and to diet.? Only two of the Skylab 1/2 crewmen were virtually unprotected from muscular deconditioning and only the Skylab 4 CDR suffered no weight loss. This implies a need for controlled study with preflight, postflight, and possibly in-flight measurements.

• To improve measurement techniques of muscle and associated systems. A muscle itself is not measured, but rather the force from the muscle whose potential maximum force is greatly reduced by a complex neural feedback is the measurement technique used in the Skylab program at the current state of the art. New techniques are under study which may allow a nearer approach to a "pure" muscle measurement. At the same time, the associated nervous system should be investigated by EMG, stimulation and transmission time studies and more attention given to coordinated muscular performance. For example, simple semiquantitative ciné pictures of the crewman's gait preflight and postflight would have been of great value.

• To understand interrelationships of the muscle system to other conditioning and deconditioning factors affecting other systems, i.e., the cardiovascular system. For example, it appears that the condition of leg muscles is associated with orthostatic hypotension. Studies of vascular compliance of the leg should be related to muscle condition also.

• To develop more efficient forms of exercise. These are dependent on exercise devices and, thus, are a hardware problem. But, unlike most previous efforts, the hardware development must be directed by the physiological requirements. It must truly be a "total body" device that stimulates or stresses the following functions.

a. Produce aerobic energy costs which may be continued for appreciable periods of time to insure cardiovascular conditioning.

b. Provide realistic loads for as many of the muscle groups of the body as possible, but especially leg and trunk muscles. Use of this device should also retain typical coordinated movements such as walking or jogging to maintain such coordination.

It may also be desirable to:

c. Provide lower body negative pressure or provide some other method of forcing appreciable quantities of blood into the lower extremities separately or in combination with the two functions mentioned in steps a. and b. (see leg hemodynamics, sec. 2.17).

In addition, this exercise device should meet the following operational requirements: be as light and small as possible, especially for stowage; be independent of spacecraft systems, i.e., a passive device if possible; be quantitative; and be safe.

Although these studies were constrained by the small number of samples, especially on Skylab 1/2, by variations in flight protocols and diets which resulted in significant weight losses and although exercise protocol and devices were crude and protection incomplete, a number of conclusions seem evident. These can be summarized simply by the statement: if man is provided a certain minimal amount and type of diet and exercise, both of which can be realized in practical spaceflight, his musculoskeletal system appears to be capable of sustaining spaceflights of any length practicable at this time.