The Influence of Specific Exercises in the Prevention of Debilitating Musculoskeletal Disorders; Implication in Physiological Conditioning for Prolonged Weightlessness

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THE IMPORTANCE of regular activity and exercise to normal body function is generally conceded. Normal osteoblastic capacity depends to a large measure upon the stresses of muscular contractions and weight-bearing compression forces.[17, 23, 41, 44, 47] The loss of these stimuli results in insufficient formation of bone matrix, inadequate deposition of calcium salts, and increased porosity of bone. The softened bone loses its strength and resiliency and is subject to pathological fractures. The maintenance of the healthy trophic state of striated muscle also requires the stimulus of gravitational stress and activity.[15, 27, 32, 37, 39, 40, 46] Elimination of these factors produces hypotonicity and wasting of muscle.

Good muscular tone and power to contract fully and rapidly are essential to the security of the body joints. Weak muscles directly limit normal joint function and interfere with nutrition because of the circulatory deficiency imposed by the loss of "pumping" action.[17, 24, 39, 43] Stresses applied to a joint which are not countered efficiently because of wasted muscles cause synovial irritation and effusion of fluids. Joints acted upon by weak muscles for prolonged periods undergo serious damage to the cartilages and subsequent deterioration.

BACKGROUND

The undesirable metabolic and physiological effects of lengthy confinement and inactivity on the musculoskeletal system are well documented. Clinical observations and experimental studies have demonstrated that muscle atrophy and bone demineralization readily occur under these circumstances.[1, 7, 9, 12, 17, 23, 41] The detrimental effects of enforced bed rest in regard to convalescing patients has been the subject of many clinical studies since the second world war.[2, 6, 14, 25, 29, 31, 34, 36, 42, 43, 45] General reconditioning exercises and early ambulation have proven of value in the prevention of complications and the more rapid recovery of these cases. The merit of instituting a series of appropriate active exercises for the bedridden orthopaedic patient in plaster casts or traction apparatus in order to prevent irrecoverable muscle atrophy, joint stiffness, and circulatory disorders, is universally accepted.

These observations have stimulated further studies on normal subjects in order to differentiate derangements initiated by inactivity on sick patients and healthy persons. The inactivity experiments have been conducted with variable periods of bed rest, plaster immobilization, and water submersion.[4, 5, 18, 19, 20, 21, 22] Deitrick et al,[12, 13] in 1948, reported a now classical study on the quantitative metabolic and physiological effects of plaster immobilization on four healthy male subjects. A marked decrease in muscle mass and strength of the immobilized extremities was observed over the six week period. There were significant decreases in metabolic rate, nitrogen content, and bone calcium. The recovery of metabolic functions was slow, requiring about six weeks for restabilization of calcium metabolism. Recovery of exercise tolerance and leg girth required four to six weeks.

Whedon et al,[49] in 1949, reported the use of passive exercise by means of an oscillating bed on three normal male subjects immobilized in plaster casts. Impairment of the cardiovascular postural mechanism was largely prevented and metabolic abnormalities were reduced by approximately one-half as compared to Deitrick's experiment.

In 1960 and 1961, Graybiel and Clark[21, 22] reported the results of water submersion tests. Their subjects were exposed to water ten hours daily for two weeks. The remainder of the time was spent at bed rest. Although marked postural hypotension developed during and following the period of immersion, no decrements in muscular strength and coordination occurred.

The confinement of normal humans to prolonged recumbency and inactivity by bed rest does not exactly simulate the unique state of weightlessness, but a fair approximation is made from the musculoskeletal standpoint. Consequently similar debilitating musculoskeletal effects might be anticipated as a result of long term exposure to a subgravity or a weightless situation

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in which the energy requirements of the body musculature are considerably diminished, such as a journey to the attenuated gravitational environment of the Moon (0.17 G) or Mars (0.38 G).[8, 28, 33, 48]

Actually there is a dirth of knowledge concerning the minimal threshold of exercise necessary to maintain muscle and bone integrity in the healthy individual.[28, 35] A requirement does exist for an optimum exercise method to assure normal muscle tone and bone strength when normal activity is not possible.

PURPOSE AND PLAN

This project was an effort to determine the type, frequency, and duration of exercises required to maintain the healthy state of the musculoskeletal system in a group of thirty normal human subjects confined to a sixty day period of varying activity and bed rest. The project was a clinical study which utilized professional personnel and existing facilities of the Wilford Hall USAF Hospital, San Antonio, Texas. No provision was made for research funds or additional support.

The investigation was designed to include laboratory, physiological, and x-ray studies. Exact metabolic balance studies could not be accomplished because of limited capability in the collection, preparation, and analysis of the specimens for thirty subjects. The environment, diet, activity, and health of the participants were strictly controlled. All participants were secluded in an isolated open bay ward of the hospital in which ultraviolet light was blacked out (Fig. 1). The area was under close supervision twenty-four hours daily and restricted to only those personnel directly concerned with the project. Standard recreational and diversional activities such as radio, television, movies, books, handicraft projects, and games were available.

Fig. 1. Project "Strong Bones" volunteer subjects in secluded and blacked out open bay ward of Wilford Hall USAF Hospital.

All subjects were given the same 2300 calorie diet which included a daily average of 1.25 grams of calcium (Table I). Meals were served three times daily. Upon completion of the sixty-day bed rest period, the subjects were allowed resumption of normal activities and were carefully observed for the first ten days after which they were given a thirty day convalescent leave. A final evaluation was made upon return from leave status.

SELECTION OF SUBJECTS

The thirty participants were selected from a pool of seventy-five healthy and single male volunteer airmen between the ages of eighteen and twenty-two years. The airmen had just finished a six-week period of basic military training during which they had all been restricted to the base and subjected to the same dietary and conditioning regimen. A thorough baseline physical examination was given and all selectees were found in peak physical condition. Selection was also made on the basis of a psychological evaluation for emotional stability and motivation. The inducement of a thirty day leave following completion of the study was no doubt a significant motivation factor.

EXERCISES AND CATEGORIES

Specific exercise routines were programmed for the bed rest period. The types of controlled exercises were the following:

1. 5 BX Plan. The official USAF physical fitness program in which all subjects had participated during the basic training period. These were basic active exercises of the calisthenic type.
2. Isotonic Exercise. The shortening of a muscle group during contraction against a movable load in which a portion of the liberated energy is converted to work. The resistance was either the weight of the body or the applied weight of a metal object.
3. Isometric Exercise. The length of the muscle group remains essentially the same during contraction against a fixed resistance and a portion of the liberated energy is converted to tension. This exercise employed the resistance of the antagonist muscle contracting against its prime mover or the resistance of the bed. (Figs. 2A-F).

In order to make comparisons, the thirty men were divided into five categories of six subjects each and the varied activity was precisely defined (Table II). A responsible leader was selected for each category and this gave impetus to performance.

Category I. Subjects were restricted to the ward but

TABLE I

DIETARY INTAKE		(DAILY AVERAGE)		
CALORIES	PROTEIN (Gm.)	FAT (Gm.)	CARBOHYDRATE (Gm.)	CALCIUM (Gm.)
2,300	106	100	250	1.25

TABLE II

CATEGORIES AND EXERCISES

Category I:	Normal activity on isolated ward. Performed 5 BX twice daily (11 minute periods).
Category II:	Bed rest and isotonic exercises with weights.
Category III:	Bed rest and isotonic exercises without weights.
Category IV:	Bed rest and isometric (or dynamic tension) exercises.
Category V:	Bed rest and no exercise routine. Movements limited to turning, sitting, eating, washing, handwork, and bed pan.

NOTE: Isotonic and isometric exercises done for ten minute periods either 2, 4, or 6 times daily.

allowed normal activity and used as a work detail in the area. Chart 4 of the 5 BX Plan was instituted twice daily for eleven minute periods. This was the control group.

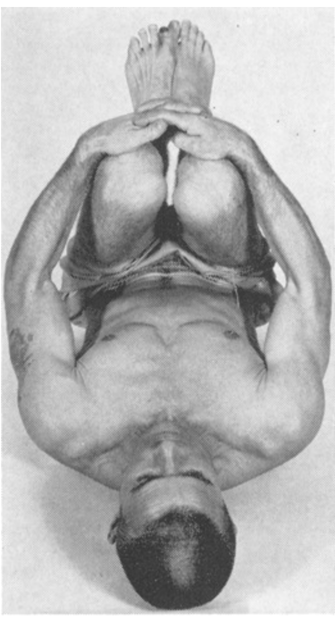
Category II. Subjects were confined to bed rest and given a series of isotonic exercises with ten pounds applied resistance and ten repetitions of each exercise.

Category III. Subjects were confined to bed rest and given isotonic exercises without applied resistance and ten repetitions of each exercise.

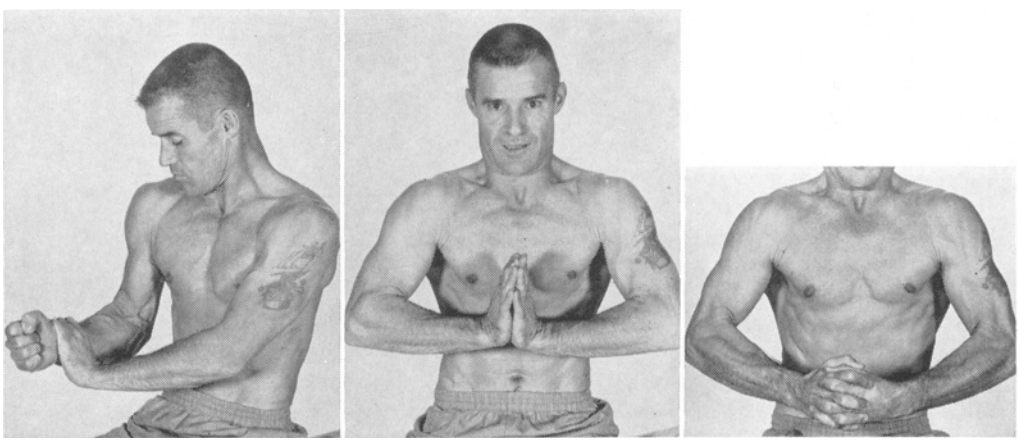
Category IV. Subjects were confined to bed rest and given isometric exercises using the resistance of the agonist muscle or the bed. Each exercise was held for a count of six during muscle contraction and there were ten repetitions of each exercise.

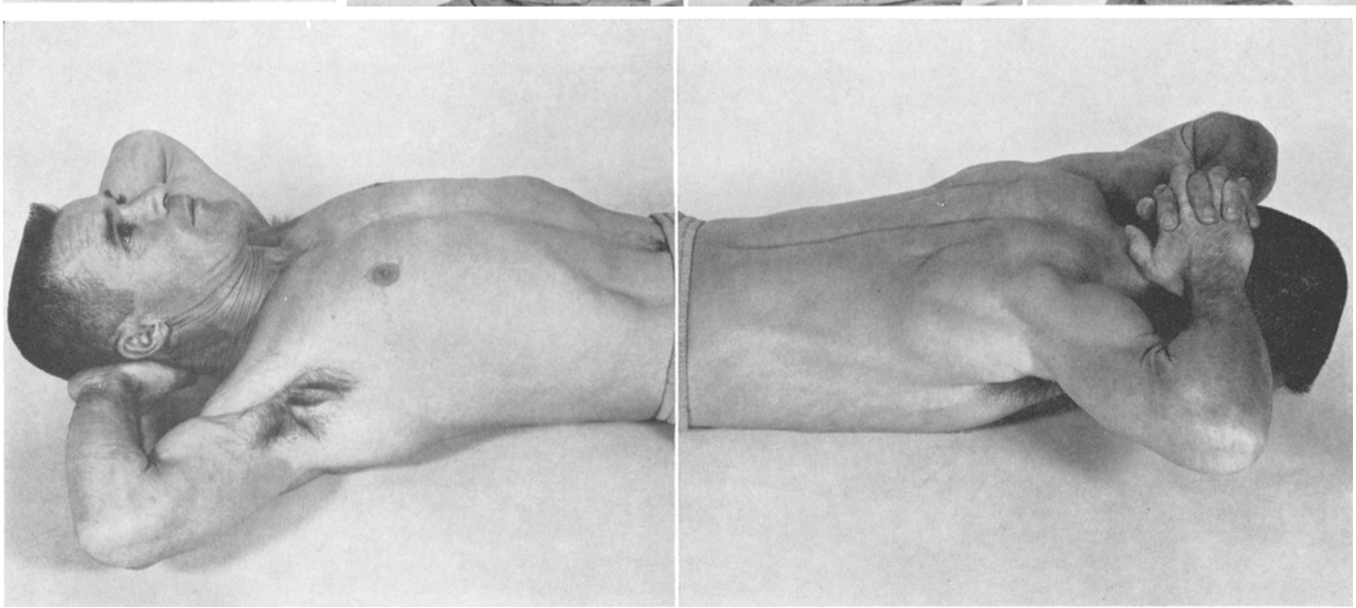
Category V. Subjects were confined to bed rest and given no exercise routine. Movements were limited to sitting, turning, eating, washing, handicraft projects, and use of the bed pan.

Each exercise participant was thoroughly indoctrinated in the exact routine for three days prior to initiating the experiment. The isometric group was taught the three essential phases of contraction, sustained contraction, and complete relaxation. The exercise routines were done for ten minute periods in Categories II, III, and IV. Two subjects in each of these categories performed the given exercises two times a day, four times a day, and six times a day. All exer-



Figs. 2A-F. Series of photographs illustrating representative isometric exercises. Note contraction of major muscle groups.





cises were done on a seven-day a week basis. Over the sixty day period of study, the exercise schedule was strictly adhered to and carefully supervised by a physical therapist and physician.

METHODS OF STUDY

Laboratory studies included blood and urine determinations initially and at weekly intervals. Routine blood counts were made as well as hemoglobin, hematocrit, prothrombin time, sedimentation rate, and chemistry determinations in the clinical laboratory. Urine determinations were made on aliquots of the twenty-four hour collections. Routine urinanalyses and selected chemistries were done.

Physiological studies included weight, pulse, blood pressure, basal metabolic rate, vital capacity, electrocardiogram, visual acuity, reaction time, muscle strength tests, and extremity girth measurements initially and at weekly intervals. Muscle strength observations were made with a dynamometer and Kendall testing. The circumference measurements were made by the same observer in all subjects using skin dye markers and a metal tape.

A standardized x-ray technique was employed on the ward. All the films were taken by the same x-ray technician. Roentgenograms of the chest, spine, and hands were obtained before, during, and upon completion of the project.

RESULTS

The laboratory determinations showed no significant variations in the blood chemistry levels (Table III).

TABLE III

LABORATORY DETERMINATIONS —	— BLOOD	
1. WBC*	8. Phosphorus	15. Cholesterol
2. RBC	9. Alkaline Phosphatase	16. Urea-N
3. Hemoglobin	10. Potassium	17. Glucose
4. Hematocrit	11. Sodium	18. Total Protein
5. Prothrombin Time	12. Creatine	19. Albumin
6. Sedimentation Rate*	13. Creatinine	20. A:G Ratio
7. Calcium	14. Chlorides	21. Electrophoresis

Results: No significant variations except WBC and Sed rate.

Elevation of the sedimentation rate and white blood count were evident in two subjects in Category III and one subject in Category V who incurred acute streptococcus pharyngitis during the early phase of the study. The cases responded favorably to penicillin therapy and were cured within seventy-two hours. There was no other episode of illness during the course of investigation. No abnormal alterations were found in the red blood count, hemoglobin, hematocrit, and prothrombin time. Urine determinations made on the twenty-four hour total volume aliquots failed to show significant variations in the specific gravity, reaction, or chemical tests (Table IV). The daily urine outputs for each subject did not fluctuate appreciably for the sixty day period.

TABLE IV. LABORATORY DETERMINATIONS — URINE

(Tests made on 24 hour total volume)		
1. Specific Gravity	4. Calcium	7. Chlorides
2. Reaction	5. Potassium	8. Creatine
3. Microscopic	6. Sodium	9. Creatinine

Results: No findings of significance.

TABLE V. BODY WEIGHT CHANGES

(Bed Rest Period)				
Category I	Category II	Category III	Category IV	Category V
+1.4	—2.0	—4.2	—3.0	—2.7

Note: Category average in kilograms.

Body weight changes are shown in Table V. Category I subjects gained an average of 1.4 kilograms during the study period, but the subjects in the bed rest categories sustained weight losses. The greatest loss averaged 4.2 kilograms in Category III in which two subjects had acute strep throat infections. There were no other derangements of significance in the physiologic studies except the muscle impairment (Table VI).

TABLE VI. PHYSIOLOGICAL STUDIES

1. Weight	5. Vital Capacity
2. Pulse	6. EKG
3. Blood Pressure	7. Visual Acuity
4. BMR	8. Reaction Time

Results: No significant alterations except for weight.

The losses in muscle mass and strength became apparent after the second and third weeks of bed rest and were most striking in the lower extremities of the Category V subjects (Table VII). This group did use their arms and hands to an appreciable degree for diversional activities and eating. There was no loss of power in hand grip in Category V, but atrophy in the forearm and arm averaged seven-tenths of a centimeter. Subjects in Categories III and IV did sustain slight losses in strength and mass of the thigh as compared with a substantial decrease in Category V. The average thigh circumference decrement in Category V measured two and one-half centimeters.

TABLE VII. EXTREMITY MUSCLE STRENGTH AND MASS

Category	I	II	III	IV	V
Grip	M	M	M	M	M
Forearm	M	M	M	M	D
Arm	M	M	M	M	D
Thigh	M	M	D	D	DD
Calf	M	D	DD	D	DD

M—Maintain D—Decrease

All bed category subjects showed a decrease in the girth and strength of the calf muscles. This was most evident in Categories III and V. The average decrease in calf measurements in Category V was two and seven-tenths centimeters and in Category III, approximately two and one-half centimeters. There was an average deficit of nearly one and eight-tenths centimeters in the Category III and IV subjects.

The average impairment in calf and thigh girth measurements was less in Categories III and IV when the prescribed exercises were done four or six times daily as compared to those subjects in each category who performed only twice daily. No significant differences were recorded for Category II subjects in this regard.

Interestingly, no particular exercise was given to maintain normal strength of the medial gluteal muscle. Several subjects in Categories III and IV, and all subjects in Category V revealed a pronounced weakness of this muscle which resulted in a waddle gait and back pain during the recovery period.

Most of the bed category subjects complained of transient dizziness, unsteady gait, easy fatigue upon exertion, and pain referable to the back and lower extremities during the initial recovery phase (Table VIII). The residual discomfort and debility of weight bearing muscle and joint functions were marked in Categories III and V and to a lesser extent in Categories II and IV. The symptoms in Categories II, III, and IV regressed within ten days with return of essentially normal strength and function. The subjective complaints and leg atrophy in the Category V subjects gradually improved over the ensuing thirty days. Several men still had minimal pain in the foot and knee joints at the time of final evaluation.

TABLE VIII. RECOVERY PERIOD—FINDINGS

Category	I	II	III	IV	V
Dizziness	0	+	+	+	++
Exertion Fatigue	0	0	+	+	+++
Unsteady Gait	0	+	++	+	+++
Waddle Gait	0	0	++	+	+++
Backache	0	0	++	+	+++
Trendelenberg	0	+	++	+	+++
Gluteal Weakness	0	0	++	+	+++
Hip Pain	0	0	++	+	+++
Quadriceps Pain	0	0	+	0	+++
Calf Pain	0	+	++	+	+++
Ankle Pain	0	+	++	+	+++
Foot Pain	0	+	++	+	+++

The pain in the joints of the hip, knee, ankle, and foot was probably attributable to the sudden stress of ambulation with the loss of the stabilizing power of the muscles and tendons. The back pain in Category V subjects was partially due to weakness of the erector spinae and abdominal muscles, but predominately the result of poor medial gluteal muscle support during resumption of weight bearing.

The x-ray studies showed no demonstrable changes. This observation was anticipated since there was no apparent calcium depletion of significance. It has been estimated that ten to thirty per cent of the total skeletal calcium must be lost before the roentgenogram will detect any disorder.[13, 47]

No special psychological studies were made during the experiment and no untoward problems were encountered. The equanimity of the subjects was exceedingly good. There were varied reactions observed, such as restlessness, anxiety, aggression, dependency, depression, sexual tension, and occasional hostility, as might be expected. These were expressions of the dominant personality traits of the subjects, but the degree was mild and insufficient to interrupt the course of the study. Morale of the airmen was considerably boosted during the fifth week of bed rest when they were visited and shown a personal interest by two of the Mercury astronauts.

DISCUSSION

Deitrick[12, 13] emphasized that care must be taken to consider experimental observations in relation to the amount of activity permitted the subjects. The activity or inactivity should be carefully described and regulated. Investigations have readily demonstrated that the severity of musculoskeletal derangements is influenced by the degree and duration of inactivity.[1, 10, 11, 13 19, 22, 49]

It should be reasserted that the subjects in this project were young and healthy males in top physical condition with excellent muscular reserve. The intensive prior conditioning during basic military training was a salient factor. The subjects in Category V were allowed nominal movements of the arms and legs while confined to bed and apparently had sufficient muscular activity to avert extreme deleterious effects. The findings corresponded to those in Graybiel's experiments and the control group in Deitrick's study. Although our project was essentially clinical in nature and not a controlled metabolic study, the laboratory determinations as such did not suggest any momentous metabolic deterioration.

The notable alterations of strength and function in the Category V subjects were found in the muscles of the hips and lower extremities. No doubt greater losses would have prevailed if these men had been confined for a longer period or had been rigidly immobilized in bivalved plaster casts for several weeks such as Deitrick's cases. Minimal decreases in lower extremity strength occurred in the other bed rest categories, but the prescribed exercises countered major decrements. The isometric exercises appeared to maintain muscle integrity about as well as the classical isotonic exercises with applied resistance and better than the isotonic routine without weights.[24, 30, 38] It was evident that additional exercises for the legs should be incorporated into the schedule to check the mild deficiencies that did occur. This would be especially applicable for the maintenance of the medial gluteal and calf muscles.

The symptoms referable to the weight bearing joints during the recovery period deserve attention. The resumption of the upright position and ambulation in the presence of weak musculature and subsequent lack of stabilization about weight bearing joints is an important consideration. Category V subjects continued to have some degree of pain and instability even forty days after completion of the bed rest period.

It is appreciated that absolute bed rest or immobilization in plaster casts is not analogous to the state of weightlessness in a spacecraft. The space traveler will not be totally restricted, but will exert muscular action to some extent in overcoming inertial effects and performing required tasks aboard the spacecraft. The situation of the astronaut crew might be somewhat comparable to the subjects in Category V. Other studies indicate that artificial stimulation or passive involuntary movements of muscles are incapable of sustaining normal muscle mass and strength and would not be feasible for space flight.[16, 28, 37, 40, 49] The isometric or dynamic tension exercise is the only practical sort which could be done in a weightless or subgravity state, since the isotonic or calisthenic types of exercises are dependent upon the effect of gravitational force for the resistance of a movable load (weight of body or metal object). Moreover isometric exercises require no special equipment for performance, such as weighty gymnastic gadgets or power consuming muscle stimulation devices. The contractions can be accomplished against the agonist muscle, the opposite extremity, or the resistance of the couch or chair. A simple adjustable restraint strap or a fixed bar would facilitate the exercise performance.

Obviously the appropriate physical conditioning of a space crew prior to prolonged space travel is important. This would be of definite concern in tolerating the reentry stresses and returning to the influence of the one G earth environment. The weight bearing joints must be kept in a fit condition to withstand the sudden and sustained gravitational stress. The fitness of the postural musculature should also receive proper maintenance. The older non-pilot crew members of the future will require particular attention to these factors.

The use of isometric exercises has widespread clinical application to bedridden chronic and convalescent patients who are unable to perform calisthenics or isotonic exercises with applied resistance. Isometric exercises have been routinely instituted in the treatment of these patients at our hospital (Table IX).

TABLE IX. ISOMETRIC EXERCISE ROUTINES

Suggested isometric exercise routines are listed. Each exercise should be held for a count of six seconds during muscle contraction. Ten repetitions of each exercise are recommended.

A. PRONE POSITION

1. Contract muscles of neck, back, buttocks, and legs with minimal movement off bed.
2. Hands behind head, push down on head with hands while attempting to lift head.
3. Hands straight above head on the bed, hands clasped, attempt to pull hands apart.
4. Legs straight, cross feet and attempt to pull apart.
5. Legs straight, cross feet, push down top foot and push up bottom foot. Reverse and repeat.

B. SUPINE POSITION

1. Tighten back, buttocks and leg muscles, at the same time push down with the head and heels, attempt to arch back off the bed.
2. Knees to chest, hold legs with arms, attempt to straighten back and legs.
3. Hands behind head, pull up with hands and down with head.
4. Hands clasped across chest, attempt to pull hands apart.
5. Hold arms tight at sides, at same time attempt to pull arms away from body.
6. Hold arms straight and contract biceps with palms up.
7. Hold arms straight with palms down and attempt to bend elbows.
8. Make a fist, contract muscles of hand and forearm.
9. Arms at 90° from body, elbows bent, contract internal and external rotators.
10. Contract quadriceps against hamstrings, both sides.
11. Cross feet, attempt to pull legs apart resisting with feet as fulcrum. Reverse feet and repeat.
12. Cross feet, push down top foot and push up bottom foot. Reverse top leg and repeat.
13. Curl toes and then pull up as forcefully as possible.

C. SITTING POSITION

1. Palms together in front of body, chest level, elbows bent—push one palm against the other.
2. Place left hand over right wrist—press down with left, pull up with right. Reverse arms.
3. Cross forearms, elbows bent—push down on top arm, up on bottom. Reverse procedure.
4. Fingers entwined—attempt to pull hands apart. Try with elbows bent and then straight.
5. Hands behind neck—push neck against hands and at same time attempt to bring elbows together in front.
6. Elbows bent, arms at side—attempt to pull arms away from body while holding them to body as tightly as possible.
7. Elbows bent and tight against body over stomach—attempt to pull forearms away from body.
8. Arms at side, elbow straight—attempt to bend elbow, at same time hold straight.
9. Make tight fist—hold tight while attempting to straighten fingers.
10. Spread fingers apart—attempt to bring together while holding apart as strongly as possible.
11. Finger tips of hands together with fingers straight—push finger tips against each other.
12. Push back against chair with upper trunk.
13. Tighten abdomen, flatten low back against chair.
14. Tighten buttock on one side, lift up off chair and push down with other buttock against chair. Reverse procedure.
15. Abdominal and chest breathing.
16. Tighten buttocks together, tighten pelvic floor and pull up on abdomen as if checking a bowel movement.
17. Hold trunk upright and attempt bending a few degrees to each side.
18. Cross legs below knees—pull down on top leg and attempt to straighten bottom leg. Raise toes of bottom leg and depress toes of top leg. Reverse top leg.
19. Hold knees together by inside thigh muscles and attempt to pull knees apart.
20. Tighten buttocks and backs of legs—attempt to "sit tall."
21. Hold feet together—attempt to pull apart by using hip and thigh muscles.
22. Knees together, hands on sides of knees—attempt to pull legs apart while holding them together by hands and leg muscles. Reverse procedure with hands inside of knees.
23. Push foot down against floor while attempting to pull foot up.
24. Pull up with muscles on inside of foot while trying to hold foot flat.

CONCLUSIONS

No attempt is made to draw definite conclusions from this study; however, the impression is gained that only a small amount of exercise is necessary to preserve muscle integrity and prevent bone rarefaction in the well-conditioned individual. A cyclic regimen of isometric exercises appears ample to counter the detrimental consequences of lengthy bed rest and relative inactivity. This type of exercise would offer a reasonable and practical conditioning program to insure a sound musculoskeletal system when normal activity could not be accomplished during manned space ventures.

It is hoped that this project will stimulate increased efforts by other investigators toward comparative exercise studies. The accumulation of more data is requisite for the intelligent planning of lengthy sojourns in space.

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