Pergamon

Acta Astronautica Vol. 33, pp. 89–96, 1994
Elsevier Science Ltd. Printed in Great Britain

0094-5765(94)00097-2

EXERCISE AGAINST LOWER BODY NEGATIVE PRESSURE AS A COUNTERMEASURE FOR CARDIOVASCULAR AND MUSCULOSKELETAL DECONDITIONING

G. MURTHY, D.E. WATENPAUGH, R.E. BALLARD, AND A.R. HARGENS

Life Science Division (239-11)
NASA Ames Research Center
Moffett Field, CA 94035-1000

ABSTRACT

Exposure to lower body negative pressure (LBNP) with oral salt and water ingestion has been tested by astronauts as a countermeasure to prevent postflight orthostatic intolerance. Exercise is another countermeasure that astronauts commonly use during spaceflight to maintain musculoskeletal strength. We hypothesize that a novel combination of exercise and simultaneous exposure to lower body negative pressure during spaceflight will produce Earth-like musculoskeletal loads as well as cardiovascular stimuli to maintain adaptation to Earth's gravity. Results from recent studies indicate that leg exercise within a LBNP chamber against the suction force of 100 mmHg LBNP in horizontal-supine posture produces an equivalent, if not greater exercise stress compared to similar leg exercise in upright posture (without LBNP) against Earth's gravity.[12] Therefore, the concept of LBNP combined with exercise may prove to be a low cost and low mass technique to stress the cardiovascular and the musculoskeletal systems simultaneously.

RESPONSES DURING AND AFTER SPACEFLIGHT

Astronauts exposed to long duration spaceflight experience muscle atrophy, especially in slow-twitch postural muscles such as the soleus[3]; demineralization in weight-bearing bones, particularly in the *os calcis*, proximal tibia and fibula;[14] and reduced neuromuscular function.[4] Following spaceflight, astronauts experience orthostatic hypotension and reduced exercise capacity.[3,5] These postflight conditions are possibly due to microgravity-induced hypovolemia[5], decreased baroreflex responsiveness[3], decreased skeletal muscle tone[18], and increased leg compliance.[16] In order to prevent postflight orthostatic intolerance and to facilitate readaptation to Earth's gravity, it is crucial to maintain cardiovascular conditioning as well as musculoskeletal strength during spaceflight.

LBNP AS A COUNTERMEASURE

Current U.S. countermeasures employed during spaceflight include salt and water ingestion during exposure to low magnitudes of LBNP[6], and aerobic exercise on cycle ergometers, treadmills, and rowing machines.[3] However, there is no standard exercise regimen that astronauts follow during flight. Furthermore, none of these countermeasures completely ameliorates postflight orthostatic and exercise intolerance.[3] Therefore, more effective countermeasures are necessary.

LBNP has been primarily used in microgravity to sequester blood and other tissue fluids in the lower body and thereby stress the cardiovascular system.[1,2] In the absence of gravity-induced hydrostatic pressure gradients (as in the case of bedrest or exposure to microgravity), cephalad fluid shifts probably increase central blood volume.[17] LBNP has been employed during simulated microgravity to reduce central blood volume, to elevate lower body blood and extravascular fluid volume, and to counteract orthostatic intolerance.[6] Although LBNP as a countermeasure for orthostatic intolerance has been used since the 1960s,[11] a totally effective LBNP protocol has yet to be tested during flight. Ground-based studies indicate that exposure to 30 mmHg LBNP for 4h combined with salt and water ingestion reduces post bedrest orthostatic intolerance.[10] However, reducing exposure time from 4h to 2h provides little protection from orthostatic intolerance.[10]

Exposure to 100 mmHg in horizontal supine or upright posture generates approximately one equivalent body weight of reaction force at the feet.[9] Figure 1 illustrates a linear relationship between reaction force generated at the feet and exposure to LBNP. Furthermore, simple leg exercise while exposed to 100 mmHg LBNP significantly improves tolerance to LBNP by skeletal muscle pumping of venous blood from the legs as well as exercise-induced sympathetic nerve stimulation, increased heart rate, and peripheral vasoconstriction.[19] These findings have important implications for using LBNP to simulate Earth's gravity in space and thereby to minimize musculoskeletal atrophy and cardiovascular deconditioning experienced by crew members during long duration spaceflight.

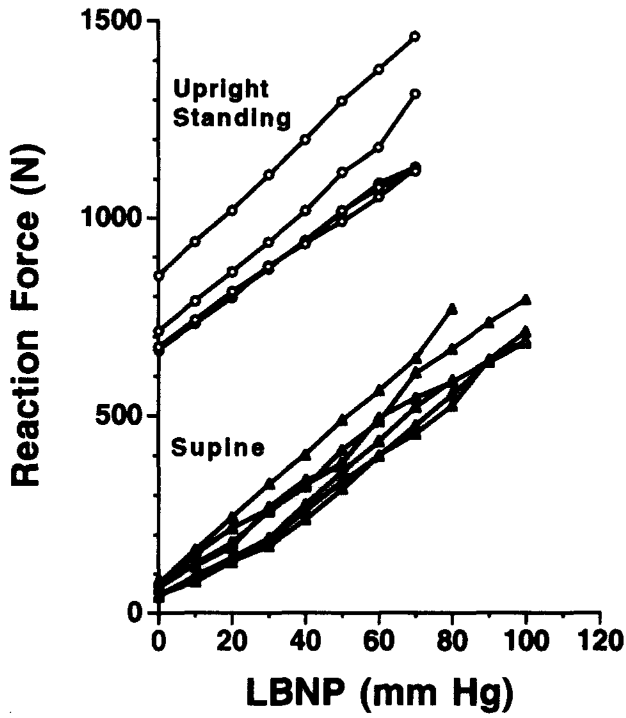
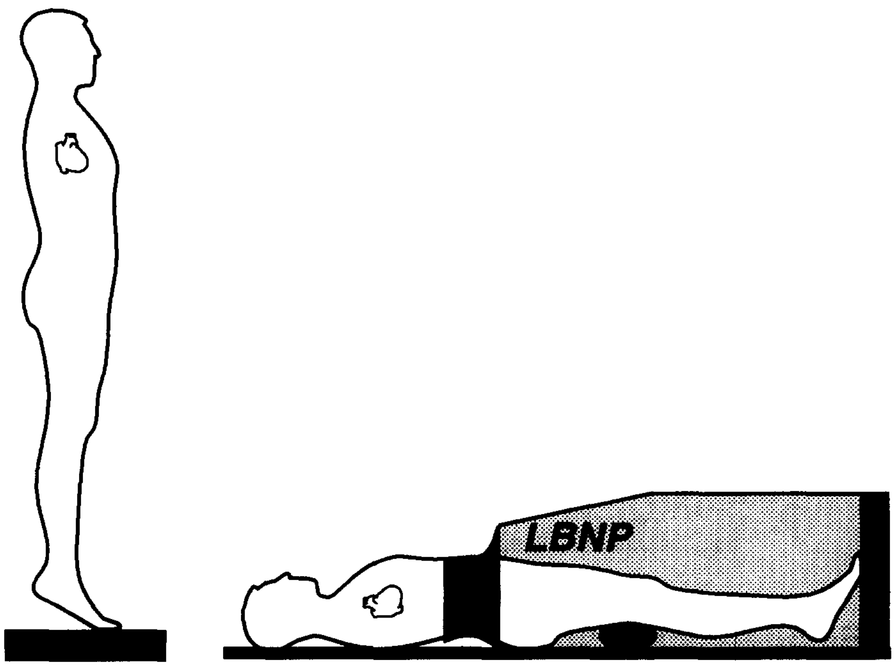


Figure 1: Increased reaction force (Newtons, 1N=0.102kg of force) with LBNP during upright standing (upper results) and supine posture (lower results).[9]

COMPARISON OF EXERCISE WITH AND WITHOUT EXPOSURE TO 100 mmHg LBNP

A study was conducted to establish whether exercise within a LBNP chamber in horizontal-supine posture effectively stresses the cardiovascular and leg musculoskeletal systems similar to exercise in upright standing posture (without LBNP) against Earth's gravity.[12] Nine male volunteers (age: 38 ± 10 yrs; weight: 72 ± 7 kg; height: 173 ± 8 cm, means ± SD) participated in the study after giving their informed written consent. Subjects were in good health, maintained normal daily activities, and refrained from caffeine, alcohol, medications, and exercise of unusual magnitude 24 h prior to and during the study. This investigation was approved by the Human Research Experiments Review Board at NASA Ames Research Center.

Subjects were instrumented with ECG electrodes to monitor heart rate, a transducer-tipped catheter in the soleus muscle (this muscle undergoes the greatest atrophy in microgravity[8]) to quantify intramuscular pressure, and a strain gauge around mid-calf of the right leg to measure pooling of blood and fluid in the leg. Following instrumentation, subjects either: (1) stood on a forceplate with both legs bearing equal body weight (exercise-1G), or (2) were positioned horizontal-supine in the LBNP chamber, sealed at the superior iliac crest such that their feet were resting against the forceplate (exercise-LBNP). The order of these two conditions (Fig. 2) was randomized.



Exercise-1G Exercise-LBNP

Figure 2: Exercise in upright posture against normal gravity (without LBNP) was compared to that during similar exercise in supine posture within the LBNP chamber.

In the designated posture, subjects remained relaxed for one min as baseline control measurements of reaction force, soleus intramuscular pressure (IMP), leg volume, heart rate, and blood pressure were recorded. Subjects then exercised (ankle dorsi- and plantarflexion) in the LBNP chamber at a rate of 25 cycles/min for five min in supine posture during exposure to 100 mmHg LBNP. Subjects exercised similarly in the upright posture against 1G (without LBNP) prior to or following exercise-LBNP. After 5 min of exercise, subjects were monitored until all parameters returned to control, baseline values.

Data were collected during the final 15 s of each min of the five min protocol. Peak, mean, and oscillatory reaction forces and IMP (an index of muscle contraction force) of the soleus muscle were analyzed for 5 exercise cycles.

Force oscillations during exercise relate to IMP oscillations and therefore to skeletal muscle pump function. Data were analyzed using repeated measures ANOVA followed by paired t-tests with significance set at $p < 0.05$. Means ± SE are reported for all variables.

Reaction force, LBNP chamber pressure fluctuation, and IMP responses during exercise-1G and exercise-LBNP of a typical study are illustrated in Fig. 3.

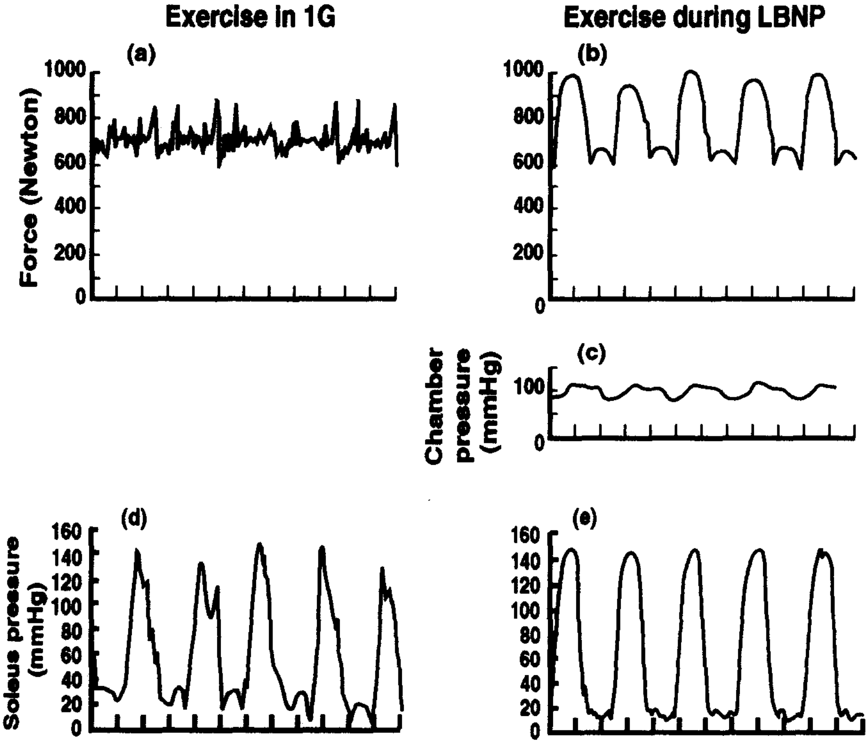


Figure 3: Representative recordings during exercise-1G and exercise-LBNP. a & b) Comparison of reaction force waveforms during upright exercise in 1G and supine exercise during 100 mmHg LBNP; c) LBNP chamber pressure fluctuations created by leg exercise-induced movement of the subject; d & e) soleus pressure during exercise-1G and exercise-LBNP.[12]

Mean reaction force generated during supine exercise against 100 mmHg LBNP was similar to that during exercise-1G in upright posture (Table 1). However, peak reaction force generated during exercise-LBNP was significantly higher than that for exercise-1G. Likewise, force oscillation (peak-to-peak amplitude) was significantly higher during exercise-LBNP than exercise-1G. Mean, peak and oscillatory pressures in the soleus muscle during exercise in the LBNP chamber were similar to that of exercise-1G. Calf volume increased significantly during exercise-LBNP compared to baseline value. Baseline heart rate was not significantly lower for supine (69 ± 4 beats/min) than upright (77 ± 3 beats/min) resting postures. However, heart rate during exercise-LBNP was significantly higher compared to that of exercise-1G. Furthermore, heart rate significantly increased with duration of exercise at 100 mmHg LBNP. Baseline arterial blood pressure without LBNP was similar in the supine posture (94 ± 5 mmHg) and in the upright posture (96 ± 8 mmHg). Mean arterial blood pressure during exercise-LBNP was similar to exercise-1G. The results suggest that leg musculoskeletal stresses (as indicated by reaction force and soleus muscle pressure) were similar during exercise-LBNP and exercise-1G and cardiovascular stress (as indicated by increased leg volume and heart rate) during exercise-LBNP in supine posture exceeded that produced by exercise-1G in upright posture.

Table 1: Comparison of upright exercise-1G with supine exercise-LBNP

Parameters	Upright Exercise-1G	Supine Exercise-LBNP
Reaction force (N)		
peak	808 ± 26	981 ± 57*
mean	701 ± 24	743 ± 37
oscillatory	202 ± 25	369 ± 41*
Soleus IMP (mmHg)		
peak	103 ± 13	115 ± 10
mean	47 ± 7	55 ± 8
oscillatory	94 ± 8	103 ± 10
Leg volume increase (%)	0.4 ± 0.4	3.3 ± 0.5*
Heart rate (beats/min)	81 ± 3	99 ± 5*
Mean arterial blood pressure (mmHg)	97 ± 3	99 ± 4

* indicates significantly higher value than exercise-1G

Although mean reaction force during exercise-LBNP was similar to that during exercise-1G, peak reaction force and oscillatory force were higher during exercise-LBNP than during exercise-1G. Four factors may contribute to this LBNP-induced increase in reaction force. First, friction between the supine subject and the LBNP chamber results in an increase in force required to push off the forceplate. Although Teflon sheets are placed beneath the subject to minimize friction, coefficient of friction is significant (6.6 x 10^{-2}). Second, dorsi- and plantarflexion exercise-induced movement of the subject in and out of the chamber creates fluctuations in chamber pressure above and below 100 mmHg. These pressure fluctuations decrease and increase chamber volume which, in turn, elevate peak and oscillatory reaction forces. Third, application of LBNP induces abdominal distension, which increases cross-sectional area just below the chamber waist seal. This, in turn, raises peak and oscillatory force because reaction force at the feet is directly proportional to cross-sectional area. Fourth, 100 mmHg LBNP was applied to each subject regardless of subject body cross-sectional area variability. In our study, this factor produced a reaction force that exceeded one body weight of force in some of our subjects. If all the factors were applied to correct peak and oscillatory forces, then the reaction forces generated during exercise-LBNP and exercise-1G become virtually equal. Similar IMPs suggest that skeletal muscle exertion is the same for both conditions (Fig. 4).

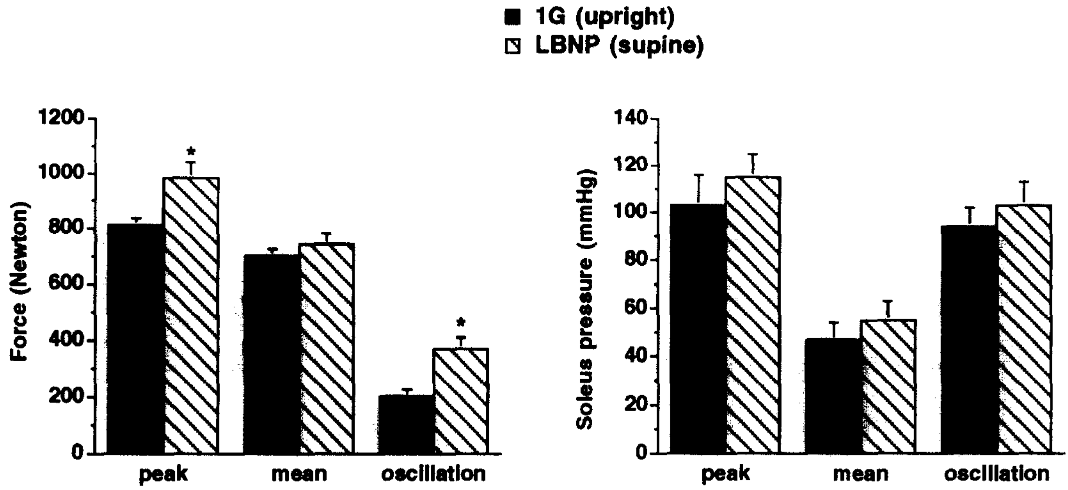


Figure 4: LEFT: Mean force generated during exercise-LBNP is similar to that produced during exercise-1G, yet, peak and oscillatory reaction forces generated during exercise-LBNP exceed those for exercise-1G. RIGHT: Peak, mean, and oscillatory soleus pressures were similar during exercise-LBNP and exercise-1G.[12] * indicates significantly higher value than exercise-1G.

Elevations of leg volume and heart rate indicate that cardiovascular stresses during exercise-LBNP exceeded that during exercise-1G. LBNP uniformly increases transmural pressures throughout the lower body, causing cutaneous and venous engorgement and subsequent calf volume increase.[1] LBNP-induced upper-body volume depletion may increase sensitivity of baroreceptor unloading, which can result in sympathetic nerve stimulation, parasympathetic withdrawal, and tachycardia.[13] Partial reduction of LBNP-induced venous pooling in the lower legs may optimize cardiovascular stress to a level similar to that found on Earth during exercise. Venous pooling can be reduced with a compression suit which provides lowest compression at the ankle and highest at the level of the waist seal.[8] Importantly, a compression suit will not counteract the reaction forces produced by LBNP, but hopefully will normalize the cardiovascular stress to that present during exercise on Earth.

ADVANTAGES AND DISADVANTAGES OF EXERCISE AGAINST LBNP

The advantages of using exercise combined with LBNP as a possible countermeasure in microgravity are that cardiovascular and musculoskeletal systems can be stressed simultaneously. Exercise within the LBNP chamber can be resistive training exercise (concentric and eccentric muscle action) where the eccentric exercise is probably more important in maintaining muscle strength.[15] Exercise in this study was limited to ankle dorsi- and plantarflexion because of the small LBNP chamber size available for this study. Importantly, exercise-LBNP could be a more effective and viable alternative to rotating artificial gravity. A centrifuge is relatively expensive and technically challenging to accommodate on any spacecraft. Also, centrifugation-induced Coriolis effects on the vestibular system and the consequent motion sickness associated with using an onboard centrifuge may be a problem for crew members.

The disadvantage of using exercise-LBNP to simulate Earth-like effects is that the concept does not address the vestibular and the optokinetic dysfunction experienced in microgravity. Although LBNP provides substantial footward reaction forces, it does not load the otolith organs of the inner ear.

CONCLUSIONS

Future studies should include a larger LBNP chamber so that subjects can run on a treadmill and produce high reaction forces similar to those seen on Earth during running. A compression suit that will enable subjects to tolerate 100 mmHg LBNP for a longer duration of time (30 min) should be tested. These high pressure magnitudes and short periods of exercise will maximize astronauts' benefit/time ratio during spaceflight and may help maintain their health and well-being during long-duration spaceflight. Furthermore, exercise during exposure to LBNP may facilitate cardiovascular and musculoskeletal readaptation to Earth's gravity postflight. Exercise within a LBNP chamber may prove a low cost, low mass alternative to rotating artificial gravity during prolonged exposure to microgravity.

ACKNOWLEDGEMENTS

The research was supported by the National Aeronautics and Space Administration grant 199-14-12-04.

REFERENCES

1. ARATOW, M., S.M. FORTNEY, D.E. WATENPAUGH, A.G. CRENSHAW, AND A.R. HARGENS. Transcapillary fluid responses to lower body negative pressure. *J. Appl. Physiol.*74:2763-2770, 1993.
2. COLES, D.R., B.S.L. KIDD, AND W. MOFFAT. Distensibility of blood vessels of the human calf determined by local application of subatmospheric pressures. *J. Appl. Physiol.* 10:461-468, 1957.
3. CONVERTINO, V.A. Physiological adaptations to weightlessness: Effects on exercise and work performance. In: *Exerc. Sport Sci. Rev.*, edited by K.B. Pandolf. Baltimore: Williams & Wilkins, 1990, pp.119-163.
4. CONVERTINO, V.A., D.F. DOERR, D.L. ECKBERG, J.M. FRITSCH, AND J. VERNIKOS-DANELLIS. Head-down tilt bedrest impairs vagal baroreflex responses and provokes orthostatic hypotension. *J. Appl. Physiol.* 68:1458-1464, 1990.
5. DIETLEIN, L.F. Summary and conclusions. In: *Biomedical Results of Apollo*, edited by R.S. Johnston, L.F. Dietlein, and C.A. Berry. Washington D.C. National Aeronautics and Space Administration SP 368, 1975. pp.573-574.
6. FORTNEY, S. Development of lower body negative pressure as a countermeasure for orthostatic intolerance. *J. Clin. Pharmacol.* 31:888-892, 1991.
7. GAYEVSKAYA, M.S., L.M. KURINA, Ye.V. KOLCHINA, N.S. KOLGANOVA, AND N.A. VERESOMSKAYA. The change in protein fractions of a human skeletal muscle (soleus muscle) under the effects of hypokinesia and the possibility of preventing such exchanges by means of a special set of exercises. *Fiziologiya Cheloveka* 2(6):997-1001, 1976.
8. HARGENS, A.R., D.E. WATENPAUGH, AND G.A. BREIT. Control of circulatory function in altered gravitational fields. *The Physiologist* 35:S80-S83, 1992.
9. HARGENS, A.R., R.T. WHALEN, D.E. WATENPAUGH, D.F. SCHWANDT, AND L.P. KROCK. Lower body negative pressure to provide load bearing in space. *Aviat. Space Environ. Med.* 8:934-937, 1991.
10. HYATT, K.H. AND D.A. WEST. Reversal of bedrest-induced orthostatic intolerance by lower body negative pressure and saline. *Aviat. Space Environ. Med.* 48:120-124, 1977.
11. LAMB, L.E. AND P.M. STEVENS. Influence of lower body negative pressure on the level of hydration during bed rest. *Aerospace Med.* 36:1145-1151, 1965.

12. MURTHY, G., D.E. WATENPAUGH, R.E. BALLARD, AND A.R. HARGENS. Supine exercise during lower body negative pressure effectively simulates upright exercise in normal gravity. *J. Appl. Physiol.*, in review, 1993.
13. ROWELL, L.B. *Human Circulation: Regulation During Physical Stress.* Oxford University Press: New York, 1968. pp.147-158, 287-327.
14. SMITH, M.C. Jr., P.D. RAMBAUT, J.M. VOGEL, AND M.W. WHITTLE, Bone mineral measurement-Experiment M078, In: Johnston R.S., and L.F. Dietlein, eds. *Biomedical Results from Skylab.* Washington DC: National Aeronautics and Space Administration SP 377, 1977. pp.183-190.
15. TESCH, P.A. AND E.B. COLLIANDER. Effects of eccentric and concentric resistance training on muscular strength. *Med Sci. Sports Exerc.* 21(Suppl.):S88, 1989.
16. THORNTON, W.E. AND G.W. HOFFLER. Hemodynamic studies of the leg under weightlessness. In: *Biomedical Results from Skylab*, edited by Johnston R.S., and L.F. Dietlein, eds. Washington DC: National Aeronautics and Space Administration SP 377, 1977. pp.324-329.
17. THORNTON, W.E., G.W. HOFFLER, AND J.A. RUMMEL. Anthropometric changes and fluid shifts. In: *Biomedical Results from Skylab*, edited by R.S. Johnston, L.F. Dietlein, and C.A. Berry. Washington, D.C. National Aeronautics and Space Administration SP-377, 1977. pp. 330-338.
18. THORNTON, W.E. AND J.A. RUMMEL. Muscular deconditioning and its prevention in space flight. In: *Biomedical Results from Skylab*, edited by R.S. Johnston and L.F. Dietlein. Washington, D.C.: National Aeronautics and Space Administration SP-377, 1977. pp.191-197.
19. WATENPAUGH, D.E., R.E. BALLARD, M.S. STOUT, G. MURTHY, R.T. WHALEN, AND A.R. HARGENS. Dynamic leg exercise increases tolerance of lower body negative pressure. *Aviat. Space Environ. Med.* (in press), 1993.