CLINICAL APPLICATION

Improvement in Knee Extensor Strength After Horizontal Squat and Jump Training

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Long space flights will require astronauts to perform progressive resistance exercise, which is difficult to achieve in microgravity, to maintain skeletal muscle strength and bone mineralization. We assessed changes in knee extensor strength in 10 healthy men in response to a 10-week ground-based training program of concentric and eccentric muscle contractions as well as plyometric movements. Isokinetic knee extensor strength and vertical jump were measured before and after the training period, which involved a progressive resistance protocol of horizontal jumps and squats using the Shuttle 2000-1 Cardiomuscular Conditioner (Contemporary Design Inc., Glacier, WA). This device provides resistance by use of elastic cords attached to a movable sled positioned between two parallel runners on a fixed base. Both concentric and eccentric strength increased in the trained subjects relative to 10 untrained controls. Improvements in strength ranged from 21.5% for concentric contractions and 26.2% for eccentric contractions. We conclude that the Shuttle 2000-1 device effectively improved muscular strength.

Keywords: Eccentric; isokinetic; microgravity; plyometric

Introduction

As the human presence in space expands, understanding the physiological effects of long-duration space flight on the human body becomes increasingly important. Results from the American Skylab experience and the Russian long-duration flight program indicate that long-term exposure to microgravity results in a reduction of muscle mass and strength, particularly in lower limb extensor muscles.[12,26] The present investigation focused on knee extensor strength because reports indicate that lower limb extensor strength is degraded to a greater extent than is flexor strength after space flight or bed rest.[10,26]

Decrements in lower limb neuromuscular functioning may be associated with several posture and locomotion control problems experienced by space travelers after landing. For instance, immediately after returning to Earth, crew members experience static postural instability involving high-frequency oscillations during quiet standing, decreased ability to respond to postural perturbations, and increased reaction times associated with limb movements.[3,14,17,18,21] Although a variety of in-flight exercise devices and protocols have been used (e.g., isometric exercises, mini-gym), none has proven totally effective in preventing the loss of muscle mass and strength experienced during space flight.[10] Dudley *et al.*[10] suggested that the marginal effectiveness of the resistance training protocols used during flight may be related to their lack of eccentric muscle actions. Combining both concentric and eccentric muscle contractions during resistance training in the 1-G environment has resulted in greater strength increases relative to training protocols composed exclusively of concentric contractions.[9,10,13] Additionally, Dudley *et al.*[10] have reported that subjects who trained using a combined eccentric and concentric contraction protocol maintained greater strength increases after 1 month of detraining than did subjects who trained only concentrically.

In microgravity, eccentric loading cannot be achieved without a means of providing resistance during isotonic exercise. The Shuttle 2000-1 Cardiomuscular Conditioner (Contemporary Design Inc., Glacier, WA) provides resis-

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tance by use of elastic cords attached to a moveable sled positioned between two parallel runners on a fixed base (*Figure 1*). The design of the Shuttle 2000-1 provides progressive resistance without relying upon the force of gravity. It also minimizes the potential for injury by allowing plyometric training without exposing muscles and joints to full body weight during the eccentric loading phase of the movement. This characteristic is an important feature for any potential space flight countermeasure intended to maintain preflight levels of neuromuscular function. However, the effectiveness of such a design in 1 G has not been extensively documented.

Plyometrics is an exercise technique that incorporates ballistic eccentric (i.e., fiber lengthening) loading of the muscles followed immediately by rapid concentric contractions that result in a rapid movement.[7,27] Although plyometric training increases explosive strength, it does not allow maximal eccentric loading because of the brief contact time on the support surface (and thus minimal joint flexion) before the explosive movement. Exercise protocols including both plyometrics and extended eccentric loading may maintain full neuromuscular functioning during space flight more effectively than would a protocol consisting exclusively of plyometric training.

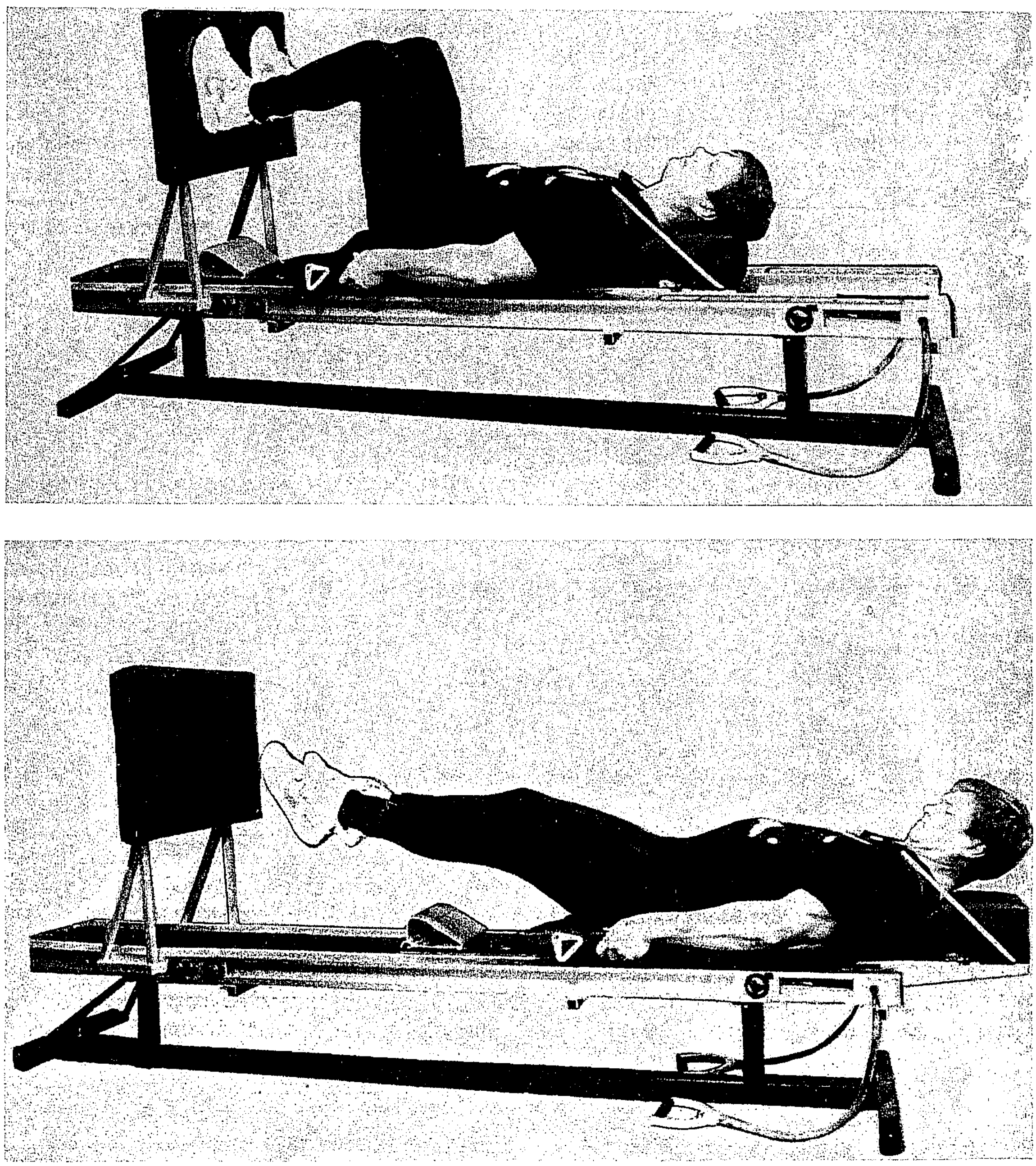

Figure 1 The Shuttle 2000-1 Cardiomuscular Conditioner. Top, subject positioned for horizontal jump; bottom, after horizontal jump.

The purpose of this investigation was to examine, in a ground-based study, the effect of a combination horizontal squat-and-jump training program on knee extensor strength using the Shuttle 2000-1 as the training platform.

Methods

Subjects and Strength Test Protocols

Twenty untrained male volunteers (mean age 31.8 years ± 4.2) participated in this study: 10 in an exercise group and 10 in a nonexercising control group. All subjects passed an Air Force Class III physical examination, were briefed on the study protocol, and provided written informed consent before being admitted to the study. Although all subjects were advised of their freedom to withdraw from the study at any time, all completed the 10-week protocol. All activities were approved by the Johnson Space Center Human Research Policy and Procedures Committee. One week before the training began, subjects spent 2 hours becoming familiar with the test equipment and protocols. All tests were preceded by a 5-minute warm-up on a Monark Ergomedic, Battle Creek, MI model 818E ergometer and lower-limb stretching. Concentric and eccentric knee extensor strength and vertical jump height were assessed before and after the 10-week training period. Both groups were retested after the training period using the same procedures.

Knee-extensor strength was tested using the Biodex Isokinetic Testing System (Biodex Corporation, Shirley, NY). The subjects were seated in the Biodex chair and secured with Velcro straps at the waist, trunk, and thigh to stabilize the femur of the tested (dominant) lower limb. Tibial pad placement, dynamometer height, and seat angle were recorded to maintain reliability and reproducibility during testing. After the dynamometer was calibrated, concentric knee extensor strength was tested at 60, 90, 120, and 240 deg/sec, and then eccentric strength was measured at 30 and 60 deg/sec. The knee joint range of motion was limited to 20 to 100 degrees. Five consecutive maximum repetitions at each velocity were tested, with a 2-minute rest between velocities. The data were sampled at 100 Hz before analog-to-digital conversion and storage. Angle-specific peak torque was measured using electronic cursors between the knee angles of 30 and 90 degrees in 10-degree increments for each movement velocity. The peak value of each of the five test repetitions was recorded for subsequent statistical analysis. Group means were obtained for the angle-specific peak torques at each movement velocity. Analysis of covariance (ANCOVA) was used to determine whether training affected strength in the exercise and control groups at each joint angle measured. Strength scores before the training period served as the covariant.

The electronic cursors also were used to measure peak concentric power (i.e., the rate at which muscle work is performed) at the four tested velocities for six subjects in the exercise group. A one-way repeated-measures analysis of variance (ANOVA) followed by planned comparisons was used to assess potential differences in muscle power at each velocity. An α level of 0.05 was chosen for all statistical tests.

Vertical jumping performance also was used as an index of lower limb power.[1] Subjects stood parallel to a vertical jump board, flexed their dominant shoulder to 180 degrees, and touched the board at the point of maximal reach. The subjects then jumped vertically, with no rocking of the body or arm swinging before the jump. Chalk was applied to the volar surfaces of the distal phalanges of the second through fifth digits so that a chalk mark was recorded with each touch of the board. Subjects completed five jumps, with 30-second rest periods between each jump. The jump resulting in the greatest difference between the standing reach height and the chalk mark on the board was used as the measure of vertical jumping. Differences in test scores of the exercise and control groups after the training period were assessed by using ANCOVA, with the pretraining scores serving as the covariant.

Strength Training Protocol and Exercise Platform

The exercise group trained their lower extremities for 3 days per week for 10 weeks using the Shuttle 2000-1 Cardiomuscular Conditioner. Subjects lay on the sled of the Shuttle 2000-1 as shown in *Figure 1,* with the back parallel to the floor, the hips and knees flexed at approximately 90 degrees, and the feet positioned against the vertical foot platform. Horizontal jumps and squats were performed using lower limb muscle contractions that resulted in extension as the sled was accelerated backward (i.e., away from the vertical foot platform) along two parallel runners. After each movement, elastic cords pulled the subject back toward the vertical foot platform until the initial position was achieved, at which time the movement was repeated. Resistance was increased progressively throughout the 10 weeks of training by attaching additional elastic cords between the movable sled and the stable frame of the Shuttle 2000-1 (*Table 1*). Both jumps (when subjects' feet left the platform) and squats were used during the training. Subjects squatted and jumped in tempo to a metronome set for 35 to 55 beats per minute depending on the specific block of trials. Blocks of plyometric jumps were also incorporated into the training protocol. During the plyometric jumps, the subjects jumped off of the vertical platform as rapidly as possible after their feet contacted the vertical platform. During the training period, the control group refrained from any exercise but continued their normal daily activities.

Table 1 Ten-week training schedule, progressive resistance protocol.

Training activity*	No. of tension cords used during activity									
	Wk 1	*Wk 2*	*Wk 3*	*Wk 4*	*Wk 5*	*Wk 6*	*Wk 7*	*Wk 8*	*Wk 9*	*Wk 10*
Warm-up squats	1	1	1	2	2	2	3	3	3	3
Warm-up squats	1	2	2	3	3	3	4	4	4	4
Squats	2	3	3	4	5	6	7	7	8	8
Squats	3	4	4	5	5	6	7	8	8	8
Squat jumps	2	3	3	4	4	5	5	6	6	7
Plyometric jumps†	1	2	2	3	3	4	4	5	5	6
Cool down	1	1	1	2	2	3	3	4	4	5

*All seven training activities were completed three times per week during each of the 10 weeks of the protocol.
†Jumps were completed as quickly as possible so that the time of foot contact on the board was minimized.

Results

The 10-week horizontal squat and jump training program significantly increased lower limb strength in the exercise group. Of the 42 ANCOVAs (six velocities at seven joint angles), 37 showed significant differences between the exercise and control groups after the training period ($p < 0.028$ to $p < 0.0001$). For concentric contractions, percentage increases in peak torque averaged 21.5 ± 4.7% across all of the tested angles and movement velocities. However, strength increases were greatest at the largest joint angles (80 and 90 degrees). A one-way repeated-measures ANOVA ($p < 0.0003$) followed by post hoc testing showed that the strength increases across all movement velocities at the joint angles of 80 and 90 degrees were significantly greater than those at the other five angles (*Figure 2*). Only at 240 deg/sec was the statistical significance of strength gains inconsistent across the various joint angles (*Table 2*). Four of the seven joint-angle comparisons were statistically significant; no strength was gained at joint angles of 30, 40, and 70 degrees at movement velocities of 240 deg/sec.

Eccentric contraction strength improved at all joint angles for both movement velocities (30 and 60 deg/sec) (*Figure 3*). Vertical jump height also increased an average of 5.72 ± 0.98 cm ($p < 0.0004$) (*Figure 3*). The exercise group showed significant increases in peak muscle power at movement velocities of 120 ($p < 0.0001$) and 240 ($p < 0.007$) deg/sec (*Figure 4*).

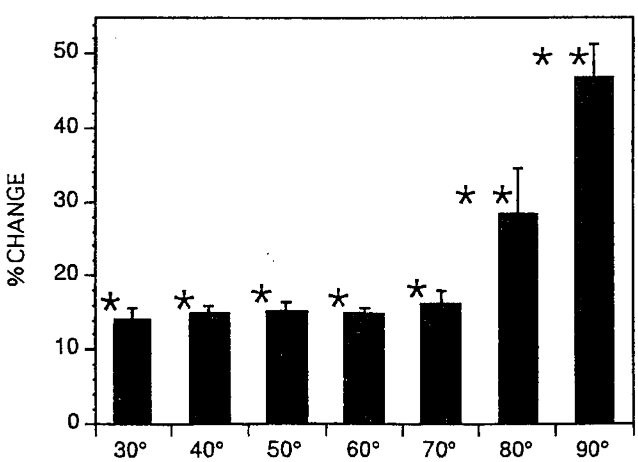

Figure 2 Percentage change (before-to-after training) in angle-specific concentric contractions at several movement velocities. Results are presented as means with standard error bars; * significantly different from before training, $p < 0.05$; **significantly different from 30° to 70°, $p < 0.05$.

Discussion

The present findings indicate that a unique training protocol, combining horizontal squats and jumps using a device that provides progressive resistance without relying on gravity, produced significant increases in knee extensor peak torque across a range of joint angles and movement velocities. The additional finding of increased vertical jump height is consistent with the observed changes in knee extensor strength and power. Perhaps most important are the large increases in eccentric peak torque values across all joint angles and at both movement velocities (30 and 60 deg/sec). Our training protocol of horizontal jumps and squats included a relatively long phase of high eccentric loading as the subjects moved from lower limb extension at the completion of the movement toward knee and hip flexion as they returned to the starting position (*Figure 1*). This prolonged eccentric loading likely is responsible for the large increases in eccentric peak torque strength.

Dudley *et al.*[10] found that training subjects with a combination of eccentric and concentric contractions for 19 weeks produced a 33% ± 1% increase in knee extension strength. The overall improvement of 21.5% ± 4.7% in concentric knee extension strength in our subjects after 10 weeks of training compares favorably with Dudley's results, considering that Dudley's tests consisted of maxi-

Table 2 Mean change in angle-specific peak torque produced by the knee at several angular velocities.*

	Joint Angles						
Angular velocity	30°	40°	50°	60°	70°	80°	90°
of contraction	%Δ ± S.E. p	%Δ ± S.E. p	%Δ ± S.E. p	%Δ ± S.E. p	%Δ ± S.E. p	%Δ ± S.E. p	%Δ ± S.E. p
Concentric Contractions							
60 deg/sec	16.8 ± 6.6 0.018	11.6 ± 3.7 0.001	10.6 ± 2.9 0.011	14.6 ± 5.2 0.001	10.1 ± 4.4 0.001	12.9 ± 4.2 0.001	32.9 ± 12.0 0.017
90 deg/sec	18.5 ± 4.5 0.003	19.2 ± 4.6 0.033	19.6 ± 4.2 0.001	18.3 ± 4.0 0.001	16.1 ± 4.8 0.001	21.1 ± 5.0 0.001	50.2 ± 10.5 0.001
120 deg/sec	12.5 ± 3.2 0.137	16.5 ± 2.3 0.001	14.5 ± 2.6 0.001	13.4 ± 3.7 0.001	16.6 ± 5.9 0.107	25.6 ± 7.8 0.020	63.6 ± 12.6 0.007
240 deg/sec	9.0 ± 3.3 0.199	11.9 ± 4.5 0.139	16.2 ± 3.4 0.002	13.3 ± 3.4 0.003	22.4 ± 7.2 0.126	54.5 ± 14.4 0.011	40.7 ± 5.9 0.001
Eccentric contractions							
30 deg/sec	16.0 ± 7.3 0.048	16.0 ± 3.0 0.001	15.6 ± 3.4 0.004	22.8 ± 7.3 0.001	21.8 ± 5.1 0.001	22.1 ± 5.1 0.003	40.5 ± 11.9 0.001
60 deg/sec	20.2 ± 6.2 0.007	21.3 ± 3.9 0.001	22.4 ± 4.8 0.001	28.3 ± 6.1 0.001	33.6 ± 7.9 0.001	46.6 ± 13.8 0.001	39.8 ± 12.7 0.003

p values indicate ANCOVA significance levels (see text for details).
*Mean percent change in strength between baseline testing (n = 10) and after 10 weeks of strength training (n = 10).

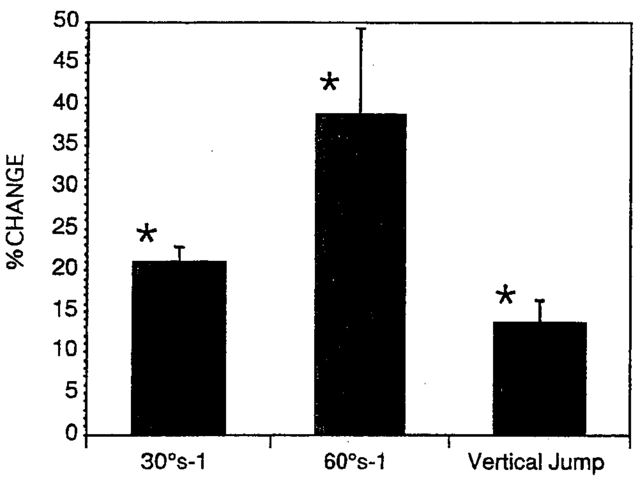

Figure 3 Percent change (before-to-after training) in eccentric contractions at 30 deg/sec and and at 60 deg/sec and in vertical jump. Results are presented as means with standard error bars; *significantly different from before training, $p < 0.05$.

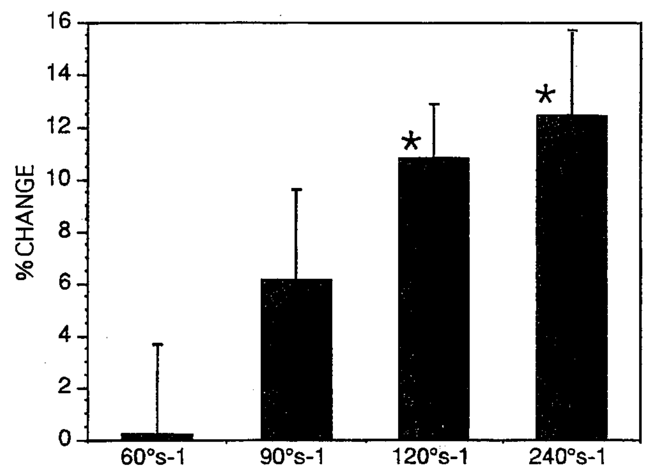

Figure 4 Percent change (before-to-after training) in muscle power at several movement velocities. Results are presented as means with standard error bars; *significantly different from before training, $p < 0.05$.

mal performance of the same movements used during training. Moreover, our findings strongly support the contention of Dudley *et al.*[10] that resistance exercise that combines both eccentric and concentric muscle contractions substantially improves strength. Exercises involving both eccentric and concentric contractions have been reported to accentuate training intensity by providing optimal resistance per repetition.[22] It is also possible that fast-twitch, high-threshold motor units are preferentially recruited during the eccentric phase of training.[20] Eccentric contractions also use less energy per unit of tension than do concentric contractions.[2,4,15,25] Thus, incorporating eccentric and concentric contractions into an exercise regimen may reduce the metabolic cost associated with training during space flight while promoting neuromuscular fitness.

Natural human behavior involves moving limb segments through a large range of joint angles at a variety of speeds. We sought to determine not only if the training protocol resulted in increases in peak torque within the range of joint angles with the greatest biomechanical advantage (50 to 70 degrees),[26] but also if strength was improved over a range of knee joint motions and velocities. Our findings indicate that strength increased throughout the entire range of eccentric and concentric motion across all of the speeds tested (*Table 2*). Maintaining neuromuscular activation across a full range of initial fiber lengths is important if atrophy of specific fibers is to be prevented during long-duration space flight. In microgravity, purposeful lower limb activities, including movements of joints through their entire ranges of motion, are severely diminished. Fibers that are preferentially involved in producing motion at either end of a joint's range of motion could be expected to be underused during space flight and therefore would be subject to selective atrophy. Exercise countermeasures designed to maintain muscle fiber integrity across a full range of joint motions will assume greater importance during extended space flights.

For most joints, force generation tends to be greatest during the mid-range of motion and curtailed near the upper and lower limits because of biomechanical factors and the length-tension properties of working muscles. We expected to find the greatest improvements in concentric strength at joint angles of 80 and 90 degrees. However, our training protocol of horizontal jumps and squats required relatively large moments of force at knee joint angles of approximately 90 degrees in order to move the training sled. This action required activating many muscle fibers at muscle lengths not normally requiring near-maximal activation. Very few movements require knee extension against substantial resistance from a supine position. Thus, the muscle fibers activated to produce horizontal knee extension are rarely "worked" in the position needed to effectively accomplish our training movement. Large initial strength gains typically are found when untrained subjects begin resistive exercise,[19] and we speculate that this may be responsible for the large strength gains displayed by our subjects at the upper range of knee joint motion.

Measures of power represent the amount of work a muscle can produce per unit of time. Plyometric training enhances not only the amount of force generated but also its rate. Plyometrics is thought to enhance the functional link between speed and strength, leading to improved power production.[8] This improvement in the ability to develop force quickly may result from enhanced motor unit recruitment patterns, improved ability to store elastic energy, or facilitation of the stretch reflex.[1,16] For our subjects, concentric power produced at the two fastest movement velocities (120 and 240 deg/sec) improved significantly with training, which probably reflects the subjects' experience with these velocities during the plyometric training. The increases in vertical jump height also are consistent with the increases in power at the fastest movement velocities.

Conclusions

We designed and evaluated a training protocol combining plyometrics and heavily loaded eccentric contractions and found it to be effective in increasing knee extensor strength. The unique design of the test device, the Shuttle 2000-1 Cardiomuscular Conditioner, will allow progressive resistance to be provided in a microgravity environment. This capability is important not only to prevent muscle atrophy, but also to retard the degree of bone loss related to the load and strain rate applied to the limbs.[6] We recommend further investigation of this device with female subjects, with a variety of training protocols, and with measures of neuromuscular function in order to characterize its utility in preserving neuromuscular function during space flight.

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