Intermittent Pneumatic Compression Effect on Eccentric Exercise-Induced Swelling, Stiffness, and Strength Loss

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ABSTRACT. Chleboun GS, Howell JN, Baker HL, Ballard TN, Graham JL, Hallman HL, Perkins LE, Schauss JH, Conatser RR. Intermittent pneumatic compression effect on eccentric exercise-induced swelling, stiffness, and strength loss. Arch Phys Med Rehabil 1995;76:744-9.

• *Objective:* The purpose was to determine if intermittent pneumatic compression (IPC) affects muscle swelling, stiffness, and strength loss resulting from eccentric exercise-induced injury of the elbow flexors. We hypothesized that the compression would decrease swelling and stiffness. *Design:* Repeated measures design with a before-after trial comparison within each day. *Setting:* Conducted at a university Somatic Dysfunction Laboratory. *Subjects:* Twenty-two college women students were studied. They had not been lifting weights or otherwise participating in regular arm exercise for the 6 months before the study. They had no history of upper extremity injury or cardiovascular disease. *Interventions:* Subjects performed one bout of eccentric exercise at a high load to induce elbow flexor muscle injury. Uniform IPC was applied on the day of exercise and daily for 5 days at 60mmHg, 40 seconds inflation, 20 deflation for 20 minutes. *Main Outcome Measures:* Measurements of arm circumference, stiffness, and isometric strength were recorded before exercise, then before and after IPC for 5 days after exercise. Passive muscle stiffness was measured on a device that extends the elbow stepwise and records the torque required to hold the forearm at each elbow angle. *Results:* Circumference and stiffness increased and strength decreased during the 5 days post-exercise ($p < .05$). IPC significantly decreased circumference and stiffness most notably on days 2 and 3 after exercise ($p < .05$). The strength loss was not affected by IPC. *Conclusion:* IPC is effective in temporarily decreasing the swelling and stiffness after exercise-induced muscle injury.

Eccentric exercise of untrained muscles is particularly effective in producing exercise-induced muscle injury, manifested as muscle swelling, stiffness, strength loss, and soreness.[1] It is thought that mechanical disruption of the sarcolemma and sarcoplasmic reticulum leads to a disruption of calcium homeostasis possibly resulting in muscle cell degradation.[2,3] In response to the tissue damage, the inflammatory process begins and leads to, among other things, muscle swelling. One report showed that both eccentric and concentric muscle actions caused edema 24 and 48 hours after exercise in rabbit triceps surae muscle.[4] Based on animal experiments, this swelling is likely to include both intracellular and interstitial edema.[5] Swelling in the human arm reaches a maximum about 4 days after the eccentric exercise of the elbow flexors and gradually returns to pre-exercise levels 10 days after exercise.[1] Because the effects of exercise-induced muscle injury are readily measurable, reproducible, and temporary, exercise-induced muscle injury is a good model for studying therapeutic intervention.

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One such therapy that has been used for the reduction of swelling in the limbs is intermittent pneumatic compression (IPC). IPC, a mechanical squeezing of the limb, has been used effectively for treatment of swelling caused by lymphatic disorders or posttraumatic edema.[6] Specifically, studies showed a significant reduction in swelling after IPC both in cases of acute ankle sprains and after cast removal subsequent to leg fractures.[7-9] In addition to decreasing swelling, IPC treatments have produced increased range of motion of involved joints.[10,11] The use of IPC for the treatment of swelling after exercise-induced muscle injury, however, has not been studied.[6] The purpose of this study was to determine if IPC is effective in decreasing the swelling, stiffness, and strength loss that occurs after intense eccentric exercise of the elbow flexor muscles.

METHODS

Women college students were randomly assigned to either an exercise group (n = 22; 21.7 ± 0.7 years) or a group that did not exercise (n = 10; 21.3 ± 1.2 years). The subjects had not participated in strength training for the year before the study or during the study. They did not have a history of upper extremity injury or cardiovascular disease. In addition, they were asked to refrain from using aspirin or other analgesic drugs during the study. All subjects signed an informed consent approved by our university Institutional Review Board.

The exercise used to induce injury consisted of three sets of eccentric exercise performed with weights equal to 90%, 80%, and 70% of the isometric maximal voluntary contraction (MVC). The experimenter lifted the load to the starting position and the subject slowly lowered the load from full elbow flexion to elbow extension. The exercise set was stopped when the subject was no longer able to control the descent of the weight for 5 seconds. This usually occurred after approximately five repetitions in each of the three sets. A 2-minute rest period was provided between each set. Soreness, arm circumference, isometric strength, stiffness, and relaxed arm angle were measured three times before exercise, immediately after exercise (post), and daily for 5 days. The mean of the three pre-exercise measurements was used as a reference for determining the changes occuring after exercise.

Soreness was assessed using a five-point pain rating scale: 0, no pain; 1, pain on palpation; 2, mild pain on full flexion or extension; 3, significant pain on full flexion or extension; 4, continuous pain without motion. We instructed the subjects to rate their pain in the morning and afternoon; however, because of inconsistencies in recording the afternoon measurement, only the morning pain ratings were used for analysis.

Circumference was measured with a Gulick tape measure, which is designed with a spring device to control the amount of tension during measurement, at the mid-belly of the biceps (mid) and 2.5cm proximal to the lateral epicondyle (distal) while the subject stood with the arm relaxed at the side. Although significant swelling has been recorded at both locations on the arm,[1] we chose to continue making two measurements because of a possible differential effect of the IPC. We marked the location of the circumferential measurements to ensure reproducible placement of the tape measure. The reliability of the circumference measurements evaluated on the three pre-exercise values was very good, yielding an intraclass correlation coefficient (3,1) of 0.997 and 0.995 for mid and distal respectively.

Isometric MVC of the elbow flexors was measured on an apparatus similar to an arm curl apparatus. The subject sat on a bench with the nondominant upper arm supported at 30° of shoulder flexion and performed three maximum contractions on three different days before exercise. The highest torque of these nine contractions was recorded as isometric MVC. A cable and pulley system was designed to provide constant torque throughout the movement and the subject pulled against a pad at the distal forearm. A strain gauge attached to the cable measured torque exerted at 90° of elbow flexion. The strain gauge[a] was attached to a U-shaped piece of metal and calibrated to the nearest Newton meter (Nm). During eccentric exercise, the cable was attached to a stack of weights to provide resistance.

Static stiffness was measured by having the subject lie prone on a table next to the stiffness machine with the forearm resting on a freely moving platform while the upper arm was stabilized on a stationary platform (fig 1). A programmable stepper motor moved the forearm into extension in 5° steps. The position of the arm was determined by a potentiometer calibrated to provide an output in degrees of elbow motion. A strain gauge on the moveable arm of the device measured the force required to hold the arm at each step. The force was converted to torque by multiplying by the distance between the strain gauge and the axis of motion. The slope of the torque-angle curve defines stiffness of the elbow flexors. The mean slope (in Nm/degree) of three pre-exercise stiffness measurements was used as a reference for all postexercise stiffness measurements. Surface electromyographic (EMG) recordings of the biceps and triceps were used to ensure that the subjects were relaxed for the passive stiffness measurements. Stiffness and EMG data were recorded at a sampling frequency of 50Hz with a microcomputer using the RC Computerscope[b] data acquisition package. Another measurement of static stiffness is the relaxed arm angle. We measured the angle of the elbow with a standard 12-inch plastic goniometer with the subject standing with the arm hanging by the side using the ulnar styloid (because the relaxed forearm assumes a semipronated position), lateral epicondyle, and the anterior lip of the acromion as landmarks.

Each variable was measured before and after daily IPC treatments, beginning immediately after the exercise (post) and daily for 5 days. IPC was applied using a Chattanooga "PresSsion" pump[c] and a single chamber sleeve that delivered uniform compression to the whole arm. Pressure intensity was set at 60mmHg, and duration was 20 minutes alternating 40 seconds inflation and 20 seconds deflation. We chose these parameters because they are similar to those used in other recent studies and because this protocol is similar to typical clinical use.[6,10] The subject sat in a chair with the exercised arm supported at approximately shoulder level. The compression sleeve was pulled up to the axilla and included the hand. The elbow angle was about 120° within the sleeve during treatment, but was positioned at the angle of comfort for each subject. To determine the effect of the compression without exercise, we measured circumference, stiffness, and strength before and after IPC in a control group that did not exercise.

Statistical Analysis

The data were transformed for statistical analysis using an arcsin transformation to produce the best normal distribution of variables. Differences between pre-exercise and all postexercise values and differences between pre- and post-compression on each day were analyzed with a two way analysis of variance (ANOVA) with repeated measures to identify main effects. Because the assumption for sphericity was not always met, the Greenhouse-Geisser epsilon was used to correct the degrees of freedom in the univariate approach. The Bonferroni correction for alpha was used for each of the multiple comparisons (eg, pre- and postcompression $\alpha = .05/6 = .0083$). The effect of the compression on the group that did not exercise was analyzed with paired t-tests. All results are presented as mean percent change from pre-exercise $\pm$ standard error.

RESULTS

Soreness

Soreness of the elbow flexors, which was only measured before compression, peaked on the second day after the exercise (fig 2). The time course of soreness is consistent with the literature on delayed onset muscle soreness.

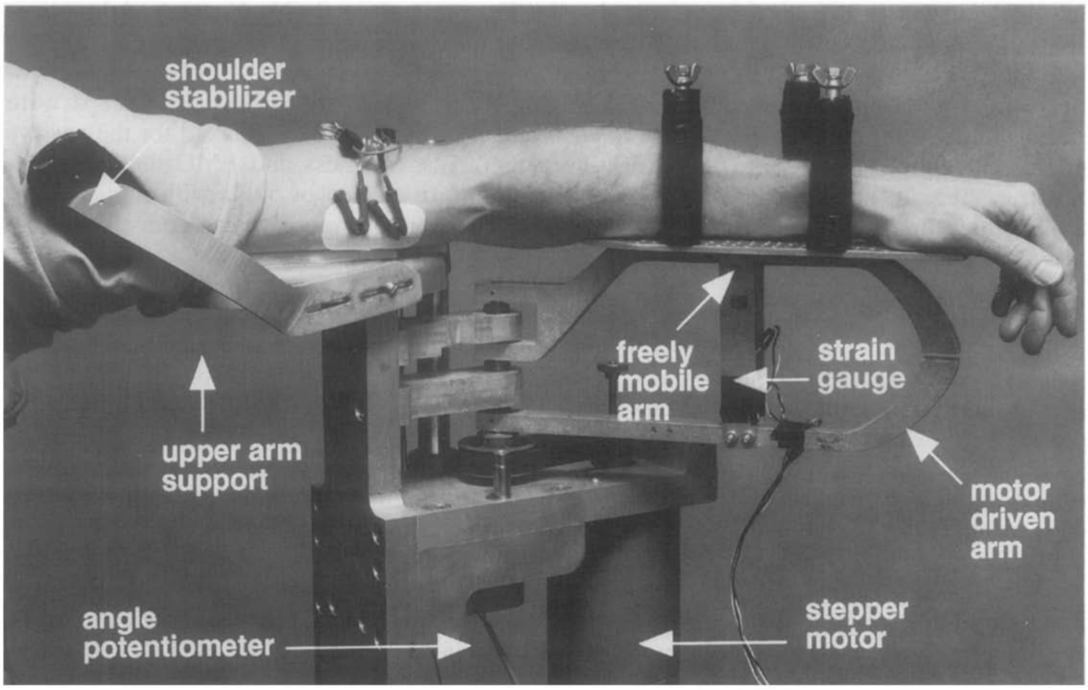

Fig 1—Apparatus for measuring stiffness.

Swelling

The mid circumference of the biceps increased significantly from pre-exercise on postexercise days 1 to 5 measured before daily compression ($p < .05$) and on days 4 and 5 measured after compression ($p < .05$). The peak change in midcircumference of 4.2% ± .9 occurred on day 4 (fig 3). Following the exercise, compression decreased the midarm circumference on days post, 1, 2, 3, and 5 (fig 3). Distal circumference likewise increased from pre-exercise values on days 2 to 5 as measured both before and after compression and on day 1 before compression ($p < .05$). The peak change in circumference (7.3% ± 1.2) was observed before compression on day 4 (fig 4). The distal circumference decreased after compression on day 2 ($p < .05$) and day 3 ($p < .01$). In the control group, circumference at mid and distal points on the arm was not significantly different pre- to postcompression ($p = .133$ and $p = .175$ respectively).

Stiffness

The slope of the torque-angle curve over the first 50° of passive elbow extension after measurable torque is first

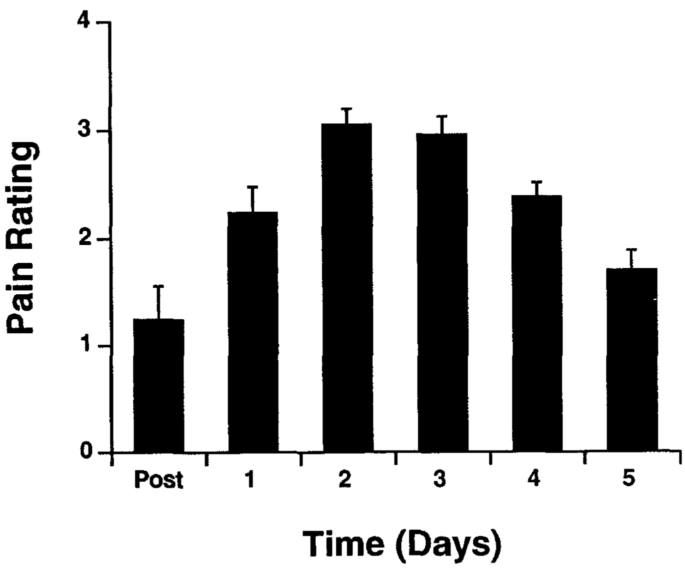

Fig 2—Pain rating measured immediately after exercise (post) and for 5 days after exercise. Subjects recorded their pain level before compression on each day. (0, no pain; 1, pain on palpation; 2, mild pain on full flexion or extension; 3, significant pain on full flexion or extension; 4, continuous pain without motion.)

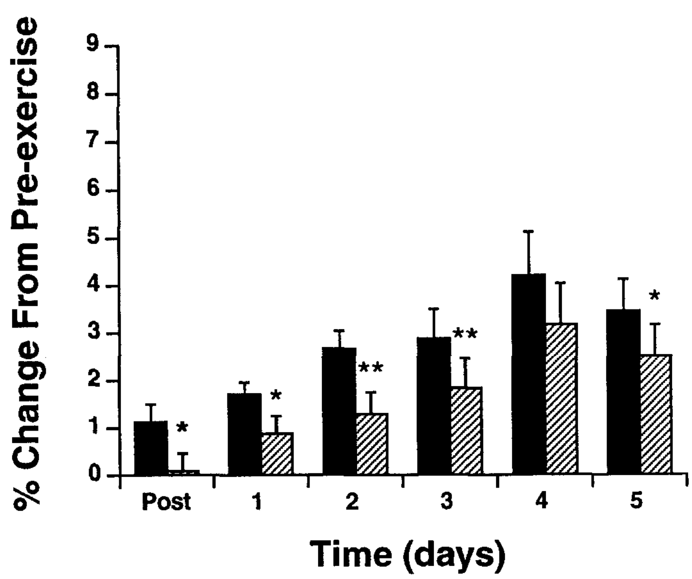

Fig 3—Mid-arm circumference measured before compression and after compression. Significant decreases in circumference caused by compression are indicated with asterisks (*$p < .05$, **$p < .01$). Mean pre-exercise midcircumference was 26.0 ± 0.7cm. In all figures, shaded histograms represent precompression and lined histograms represent postcompression.

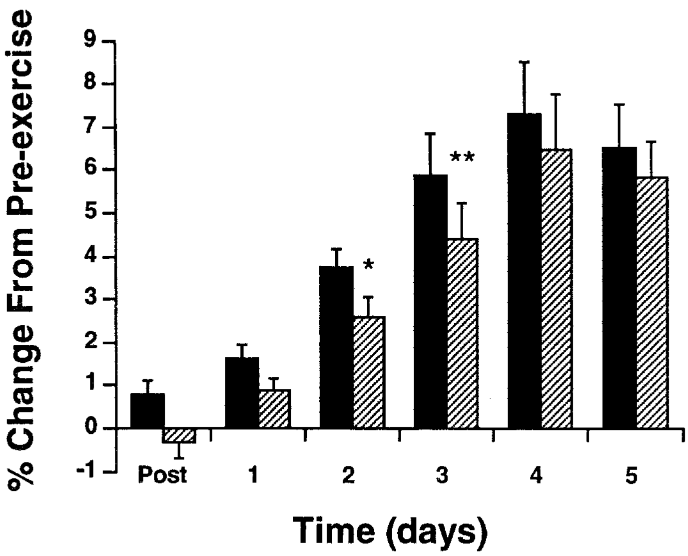

Fig 4—Distal arm circumference measured before and after compression. Significant decreases in circumference caused by compression are indicated with asterisks (*$p < .05$, **$p < .01$). Mean pre-exercise distal circumference was 23.4 ± 0.6 cm.

detected (about 100°) defines the stiffness (fig 5). The mean percent change stiffness from pre-exercise is plotted in fig 6. The muscle stiffness significantly increased by over 100% following the exercise ($p < .05$) and gradually decreased over days 3 to 5 (fig 6). IPC significantly decreased the muscle stiffness on days 2 and 3 ($p < .05$). Elbow flexor stiffness in the control group did not change pre- to postcompression ($p = .305$). Resting arm angle becomes about 12% more flexed after the exercise ($p < .05$) but was not significantly affected by IPC despite a trend toward more extended arm angles after IPC (fig 7).

Strength

Maximum voluntary isometric strength of the elbow flexors decreased by 50% after the exercise (fig 8) and was unaffected by compression. Likewise the compression had no effect on the control group elbow flexor strength ($p = .456$). This loss of strength has been discussed elsewhere and gradually returned to pre-exercise levels in 5 to 12 weeks.[1]

DISCUSSION

It has been well established that eccentric exercise, such as the exercise in this study, causes muscle injury that leads to local swelling, stiffness, and strength loss.[12] Our results suggest that IPC is effective in temporarily decreasing exercise-induced swelling and stiffness. This is consistent with others who have shown that IPC decreases posttraumatic edema and increases range of motion in patients with fractures of the lower leg[11] and with ankle sprain injuries[7-9] although the type of injury and the tissues injured are different. The present data show that the compression effect is time dependent, because IPC had the greatest effect on these two variables on days 2 and 3 after the exercise. The IPC had no statistically significant effect on the change in arm angle or the change in strength after exercise.

Compression tends to decrease circumference during the time that swelling was increasing. Significant effects in both arm locations were observed in common on days 2 and 3 after the exercise. This may be the time when the fluid is leaking from the muscle compartment to the subcutaneous space. There is some preliminary evidence based on ultrasound images of the upper arm that elbow flexor compartment volume accounts for a greater proportion of the total volume on day 1 after exercise and the subcutaneous space accounts for a greater proportion on day 4.[13] The flexor compartment accounts for 59% of total swelling on the first day after exercise, and only accounts for 43% on day 4 after exercise. The volume of the subcutaneous space increases from 41% of the total swelling on day 1 to 57% on day 4. This suggests that a substantial portion of the fluid is leaking to the subcutaneous space between days 1 and 4. On days 2 and 3 compression may assist the movement of fluid from one compartment to another and may also assist the lymphatic system, which is more abundant in the subcutaneous space than around the endomysium of muscle, in removing fluid from the local tissues.[14] By day 4 the volume of fluid in the subcutaneous space (and the muscle) may be too great for the compression to significantly decrease. Unfortunately, there are no ultrasound data for days 2 and 3, and beyond day 4. Palpatory examination of the subjects supports the notion that the fluid is moving from muscle compartment to

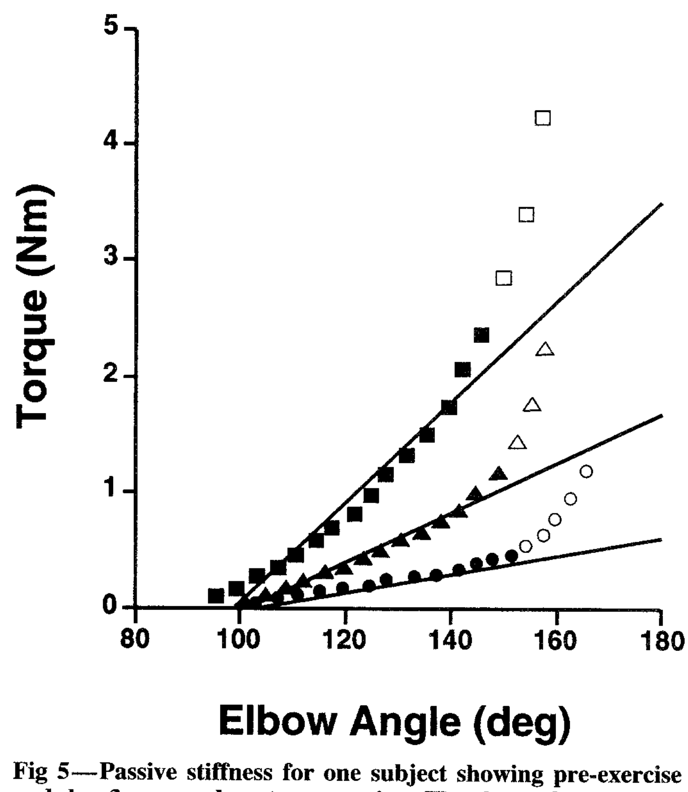

Fig 5—Passive stiffness for one subject showing pre-exercise and day 3 pre- and postcompression. The slope of the regression line fit to the points over the first 50° of elbow extension defines the muscle stiffness. Pre-exercise $f(x) = .0077x - .76$, $R^2 = .98$; day 3 precompression $f(x) = .0435x - 4.31$, $R^2 = .95$; day 3 postcompression $f(x) = .0215x - 2.19$, $R^2 = .97$. Open symbols represent the nonlinear continuation of the torque-angle curve. ■ Day 3, precompression; ▲ Day 3 postcompression; ● Pre-exercise.

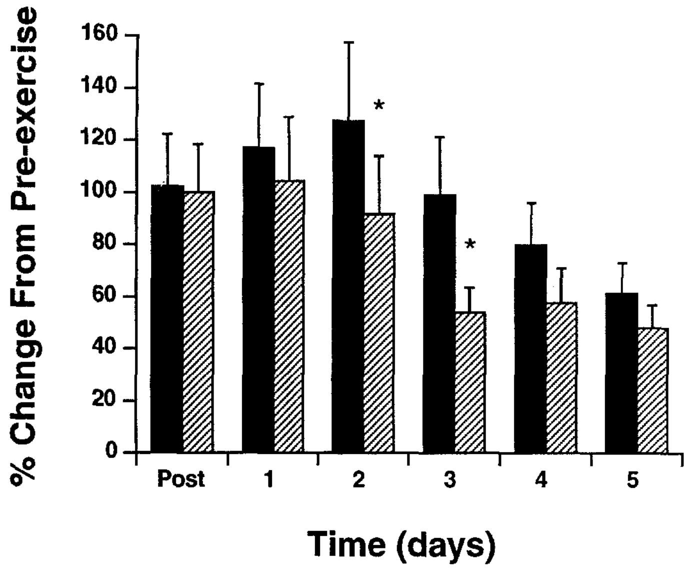

Fig 6—The effect of compression on muscle stiffness. Significant decreases between pre-compression and postcompression are indicated (*$p < .05$). The pre-exercise mean stiffness was 0.0127 ± 0.0011 nm/degree.

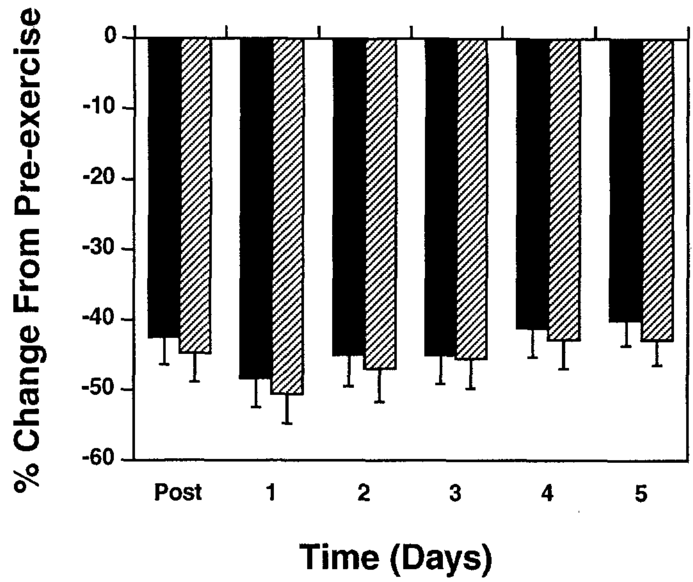

Fig 8—Strength loss after exercise. Compression did not have a significant effect on the strength loss. The pre-exercise mean strength was 42.0 ± 1.4 nm.

the subcutaneous space in that the elbow flexors are firm at day 1 with little subcutaneous swelling and on day 4 they are softer with more subcutaneous swelling.

The temporary nature of the compression effect on swelling was evident in the fact that the time course of precompression swelling was not different from the time course of swelling in a group of subjects who did not receive any treatment. Differences between these results showing an acute reduction in swelling and other recent studies showing a more prolonged IPC effect may be caused, in part, by differences in the type of compression device, uniform in this case as opposed to sequential.[6,7,10,11] Uniform compression units have a single chamber that inflates and sequential units have several chambers that inflate distally to proximally. It is possible that if a sequential unit, which has been shown to be more effective in reducing swelling, had been used the effects would have been more pronounced.[15,16] In addition, the temporary effects of IPC observed here may be caused by the acute nature of the exercise-induced injury suggesting a continuing process of edema formation, whereas in some studies the injury occurred weeks before the application of IPC.[10,11]

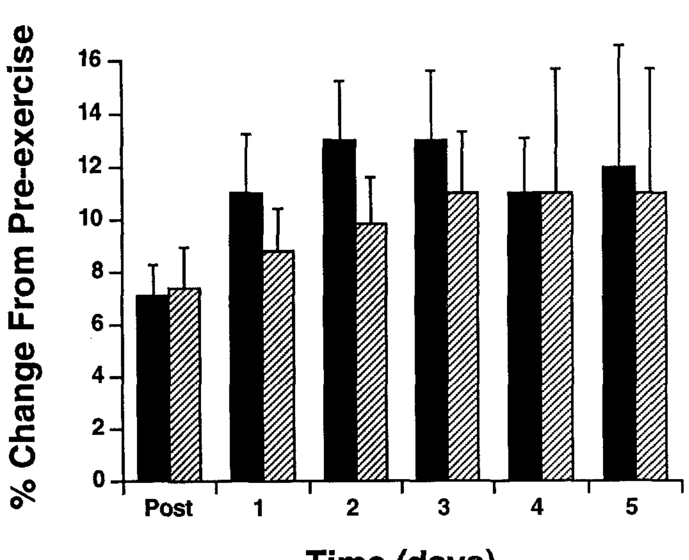

Fig 7—Change in arm angle with compression. The compression effect was not significant. The pre-exercise mean arm angle was 163.1 ± 1.6 degrees.

The origins of increased muscle stiffness in this model are less clear. If the swelling accounted for the increased stiffness then the time course of swelling and stiffness should have been about the same. This occurred neither in this study nor when subjects were followed for 10 days after the exercise.[1] Our measurement of muscle stiffness is made over elbow angles between about 100° to 150° reflecting the resistance to lengthening before the elbow reaches full extension. It has been suggested that the increased stiffness in this part of the range of motion may possibly result from a low level activation of the resting muscle rather than from strain on the connective tissue of the muscle.[1] Although the subjects were asked to relax during the stiffness measurements, we found that occasionally there was low level EMG activity during the measurement. It may be argued that the compression could decrease the muscle activity as measured by EMG thus decreasing stiffness. However, if the IPC had a significant effect on the EMG, then stiffness would have decreased after IPC in the control subjects as well. As noted previously, IPC had no affect on stiffness in the control group. Why did IPC decrease swelling and stiffness on about the same days? Although we do not have direct evidence from the present data, the answer may be related to the location of the swelling. We measured the circumference of the arm and not of the muscle compartment. If swelling within the muscle compartment accounts for some fraction of stiffness in this initial phase of the stiffness curve, and IPC decreases muscle compartment swelling at the time when fluid is leaking from the muscle compartment to the subcutaneous compartment, then we may see a temporary drop in stiffness but not an abolition of stiffness. This temporary compression effect on the stiffness is supported by the observation that the time course of muscle stiffness before compression is the same as the time course of increased muscle stiffness described in a previous study in which there was no compression treatment.[17]

Resting arm angle may also be considered a measurement of stiffness.[18] The decrease in the resting arm angle (elbow becoming more flexed) may be a function of the swelling. The time course of the change in resting arm angle from pre-exercise is consistent with the gradual increase in swelling through the first 4 days postexercise. Howell and colleagues have presented the analogy of a water balloon in a nylon stocking to represent swelling in the muscle compartment that would limit the extent of motion but not the initial stiffness.[19] Because IPC decreases the swelling then range of motion should increase. This increase in motion after daily IPC was shown in patients with acute ankle sprains.[7] However, the application of IPC in this study did not significantly change the resting arm angle. This discrepancy may be caused by the method of the goniometric measurement. We merely asked the standing subject to relax the arm, whereas Airaksinen and coworkers[6] seemed to measure active range of motion. Figure 6 shows that the IPC has a tendency toward decreasing arm angle on days 2 and 3, but the coefficient of variation in these measurements is quite high (75%) leading to very poor power of the statistical test.

Exercise-induced muscle injury is an excellent model for evaluation of the effectiveness of clinical therapeutics. The swelling, stiffness, and strength loss associated with this type of muscle injury are both reversible and reproducible. IPC was shown to be effective in temporarily decreasing muscle swelling and stiffness after eccentric exercise. Despite the temporary reduction in swelling and stiffness, IPC was not effective in changing the 5-day time course of these variables. The relationship between muscle swelling and stiffness remains to be determined.

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Suppliers

a. Strain gauge; Micromeasurements Division, PO Box 27777, Raleigh, NC 27611.
b. RC Computerscope data acquisition package; RC Electronics Inc, 5386-D Hollister Avenue, Santa Barbara, CA 93111.
c. Chattanooga Pression pump model 4322, Chattanooga Corporation, PO Box 4287, Chattanooga, TN 37405.