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A BIOMECHANICAL COMPARISON OF THE EFFECTS OF CONSTANT AND CYCLIC COMPRESSION ON FRACTURE HEALING IN RABBIT LONG BONES*

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In a biomechanical study, the strength of healing experimental fractures in rabbit tibias was compared for two different healing environments. During the healing period large constant compression was applied to one leg, while the other leg was subjected to cyclic compression forces. Rabbits were sacrificed at 3, 4, 5, 6, and 8 weeks after the operation. The healing bones were tested in a dynamic torsion testing machine. Results indicate that on an average basis the cyclic compression treated bones exhibited higher torque and energy absorption to failure, but lower stiffness as compared with the constant compression treated bones, during the 30 to 50 days' healing period. These differences were statistically significant. Additionally, it was estimated that a 27 per cent saving in healing time may be realized for a bone treated with cyclic as compared with constant compression.

Key words: biomechanics; constant compression; cyclic compression; fracture healing; torsion test

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Several different methods may be utilized for the treatment of any given long bone fracture. The most efficient treatment method remains to be discovered (White 1975). There have been several experimental studies designed to evaluate the effects of different mechanical environments on intact bones as well as healing fractures. In some the end point was a histological evaluation (Hutzchenreuter et al. 1969, Rahn et al. 1971, Harris et al. 1977), while in others it was the mechanical strength that determined the outcome (Olerud & Danckwardt-Lilliestrom 1960, Falkenburg 1961, Lettin 1965, 1968, Tonino et al. 1976, Woo et al. 1976, Panjabi et al. 1977, and White et al. 1977a). Previous investigations in this laboratory did not show any significant differences in the response of healing long bone fractures to constant compression versus intermittent cyclic compression as measured by mechanical torsional strength (White et al. 1977a). The goal of this study is to compare *more* widely disparate mechanical environments in a rigorously controlled experiment to evaluate the response of healing long bone fractures to large constant compression and rigidity versus cyclic compression and motion.

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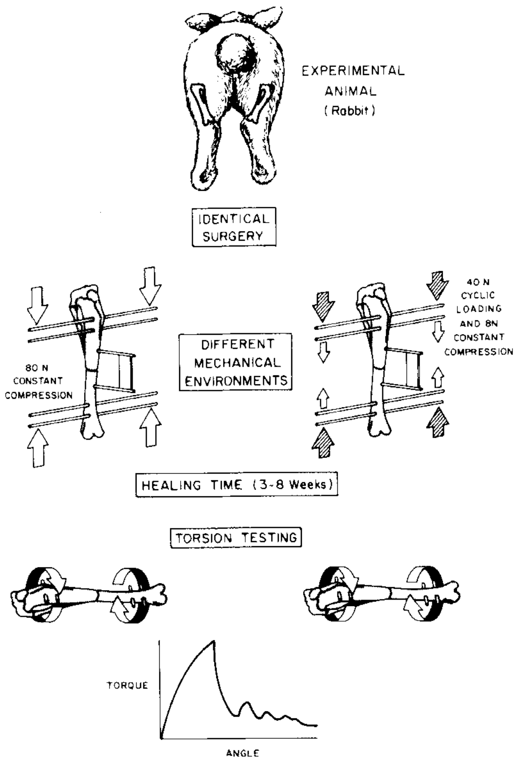


Figure 1. Experimental design.

MATERIALS AND METHODS

Experimental design and apparatus

Adult, female, New Zealand white rabbits were chosen as the experimental animal. The design of the experiment is shown in Figure 1. Identical transverse fractures were produced and fixed in the two tibias of the same animal. They were allowed to heal under different mechanical environments for varying intervals of time. After sacrifice, the mechanical characteristics of the healing fractures were determined by a dynamic torsion test. Potential biological variables of age, sex, fracture type and location, diet, and activity level were standardized and kept constant. In this design each leg served as a control for the other. Previous investigations have analyzed mechanical symmetry in rabbit long bones and found biologically normal variation with no pattern of right or left dominance (Puhl et al. 1972, White et al. 1974, Tonino et al. 1976). Therefore, for this experimental design, the assumption of mechanical symmetry in rabbit long bones is justified.

Constant compression clamp. Four compression clamps were used on each animal, one on each side of each hind leg. The clamp is shown in Figure 2A. The simple design of the clamp allowed precise force application and monitoring without the need for delicate strain gauges. The compression force applied to the fracture site was determined by the length of the spring in the compression clamp. The springs were calibrated against a load cell. Therefore, maintenance of a constant amount of compression only required the spring length to be measured and, if necessary, adjusted to a predetermined value. Each clamp was monitored and adjusted daily.

Cyclic compression system. An electro-pneumatic system was developed which applied a cyclic compressive force of predetermined magnitude and frequency to the fracture site. An air cylinder applied a compressive force to the fracture site via jaws attached to the transverse Kirschner wires above and below the experimental fracture (Figure 2B). The compressed air to the piston was controlled by a solenoid valve actuated by a rotating cam. Each cyclic unit was individually calibrated to obtain the same cyclic force. A cyclic compressive load with a square-wave pattern was generated at a frequency of 55 cycles per minute. The force pattern was frequently monitored and adjusted to the correct value throughout the experiment. One of the important features of this experiment has been the precise control of the mechanical environment of the healing fractures.

Surgical procedure

The day before surgery the rabbits were sedated with intramuscular ketamine and the hind legs were shaved. On the day of surgery the animals were anesthetized using a mixture of halothane, N_2O and O_2 delivered by mask using a standard small animal veterinary anesthesia machine. After the legs were prepped each animal was given 300,000 units of Procaine Penicillin intramuscularly as prophylaxis against infection. The animal was then placed on a sterile draped operating table. Using a template guide, two 1.6 mm ($\frac{1}{16}$ inch) stainless steel Kirschner wires were drilled above and two below the mid shaft of the tibia in the frontal plane. A constant compression clamp was then placed over the transverse Kirschner wires on each side of the leg and locked into place 6 cm apart with the legs centered between the two clamps. The springs were locked so that no compression was applied at this time. Two 2 mm ($\frac{5}{64}$ inch) threaded Steinmann pins were then drilled into each tibia in the sagittal plane from anterior to posterior. These pins were

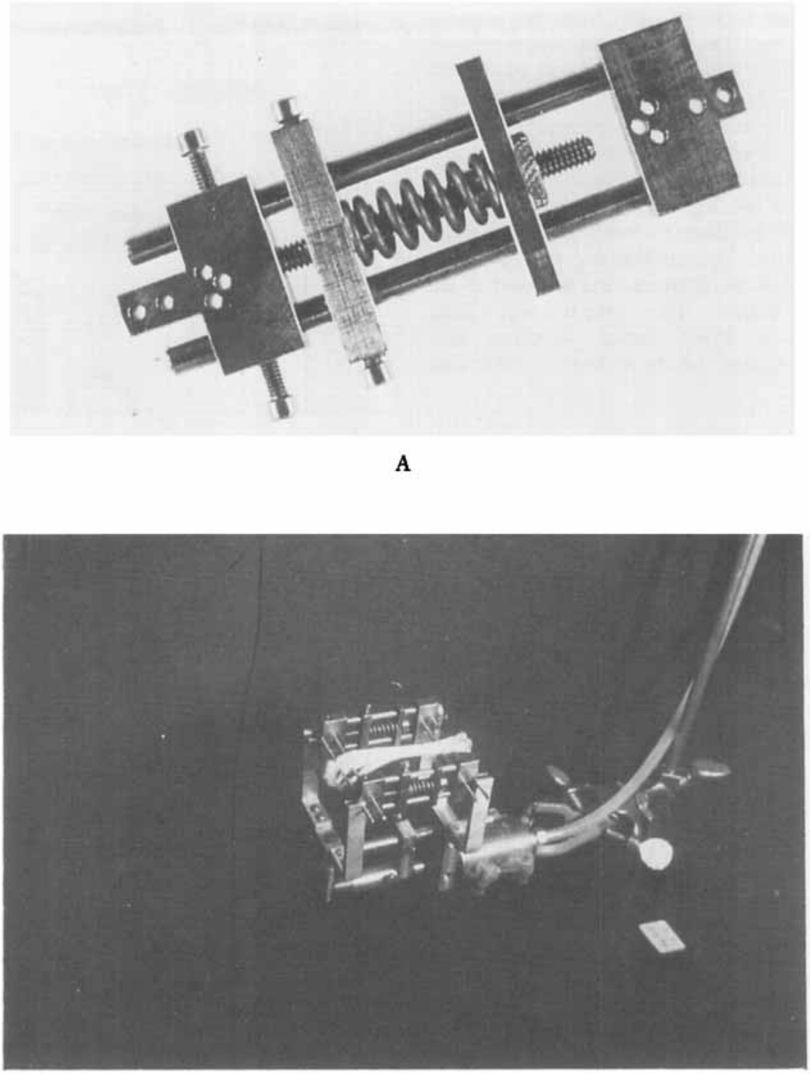


Figure 2. Apparatus for producing the two mechanical environments. (A) Constant compression clamp. (B) Cyclic compression system.

positioned 3–5 mm (about 0.2 inch) from the transverse pins, and placed so that they penetrated the anterior and posterior tibial cortices but did not exit through the skin posteriorly.

A longitudinal skin incision was then made on the anteromedial border of the tibia exposing the extensor muscle mass. The muscle was retracted laterally exposing the shaft of the tibia. The periosteum was sharply incised in line with the skin incision and elevated circumferentially. A standardized osteotomy (the experimental fracture) was then made midway between the two closest transverse Kirschner wires using a small reciprocating sagittal saw. The fracture was reduced and compression was applied by releasing the springs in the two compression clamps. The wound was irrigated and the skin was closed using a running suture of 6–0 Dexon.

The anterior threaded Steinmann pins were next secured in a custom designed sandwich clamp at a point 5 cm (2 inch) from the anterior surface of the leg. The purpose of this clamp on the two anteriorly projecting pins was to control bowing at the osteotomy site in the sagittal plane. An identical procedure was performed on both legs. The only difference between each leg was the setting of the force in the compression clamps.

The foot and the leg were then wrapped in a two inch elastic bandage to minimize subsequent dependent edema. Two orthogonal postoperative X-rays were taken to document the position of the osteotomized bones. The rabbit was then transferred to a small canvas stretcher that supported the animal on its abdomen, chest and forelegs.

Mechanical environment

The rabbits were maintained in specially constructed booths. The osteotomized hind legs were unsupported and were attached to an H-shaped aluminum splint to control lateral motion. In this way all uncontrolled, extraneous forces on the fracture were kept to a minimum. Food and water were available at all times immediately in front of the animals for demand feeding. The spring compression clamps were set to provide 80 newtons (18 lb_f) of force on one leg and 8 newtons (1.8 lb_f) on the opposite leg. The forces were monitored daily and adjusted as needed to maintain the constant settings. At 1 week following osteotomy, a pneumatic cyclic loading apparatus was attached to the leg with the compression clamp that had been set to deliver the lower constant compression force of 8 newtons. The side to receive the cyclic loading was alternated at random. The pneumatic system air pressure was adjusted to apply a maximum force of 40 newtons (9 lb_f). The forces are graphically depicted in Figure 3. The cyclic compression load was applied for 3 hours each morning and 3 hours each afternoon. Weekly weighings and X-rays were obtained. Also shown in Figure 3, for the purpose of comparison, are the mechanical environments used in a previous study (White et al. 1977a).

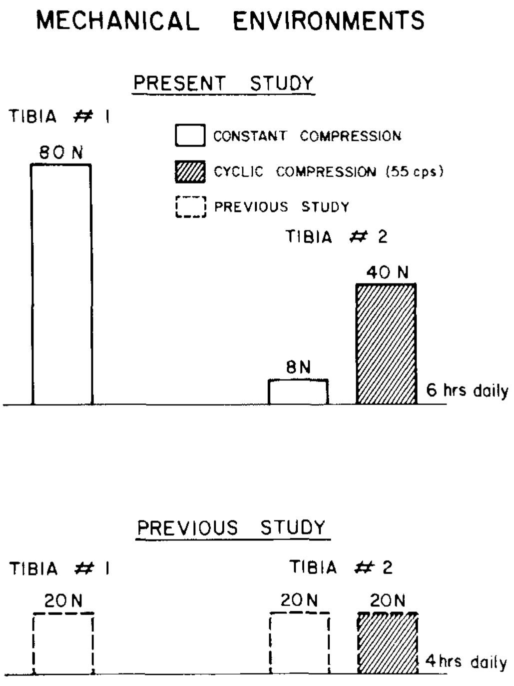


Figure 3. Mechanical environments to which the two tibiae of an experimental animal are subjected. Note that in the present study the two environments are more distinct as compared with the previous study.

Specimen preparation and testing

The rabbits were sacrificed at 3, 4, 5, 6, and 8 weeks after surgery. Each hind limb was disarticulated at the knee joint, wrapped in plastic, labeled, and placed in a freezer at −20 degrees centigrade. At the time of testing the specimen was removed from the freezer and allowed to thaw. The soft tissue at each end of the specimen was then carefully removed using sharp dissection. The soft tissue over the healing fracture was not removed. It prevented the bone specimen from drying out and protected the healing fracture callus. The two ends of each specimen were then potted in a quick setting polyester resin in a special mold to provide firm fixation of the specimen in the testing machine. AP and lateral X-rays of the prepared specimen were taken.

The bone specimen with its ends firmly fixed in the resin was tested in a dynamic torsion testing machine (Burstein & Frankel 1971). In this machine one end of the bone is held rigidly while the other end is suddenly twisted by a falling pendulum. The rate of deformation produced was 13.2 radians per second or 750 degrees per second. Two transducers continuously measured the torque and torsional deformation of the bone. The torsion testing machine was modified in our laboratory to incorporate parallel recording by a mini-computer in addition to the oscilloscope recording. Parallel recordings by computer system provided redundancies so that no results were lost due to human error. Additionally, it made it possible to reduce and analyze the data generated in an efficient manner. The data was recorded in the form of torque-angle curves. Values of three biomechanical parameters were obtained for each specimen: maximum torque, energy absorbed to failure, and average stiffness. After testing the bone specimen was again X-rayed.

FINDINGS

Three biomechanical parameters. A total of 25 rabbits successfully completed all phases of the study. The paired design of this experiment (a different treatment applied to each hind leg of the same animal) lends itself to reporting the effectiveness of the treatment in the form of the differences found in each measured biomechanical parameter. The results are displayed as a set of difference-graphs in Figures 4, 5 and 6. On the abscissa is the healing time in days, while on the ordinate is plotted the parameter difference P_D, i.e. the difference between the value of a given parameter obtained for the cyclic loading treatment Pc and the value for that parameter for the other hind leg treated with constant compression P_K. Mathematically $P_D = P_C - P_K$. Thus, each single point on the graph represents the *difference* between a pair of bones. Using the method of least squares, a curve $Y = A + BX + CX^2$ was fitted to the data. This is the middle curve in the graphs. The curves above and below it represent the 95 per cent confidence bands of the mean curve.

Figure 4 is a graphic representation of the difference in torque to failure versus healing time. As mentioned, each point represents a pair of bones. This graph thus shows that, on the average with 95 per cent certainty, the cyclically loaded bones exhibit greater torque to failure than the constant compression treated bones between the healing periods of 35 to 52 days. Figure 5 shows a similarly shaped curve for the difference in energy absorbed to failure versus healing time in days. Energy absorbed to failure is probably the best indicator of bone strength. It can be seen that, considering this parameter, there is an even larger period, 29 to 52 days, within which the cyclically treated bones had higher values.

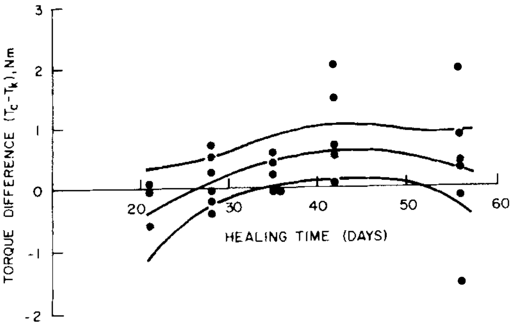


Figure 4. Torque difference ($T_C - T_K$) vs. healing time. The middle curve, representing the average behavior, was fitted to the raw data with the method of least squares. The upper and lower curves are the 95 per cent confidence bounds of the average curve.

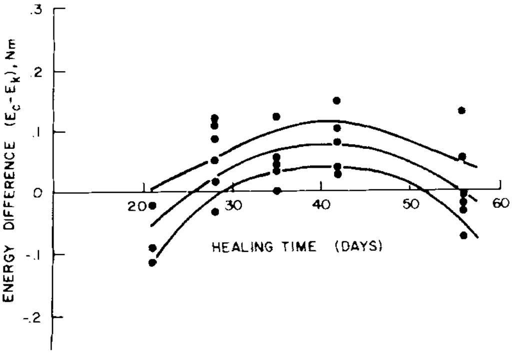


Figure 5. Energy absorbed difference ($E_C - E_K$) vs. healing time. The middle curve, representing the average behavior, was fitted to the raw data with the method of least squares. The upper and lower curves are the 95 per cent confidence bounds of the average curve.

Stiffness, as shown in the graph in Figure 6, exhibits a different pattern. In this case it is the constant compression treated bones that have the higher values in the healing period of 27 to 46 days. This combination of higher stiffness and less energy absorption before failure indicates that the compression treated bones are more brittle and will break more easily (they also have lower torque values) than their counterparts treated with cyclic compression. The data used in the graphs are also numerically analyzed and presented in Table 1. The "mean per cent" columns, for the three biomechanical

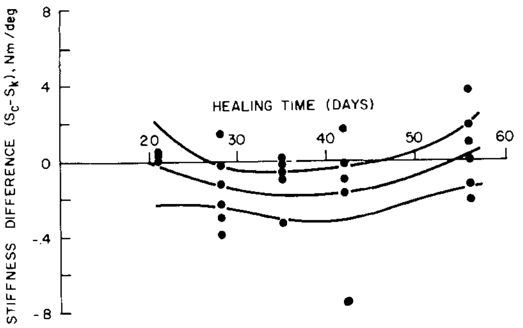


Figure 6. Stiffness difference (S_C-S_K) vs. healing time. The middle curve, representing the average behavior, was fitted to the raw data with the method of least squares. The upper and lower curves are the 95 per cent confidence bounds of the average curve.

parameters, show that after 42 days of healing, the cyclically treated bone is relatively stronger, + 62 per cent, absorbs more energy, + 117 per cent, and is less stiff, − 42 per cent.

A comparison of the results of the present study with those of our previous study is provided in Figure 7. It shows the average maximum torque versus healing time. The three curves shown are for healing bones for the *previous study, constant* compression treated bones and *cyclic* compression treated bones of the present study. The three curves were drawn by the method of least squares using the equation Y = AX + B/X. Also shown is a horizontal dash line representing the intact normal bones.

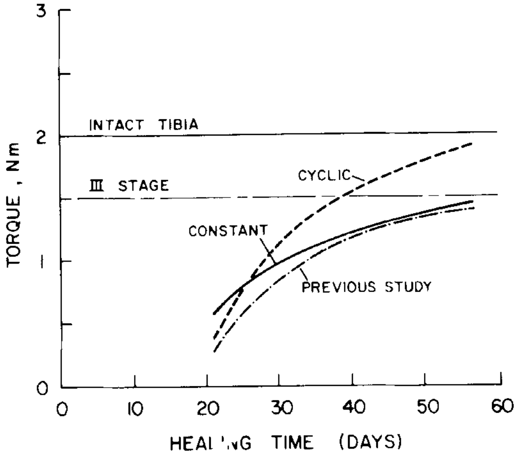


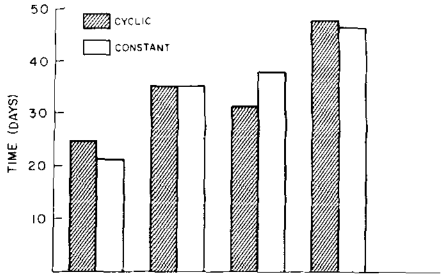
Figure 7. A composite graph of average torque strength vs. healing time for intact tibiae and for healing tibiae treated with cyclic compression, constant compression and those from the previous study. Also shown are the torque strength values for the bones that reached Stage III of healing in the previous study.

Four biomechanical stages. In a previous study, four biomechanical stages of fracture healing have been identified (White et al. 1977b). These were based upon the results of torsion testing. Specifically, the shape of the torque-angle curve and the site of re-fracture determine the biomechanical stage of healing.

Table 1. Average differences between the cyclical and constant compression treated bones. For each biomechanic parameter, i.e. Torque, Energy and Stiffness, the first column shows the mean value of the difference (cyclic minus compression) observed in the group. The second column shows the percentage difference while the third indicates the P*-value for this difference to be significantly different from zero.*

Parameter Difference: Cyclic Minus Constant Compression

Healing days	Number of animals	Torque			Energy			Stiffness		
		Mean Nm	Mean %	*P*	Mean Nm	Mean %	*P*	Mean Nm/deg	Mean %	*P*
21	3	−0.27	−36	< 0.15	−0.08	−42	< 0.02	0.01	20	< 0.10
28	6	0.05	8	> 0.25	0.05	83	< 0.05	−0.18	−82	< 0.02
35	5	0.13	10	< 0.20	0.04	67	< 0.05	−0.13	−43	< 0.05
42	5	0.86	62	< 0.02	0.07	117	< 0.01	−0.20	−42	< 0.15
56	6	0.23	13	> 0.25	0.00	0	> 0.25	0.03	6	< 0.25



BIOM. STAGES		I	II	III	IV	
BONES UNDER TREATMENT	CYCLIC	2	6	7	10	
	CONSTANT	1	4	15	5	
TOTAL BONES		3	10	22	15	n = 50

Figure 8. Time for the healing bones to reach each of the four biomechanical stages of healing is shown. Time to reach the clinically important Stage III of healing is shorter for the cyclical compression treated bones.

A bone with a flat torque-angle curve that re-fractures at the original site is placed in Stage I, while bone with a steep torque-angle curve and a re-fracture that does not recognize the original fracture site is placed in Stage IV. The other two stages have in-between characteristics. Further details may be found in the original article. Using only these criteria, and without the knowledge of the treatment given and the healing periods, each of the 50 bones were divided into the four stages.

Results for the amount of time required to reach each of the four stages of healing for the two treatments are seen in Figure 8. Time to reach Stage III is considerably shorter for the cyclically treated bones as compared with that for the bones with constant compression treatment. Another aspect of the four biomechanical stages is presented in Figure 9. This is a distribution of the number of bones that reached each of the four biomechanical stages of healing. For the sake of comparison, the cyclic and constant compression treated bones are shown separately in Figure 9.

DISCUSSION

In our previous study (White et al. 1977a) the data showed no significant differences between the biomechanical results of healing long bones treated by two different mechanical environments. The results of the present study convincingly demonstrate the opposite. It is seen from Figures 4 and 5 that during the middle phase (about 30 to 50 days) of healing, the strength parameters of maximum torque and energy absorption to failure clearly indicate the superiority of the cyclic over the constant compression treatment. This superiority is statistically significant to the 95 per cent confidence level as shown by the 95 per cent upper- and lower-bound curves.

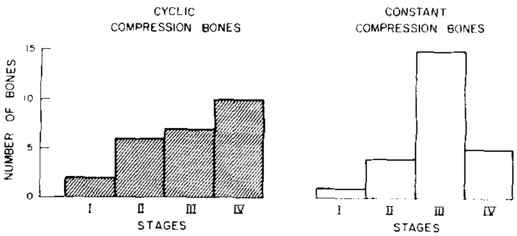


Figure 9. A histogram showing the distribution of the healing bones with respect to the four biomechanical stages of healing for the two treatments. Notice a continuous progress for the cyclic compression treated bones from Stage I to IV, while the constant compression bones show some difficulty in going from Stage III to IV.

In the early and late phases of healing, the two healing environments basically produced similar results (Figures 4 to 6). In fact, the constant compression, especially in the early phase, produced bones that were stronger than their paired counterparts treated with cyclic compression (Figures 4 and 5). This, we believe, is the result of immobilization provided by the large constant compression force. During these early phases small blood vessels are developing (Creuss & Dumont 1975) and immobilization protects the delicate vessels and facilitates repair. In the late phase, we believe, the healing bone has become sufficiently strong to carry the normal physiological loads.

Sometimes "Stiffness" is considered a biomechanical parameter synonymous with "Strength", just as torque and energy absorption. This is misleading. During the middle phase of healing, the cyclic compression treated bones show higher torque and energy values as compared with the bones with constant compression (Figures 4 and 5). In the same time period, the stiffness parameter shows a completely opposite tendency (Figure 6). We conclude that during this period of healing the cyclic bones are stronger and more flexible while the constant compression bones are weaker and more brittle. We hope the planned Histological Studies will shed some light on the above observations.

Figure 7 is a composite graph of the values for torque versus healing time for the previous study as well as for the cyclically loaded and constant compression treated bones of the present study. The dashed horizontal line represents a torque value of 1.5 newton meters, which is the torque value that correlates with failure no longer taking place at the experimental fracture site. The cyclically treated bones reached this clinically important stage of healing at 40 days as compared with more than 56 days for compression treated bones. This is a saving of 27 per cent of required treatment time. These findings clearly fit with clinical experience and recent experimental work in rats (Sarmiento et al. 1977).

In the previous study although there were differences in the environments of the two legs, these did not show up in the results. Thus, we have only one curve for this study in Figure 7. Also shown in this figure is a solid horizontal line representing the strength of the intact rabbit tibia. It is interesting to note that at 21 days of healing the constant compression is superior to both the cyclic and the previous study, while at 56 days of healing the cyclic treatment produces bones with superior strength compared with the constant compression treatment and the previous study. At this time point, the cyclically treated bones have achieved about 95 per cent of the normal intact strength as compared with 70 per cent for the other two.

Grouping the bones into the four biomechanical stages of healing was done to see if the two treatment regimens, in any manner, differentiate the bones regarding their biomechanical maturity. Figure 8 basically confirms the findings mentioned earlier that the cyclic compression treatment shortens the time taken to reach biomechanical maturity (Stage III). Another interesting finding is seen in Figure 9. Distribution of the bones according to the treatment and the four stages shows that the constant compression bones have their peak (15 bones) in Stage III, while the most cyclic compression bones (10 bones) are grouped in Stage IV. There seems to be a continuous progression from Stage I to Stage IV for the cyclic bones while the constant compression treated bones have difficulty in progressing from Stage III to Stage IV. This may indicate that the superiority of the cyclical as compared with the constant compression treatment comes into play in the transition from Stage III to IV. During this phase the bone is probably adapting to the outside mechanical environment.

What is the type of signal for this adaptation? Cyclic compression seems to do better than constant compression in this respect. However, the cyclic compression produces intermittent compression force as well as oscillatory motion at the fracture site. The latter is produced by the cyclic bending moment created by the cyclic compression forces that are not precisely aligned with respect to the fracture site. Because the cyclic compression forces are relatively small, we believe it is probably the motion at the fracture site that accelerates adaption.

It has been suggested that the loads applied at the fracture site to enhance healing should be comparable in magnitude with the physiological loads to which the bone is subjected during normal activity (Lanyon et al. 1977). Lanyon et al. determined this physiological load in the rabbit tibia to be about 200N, i.e. five times the loads used in our study. However, as we have been able to see the effects of these relatively smaller loads in our present experiment, the implication is that larger loads are not a requirement for increasing the efficiency of healing. When an animal breaks a leg in the wild and limps, the loads applied to the fracture site during the healing period are generally smaller than the normal physiological loads.

In general, our results tend to show that constant compression treatment produces a stronger bone during the early phase of healing while the cyclic treatment produces stronger union in the middle and later phases of healing. This suggests the possibility that a certain combination of the treatments may result in a type of healing that is superior to either of the two treatments given separately. One such combination may be to provide a constant compression treatment in the early phase of healing with the intermediate period designed to provide a gradual change from constant to the cyclic treatment. Experiments are being designed to explore this possibility.

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