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IN VITRO EFFECTS OF EXTERNAL FIXATION ON INTACT AND OSTEOTOMIZED TIBIAE

A Biomechanical Study

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In order to study the *in vitro* mechanical effects of external fixation on intact and osteotomized bone, human and rabbit tibiae were tested in three-point bending in an Instron testing machine. Intact tibiae were loaded in the elastic range before and after application of an external fixation device. In the human specimens the Vidal-Adrey double frame was used, and in the rabbit specimens the external mini-fixation. The bone deformation in the anteroposterior direction was measured with a linear voltage differential transformer. After application of external fixation a median bone elastic stiffness of 110.2 per cent in human tibiae and of 106.1 per cent in rabbit tibiae was found, in relation to the stiffness of intact tibiae without external fixation. The stiffness increase was significant in human specimens, but not significant in rabbit specimens.

In osteotomized human tibiae fixed with the Vidal-Adrey double frame a median stiffness of 8.5 per cent of the stiffness of intact bones was found when compression was not applied, compared to 19.9 per cent when compression was applied. In rabbit tibiae a median stiffness of osteotomized bones with external mini-fixation was 8.9 per cent of the stiffness of intact bones. There was a good agreement between the results in rabbit tibiae with the mini-fixation and human tibiae with external fixation without compression. The external mini-fixation thus seems to be a suitable model for the study of bone healing in rabbit tibiae.

Key words: cortical bone stiffness; external fixation; stress protection; fracture fixation

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External fixation of tibial fractures has gained widespread acceptance in recent years (Burny 1979, Jørgensen 1972, Olerud 1973, Aho et al. 1981, Benum & Svenningsen 1982). Biomechanical studies on the original Hoffman device revealed its limited stiffness, and the stability was greatly increased by using transfixing pins and a double external frame (Adrey 1970). However, the stiffness of tibial fractures fixed with the Vidal-Adrey double frame does not seem to have been related to the stiffness of intact tibiae.

Bone loss due to the stress-protecting effect of metal plates on bone is a well-known phenomenon (Uhthoff & Dubuc 1971, Akeson et al. 1976). *In vitro* mechanical tests have shown considerably reduced deformation of the bone under such plates applied on the intact human tibial diaphysis (Diehl & Mittelmeier 1974, Terjesen & Benum 1982). Whether a similar effect is caused by external fixation has not been investigated.

External fixation of osteotomies has been used on rabbit tibiae, but no information exists about the mechanical effects of the fixation device on the bone. Such data would be valuable as a basis for further *in vivo* studies of external fixation on intact and osteotomized rabbit tibiae.

This investigation was planned to answer the following questions:

1. To what extent is the stiffness of the intact human and rabbit tibial shaft increased after application of external fixation?
2. How rigid is external fixation of tibial osteotomies in relation to the stiffness of the intact bone?

MATERIALS AND METHODS

Intact tibia

Eight human and six rabbit tibiae were taken after death. The human bones were from six females and two males, whose ages ranged from 69 to 86 years. Some of the human bones were probably osteoporotic, but apart from that there were no bones with skeletal disease. The rabbit bones were taken from adult or nearly adult Chinchilla rabbits. The bones were wrapped in towels soaked in Ringer's solution to keep them moist, and stored at –18° Celsius. Before testing the bones were thawed to room temperature. They were kept moist during testing.

The Vidal-Adrey double frame external fixation was used on human tibiae. Each pin group consisted of three transfixing pins 4 mm in diameter with a centrally threaded portion. The pins were inserted in the midshaft tibia in the frontal plane. The distance between the two pin groups was 12 cm, and between the pins in each group 2.15 cm. The pins were fixed to universal ball joints with rod, 5 cm from the bone on the lateral side and 4 cm on the medial side. Four adjustable connecting rods were applied between the ball joints to make a double frame (Figure 1). Compression was not applied.

On the rabbit specimens the external mini-fixation was used (Ets. Jaquet Frères, Geneva, Switzerland). Each pin group consisted of two smooth transfixing pins 1.5 mm in diameter. The pins were inserted in the midshaft tibia in the frontal plane, with a pin group separation of 3 cm. The frame was mounted as shown in Figure 2. Compression was not applied.

Bending tests. To obtain stability of the tibia, the posterior part of the epiphyseal regions were ground flat and parallel. The tibial shaft was loaded in three-point bending in an Instron testing machine (type 1123) at a constant deformation rate of 5 mm/min. The load was applied on the anterior border of the tibia. The distance between the supports (the active length of bone) was 9 cm in rabbit specimens and varied from 26 to 32 cm in human specimens according to the total length of the tibia.

The deformation of the bone was measured by a Linear Variable Differential Transformer (LVDT), fixed to a bar (Figure 3). The LVDT electrical output

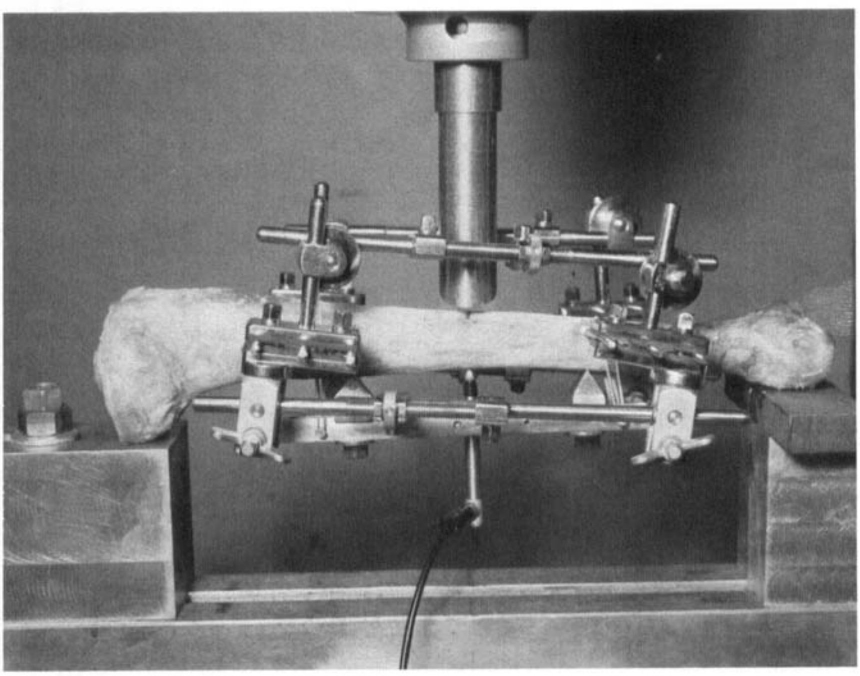

Figure 1. Human tibia with the Vidal-Adrey external fixation device loaded in three-point bending.

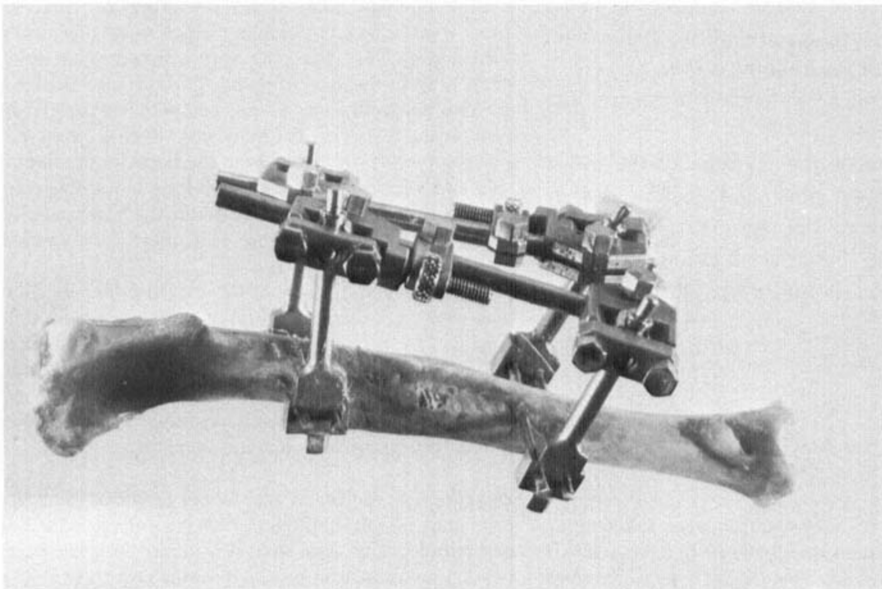

Figure 2. Rabbit tibia with external mini-fixation.

was connected via an amplifier to the abscissa of an X-Y-recorder (Yokogawa 30708). The load signal from the Instron machine was connected to the ordinate of the same recorder to obtain a load-deformation diagram. The LVDT was placed on the posterior aspect exactly at the middle of the tibia. The distance (L in Figure 3) between the outer ends of the measuring device corresponded to the distance between the pin groups (12 cm in human and 3 cm in rabbit specimens). By this method the deformation was recorded only in the segment of bone that was stabilized between the two pin groups.

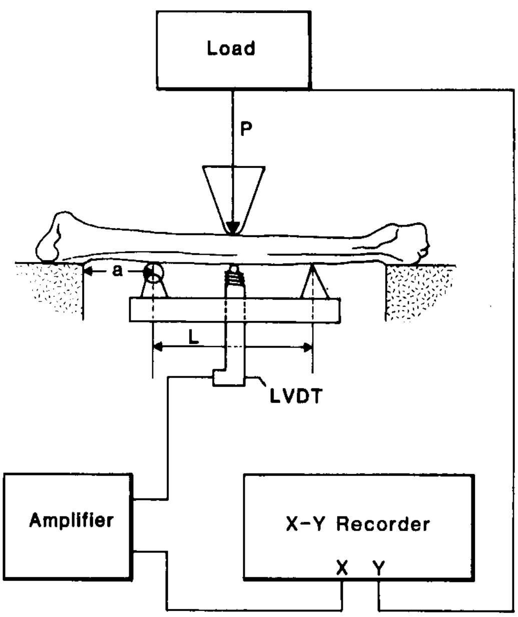

Figure 3. Tibia and the test equipment, with Instron, LVDT, amplifier and X-Y recorder. The distances L and a are indicated.

All bones were initially tested before application of the external fixation device. Then the external fixation was mounted and the testing performed as before. The intact human tibiae were loaded up to 1471.5 N, and the rabbit tibiae up to 98.1 N, within the range of elastic deformation. The elastic stiffness is dependent on the slope of the load-deformation curve (Figure 4).

In order to calculate the elastic stiffness of the bone segment between the pin groups, formulas for bending of a beam were used (Timoshenko & Gere 1972). To compare bones of different lengths, the bones are considered loaded only in the segment L (Figure 3). The elastic stiffness in this segment was calculated as earlier described (Terjesen & Benum 1983), according to the formula:

$$\frac{P(L + 3a)}{DL},$$

where P is the load, D is the deformation measured by the LVDT, and a is the distance between the measuring device and the end support (Figure 3). The elastic stiffness was expressed in N/mm. The stiffness of intact tibiae with external fixation was expressed as the percentage of the stiffness of the same bone without external fixation.

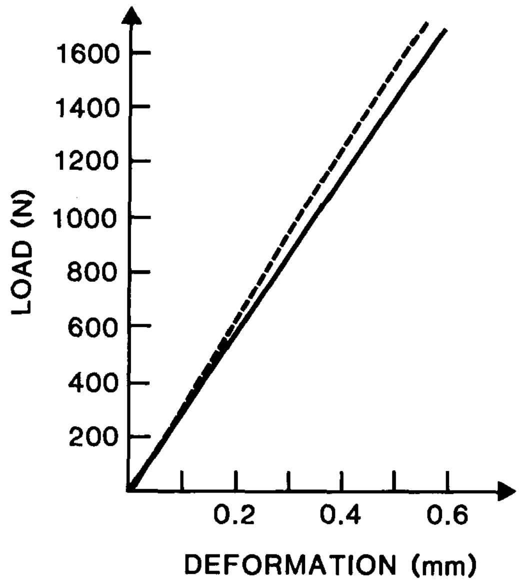

Figure 4. A typical load-deformation diagram, from an intact human tibia without external fixation (continuous line) and with external fixation (broken line).

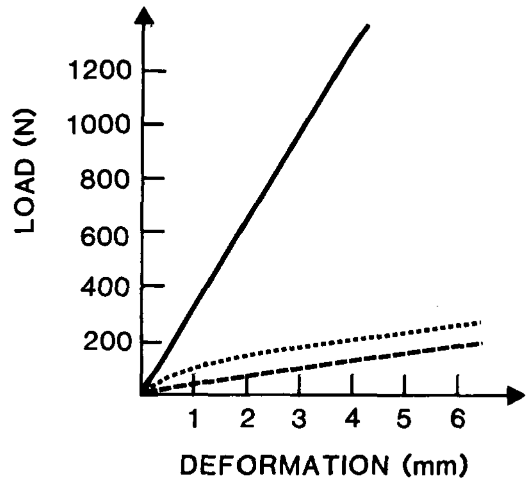

Figure 5. Load-deformation diagram, showing curves from a human tibia.
——— *intact tibia*
..... *osteotomized tibia with external fixation and compression*
------ *osteotomized tibia with external fixation without compression*

Osteotomized tibia

Seven human and five rabbit tibia were tested. The bones were collected and treated as described for intact bones, and the same methods of external fixation were used.

A midshaft osteotomy was made with an oscillating saw, and the osteotomy fixed with external fixation. In the rabbit specimens no compression was applied, whereas in human specimens compression was applied in six tests, and no compression in five. Four human tibiae were tested without as well as with compression. Compression was exerted by symmetric turning of the adjustable screws of the connecting rods until the transfixing pins were slightly bent.

Bending tests. The bones were loaded in three-point bending in the Instron testing machine. It was inconvenient to use the LVDT method in these osteotomized bones, and the load-deformation diagram from the Instron machine was used.

The Instron cross-head displacement was at a constant rate of 5 mm/min. Before osteotomy the bones were loaded only within the elastic range. The load was applied on the anterior border of the tibia, at the level where osteotomy later was performed. After midshaft osteotomy and external fixation the bones were tested as before, the load being applied at the same level.

The load-deformation diagrams from human as well as rabbit specimens without compression applied (Fig-

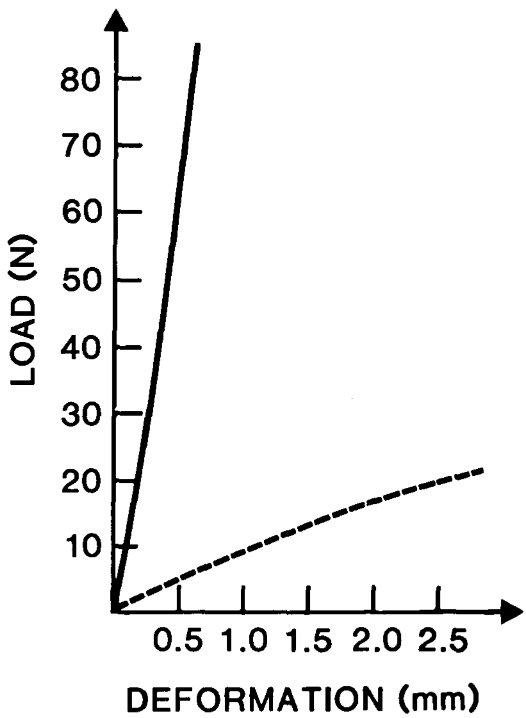

Figure 6. Load-deformation diagram showing curves from a rabbit tibia; intact bone (continuous line) and after osteotomy and external mini-fixation (broken line).

ures 5 and 6) showed almost linear relationship which means elastic deformation. In the human bones where compression was applied (Figure 5) the curves showed considerably greater stiffness in the lower load ranges than in the higher ones. The stiffness of the osteotomized bones stabilized with external fixation was measured in the lower part of the load-deformation diagram (in the deformation range 0–3 mm in human and 0–0.5 mm in rabbit specimens). The stiffness was expressed as the percentage of the stiffness for the intact bone.

The strength of the fixation was calculated as the bending moment at 5° of angulation of the bone fragments, and expressed in Newton metres.

Statistical analysis

The Wilcoxon's signed rank test for paired samples was used to calculate the statistical difference between the elastic stiffness of intact tibiae with and without fixation device. Differences were considered significant at P-values below 0.05.

Table 2. Stiffness of osteotomized tibiae after external fixation (in per cent of the stiffness of the intact bone)

	Human tibiae without compression $n = 5$	Human tibiae with compression $n = 6$	Rabbit tibiae $n = 5$
Stiffness			
Median	8.5	19.9	8.9
Range	8.2–18.1	13.1–22.4	7.8–11.6

Table 3. The strength (Newton metres) of osteotomized tibiae after external fixation (bending moment at 5° angulation of the bone fragments)

	Human tibiae without compression $n = 5$	Human tibiae with compression $n = 6$	Rabbit tibiae $n = 5$
Bending moment			
Median	13.2	18.6	0.31
Range	10.3–18.1	16.6–24.0	0.21–0.40

RESULTS

Intact tibia

The stiffness of the various intact bones varied considerably, both in human and rabbit specimens (Table 1). After application of external fixation device on human tibiae a median elastic stiffness of 110.2 per cent in relation to tibiae without external fixation was found (Table 1). The difference was statistically significant ($P = 0.007$). In rabbit tibiae with external fixation a median elastic stiffness of 106.1 per cent was found in relation to intact, unfixed bones. The stiffness increase was not significant ($P = 0.109$). In most of the cases, the stiffness due to external fixation was greater in the weaker bones (bones with less elastic stiffness) than in the stronger ones.

Table 1. Elastic stiffness (N/mm) of intact tibiae, and stiffness after external fixation (in per cent of the stiffness of the intact bone)

	Human tibiae* $n = 8$	Rabbit tibiae** $n = 6$
Elastic stiffness (N/mm)		
Median	5710.4	4243.8
Range	4188.9–12561.7	2706.6–5527.0
Stiffness after external fixation (per cent)		
Median	110.2	106.1
Range	100.0–129.4	93.0–108.1

* tested in a bone segment of 12 cm length.
** tested in a bone segment of 3 cm length.

Osteotomized tibia

The stiffness of osteotomized tibia after external fixation is given in Table 2. The median stiffness of human tibiae with the Vidal-Adrey double frame fixation without compression was 8.5 per cent of the stiffness of intact bones, compared to 19.9 per cent when compression was applied. In rabbit specimens the median stiffness of osteotomized tibiae after external mini-fixation without compression was 8.9 per cent of the stiffness of intact bones. Thus, there was a good accordance between the results of external fixation in human and rabbit bones when compression was not applied.

The bending moments needed to produce 5 degrees of angulation between the bone fragments, which reflect the strength of the fixation, are given in Table 3.

DISCUSSION

Intact tibia

The human bones were taken from old individuals, and the rabbit ones from young animals. The shape of the tibial shaft is not identical in humans and rabbits. In human tibiae six transfixing pins were used, while four pins were used in rabbits, and different external fixation devices were used in the two species. These differences make direct comparison of the results difficult, and the conclusions must be taken with caution. However, our test model should give approximate values concerning the relations between the biomechanical effects of external fixation on human and rabbit tibiae.

In biomechanical studies of various external fixation mountings on the tibia, the most rigid fixation was obtained by the double frame system (Adrey 1970). Because the Vidal-Adrey double frame represents the most rigid of the various Hoffman external fixation mountings and because this method is used in our department, it was thought appropriate for the present study.

In a previous study of the mechanical effects of metal plates on intact tibiae the bone deformation was measured by LVDT, which was found very suitable for this purpose (Terjesen & Benum 1983). The present study showed that this method was appropriate for similar experiments with external fixation. By applying the measuring device on different parts along the tibial shaft, and by varying the distance between the outer ends of the device, the deformation in any bone segment along the tibial shaft can be measured. In this study it was thought most adequate to measure the deformation only in the tibial segment that was stabilized by external fixation, which was the bone segment between the two pin groups.

In vitro biomechanical studies have shown that a rigid internal fixation plate applied on intact, diaphyseal bone reduces the strain in the bone segment underlying the plate (Cochran 1969, Diehl & Mittelmeier 1974). As the Vidal-Adrey double frame gives a rather rigid fixation, it might be assumed to cause a similar strain-protecting effect. This was confirmed in our bending tests on human tibiae, as a significantly increased stiffness was found after external fixation. A median stiffness increase of 10.2 per cent was obtained. In similar tests with tibial and femoral plates a median stiffness increase of 31 and 43.8 per cent, respectively, was found (Terjesen & Benum 1983). Thus the strain-protecting effect of external fixation is less pronounced than that of rigid metal plates. The clinical significance of this difference is that external fixation is likely to cause less bone atrophy in the stabilized bone segment than metal plates do.

In the intact rabbit tibiae a slight, but not significant, bone stiffness increase (median 6.1 per cent) was found after external mini-fixation. Thus the mini-fixation caused a relatively less rigid bone-frame system on intact rabbit tibiae compared to that of the Vidal-Adrey frame on intact human tibiae.

Osteotomized tibia

In relation to intact human tibiae the median stiffness of osteotomized bones fixed by the double frame device was 19.9 per cent when compression was applied and 8.5 per cent without compression. As might be expected, the fixation was more rigid with compression. Other reports on the effect of compression seem somewhat conflicting. Vidal et al. (1979) found that compression was the best means of increasing the stability of the fracture, whereas Chao et al. (1979) found little effect on the stiffness value by compression. In addition, asymmetric tightening of the connecting rods would tend to distort the frame and cause undesirable side effects (Chao et al. 1979).

In a previous study of tibial osteotomies fixed with tibial dynamic compression plates a median stiffness of 51.5 per cent was found in relation to that of intact bones (Terjesen & Benum 1983). This implies that a greater stiffness is obtained with a metal plate than with external fixation. However, the bending tests were performed in the anteroposterior direction, which is the weakest mode of loading the Vidal-Adrey device (Adrey 1970, Chao et al. 1979). Under other loading modes relatively high stiffness values were found (Chao et al. 1979). The transfixing pins represent the weakest part of the system (Egkher et al. 1980, Chao et al. 1979). As pins of 4 mm diameter were used in our study, a more rigid fixation would be obtained by the use of pins with greater diameter.

The overall stiffness of the Vidal-Adrey device can be improved by increasing the number of pins, by increasing pin diameter, by decreasing pin group separation and by decreasing connecting rod separation. In this study the dimensions of the pins and the frame corresponded to common practice in our department. Whether a greater ridigity in an external fixation device is desirable is uncertain, as there is no information available concerning the ideal amount of stiffness required for bone healing. In a clinical series comparing the Vidal-Adrey double frame device with the less rigid duplicated Hoffmann apparatus, no significant difference was found in healing time of tibial fractures (Benum & Svenningsen 1982). Burny (1979) maintained that he found no indication for the double frame, as it gives too great rigidity. Only further research can solve the problem of the ideal amount of stiffness in fracture fixation.

The strength of fracture fixation is given by the ability to withstand a certain amount of deformation (that is angulation of the bone fragments). In bending tests on human tibial osteotomies fixed with metal plates the strength was calculated at 5° angulation, which in most specimens was within the elastic limit (Laurence et al. 1969). In our study the curves showed elastic deformation beyond 5° angulation in specimens where compression was not applied. The slope of these curves depends on the stiffness of the weakest part of the fixation device, which is the transfixing pins. When compression was applied a greater stiffness was obtained in the lower part of the curves, up to the elastic limit for this fixation system. After that the effect of compression obviously was lost, and the curves showed further deformation like that of specimens without compression. At 5° angulation the median bending moment in human specimens with compression was 18.6 Newton metres and without compression 13.2 Newton metres. In similar bending tests on human tibial osteotomies fixed with a tibial dynamic compression plate the elastic limit was reached at about 2.5° angulation of the bone fragments, when the fixation withstood a median bending moment of 32.3 Newton metres (Terjesen & Benum 1983). Thus, a stronger fixation is obtained by metal plate fixation than by external fixation. However, it seems that greater elastic deformation can be tolerated by external fixation than by plate fixation.

Laurence et al. (1969) estimated the bending moment in the human tibia at about 80 Newton metres by quiet walking, and at 10 Newton metres by unresisted straight leg raising. The mechanical tests confirm the clinical experience that the Vidal-Adrey double frame gives sufficient stiffness and strength to tolerate straight leg raising and muscle training. However, the fixation is not strong enough to tolerate unrestricted weight-bearing, if it is desirable that the fragment angulation should not exceed 5 degrees.

In relation to the stiffness of intact bones, there was a good accordance between the stiffness of the external mini-fixation of rabbit tibial osteotomies and that of human tibial osteotomies fixed with the double frame, when compression was not applied. As one of the main clinical indications for external fixation is the comminuted tibial fracture, where compression usually is not applied, the external mini-fixation of rabbit tibial osteotomies seems to be a suitable model for the study of fracture healing. This model is used in a study which is in progress.

Compared to previous *in vitro* studies on mechanical effects of plate fixation on rabbit tibial osteotomies (Terjesen & Benum 1983), a lower stiffness and strength was obtained by external fixation. This is in agreement with the findings in human specimens.

CONCLUSIONS

1. A significantly increased elastic stiffness was found in the intact human tibia after application of external fixation with the Vidal-Adrey double frame.

2. In osteotomized human tibiae fixed with external fixation a median stiffness with and without compression of 19.9 and 8.5 per cent, respectively, was found in relation to that of intact bones.
3. A decreased stability in the anteroposterior direction is obtained in tibial osteotomies by external fixation compared to fixation with a tibial plate.
4. External mini-fixation on osteotomized rabbit tibiae gives a stiffness of the fixation which is comparable to that of external fixation without compression on human tibiae.

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REFERENCES

Adrey, J. (1970) *Le fixateur externe d'Hoffmann couplé en cadre.* Gead, Paris.

Aho, H. J., Nylamo, E. & Nieminen, S. (1981). External fixation of tibial fractures with the Hoffmann-Vidal-Adrey osteotaxis. *Acta Orthop. Scand.* **52**, 445.

Akeson, W. H., Woo, S. L.-Y., Rutherford, L., Coutts, R. D., Gonsalves, M. & Amiel, D. (1976) The effects of rigidity of internal fixation plates on long bone remodeling. *Acta Orthop. Scand.* **47**, 241–249.

Benum, P. & Svenningsen, S. (1982) Tibial fractures treated with Hoffmann's external fixation. *Acta Orthop. Scand.*, **53**, 471–476.

Burny, F. L. (1979) Elastic external fixation of tibial fractures. *External fixation.* (Eds. Brooker, A. F. & Edwards, C. C.), pp. 55–73. Williams & Wilkins, Baltimore.

Chao, E. Y. S., Briggs, B. T. & McCoy, T. (1979) Theoretical and experimental analyses of Hoffmann – Vidal external fixation system. *External fixation.* (Eds. Brooker, A. F. & Edwards, C. C.), pp. 345–370. Williams & Wilkins, Baltimore.

Cochran, G. V. B. (1969) Effects of internal fixation plates on mechanical deformation of bone. *Surg. Forum* **20**, 469–471.

Diehl, K. & Mittelmeier, H. (1974) Biomechanische Untersuchungen zur Erklärung der Spongiozierung bei der Plattenosteosynthese. *Z. Orthop.* **112**, 235–243.

Egkher, E., Martinek, H. & Wielke, B. (1980) How to increase the stability of external fixation units. *Arch. Orthop. Traumat. Surg.* **96**, 35–43.

Jørgensen, T. E. (1972) Measurements of stability of crural fractures treated with Hoffmann osteotaxis. *Acta Orthop. Scand.* **43**, 207–218.

Laurence, M., Freeman, M. A. R. & Swanson, S. A. V. (1969) Engineering considerations in the internal fixation of fractures of the tibial shaft. *J. Bone Joint Surg.* **51**-B, 754–768.

Olerud, S. (1973) Treatment of fractures by the Vidal-Adrey method. *Acta Orthop. Scand.* **44**, 516–531.

Terjesen, T. & Benum, P. (1983) Mechanical effects of metal plate fixation. *Acta Orthop. Scand.*, in press.

Timoshenko, S. P. & Gere, J. M. (1972) Mechanics of materials. Van Nostrand Reinhold, New York.

Uhthoff, H. K. & Dubuc, F. L. (1971) Bone structure changes in the dog under rigid internal fixation. *Clin. Orthop.* **81**, 165–170.

Vidal, J., Adrey, J., Connes, H. & Buscayret, C. (1979) Biomechanical study and clinical application of the use of Hoffman's external fixator. *External fixation.* (Eds. Brooker, A. F. & Edwards, C. C.), pp. 327–343. Williams & Wilkins, Baltimore.

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