

FRACTURE HEALING AFTER RIGID INTRAMEDULLARY NAILING IN RATS

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Rigid intramedullary nailing of the right tibia after osteotomy with resection of the fibula was performed on 48 male Wistar rats weighing 300–400 g. Nailing was performed with 1.4-mm nails after reaming. Nail stiffness was similar to that of intact tibiae. The left leg remained unoperated as control. The animals were sacrificed after 4, 8, 12 or 16 weeks, and both tibiae were tested in a 3-point bending test. Of the 35 animals with the nail *in situ*, nine animals showed non-union at the time of testing. At 8 weeks stiffness had reached normal values, while strength and deflection showed about half of normal values. Poor strength and small deflectability combined with near normal stiffness may be taken as evidence that Wolf's law is valid also in newly formed tissues of fracture healing; the protection given by a rigid nail makes normal strength and pliability unnecessary.

Key words: callus; mechanical properties; osteotomy; tibia

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Weakening of cortical bone by stress protection is a major problem after rigid osteosynthesis. The effects of stress protection have mainly been investigated after plate fixation, and seem to occur with or without fracture or osteotomy of the underlying bone. Axial compression or distraction along the plate does not appear to influence the occurrence or extent of weakening caused by bone resorption under the plate. The quality of the remaining bone substance is believed to be unchanged (Uhthoff & Dubuc 1971, Matter et al. 1974, Strømberg 1975, Tonino et al. 1976, Woo et al. 1976, Paavolainen et al. 1978, Uhthoff et al. 1981). Stress protection may be less pronounced in intramedullary nailing, but some weakening of cortical bone has been reported (Klopper & Tonino 1980).

The effect of rigidity on the bone formation in fracture healing is a matter of controversy. The Association for Study of Internal Fixation finds

rigid fixation beneficial, as it leads to so-called primary union of fractures, demonstrated by histological methods (Schenck & Willenegger 1964, Perren 1964, Hutschenreuter et al. 1969). Moreover, mechanical testing has indicated that primary union may be a functionally better way of fracture healing than union by external callus formation, at least in the first stages of healing (Jäger et al. 1976, Rand et al. 1981). On the other hand, evidence is accumulating that a flexible osteosynthesis favours the integrity of pre-existing bone as well as the mechanical properties of the newly formed tissue at the fracture site (Tonino et al. 1976, Woo et al. 1976, Sedel et al. 1980, Brown & Mayor 1981, Wang et al. 1981, Uhthoff et al. 1981, Tayton et al. 1982, Mølster et al. 1982).

The present study was designed to investigate the process of bone healing after rigid osteosynthesis, using the mechanical properties of

healing tissues as an expression of their supporting function. The aim was to assess the rate of change in mechanical behaviour of healing osteotomies, and to investigate whether the newly formed bone would eventually reach the same mechanical quality as normal unprotected bone when a rigid nail was present.

MATERIAL AND METHODS

Forty-eight adult male Wistar rats weighing 292–408 g (\bar{x} = 354.5 g, s = 24.3) were used. The animals were anesthetized with fentanyl-fluanisone (Hypnorm Vet., Mekos) 0.15 ml s.c. After shaving of the skin the right tibia was exposed through an anterior incision. The soft tissues were detached subperiosteally by means of a curved periosteal elevator. An oblique osteotomy was made using a fine-toothed, circular saw, 0.1 mm thick with a diameter of 19 mm, rotating at a speed of 800 rev/min under continuous saline irrigation. The osteotomy was directed from a level on the anterior aspect of the tibia 4–5 mm distal to the tuberosity, about 30° upwards and backwards. The medullary cavity of the tibia was reamed proximally and distally from the osteotomy site with a cutting reamer to a diameter of 1.4 mm under irrigation. An opening for insertion of the nail was obtained by allowing the reamer to extrude proximally through the anterior tibia between the tuberosity and the knee joint. The nail was inserted in the proximal direction from the osteotomy site so far that the osteotomy could be reduced. The nail was then carefully hammered back into the distal fragment. The fibula was fractured manually and the distal 4–6 mm was resected. Penicillin was instilled into the wound, which was closed with a one-layer continuous Dexone suture.

The unoperated left leg served as control. A solid stainless steel nail (Ni/Cr) with a circular cross-section was used; diameter 1.4 mm, length 30 mm and nail stiffness approx. 390 N/mm. Unprotected weight bearing was allowed as soon as the animal recovered from anesthesia.

X-rays were taken during the healing period, and at sacrifice (Philips Practix, Kodak X-omat film, distance 50 cm, 45 kV, 50 mA, 30 mAs). The largest callus diameter was measured from frontal and side views of the osteotomized tibia and compared to the corresponding part of the unoperated contralateral tibia. The cross-sectional area was calculated assuming it to be an ellipse.

Groups of animals were sacrificed by an overdose of ether after 4, 8, 12 and 16 weeks. Both tibiae were excised, and the nails removed from the operated side. Tight attachment between nail and bone after 12 and 16 weeks made it necessary in some cases temporarily to embed the tibia in plaster to extract the nail without

damaging the bone. The tibiae were placed in a moisture chamber and tested within 3 h.

After excision of the remaining part of the fibula a three-point bending test was performed using a mechanical testing machine (Instron 1193). The tibiae were tested in the plane of natural extension. Details of the testing procedure were described earlier (Mølster et al. 1982). Bending was applied at a speed of 10 mm/min, and continued until fracture. Strength, stiffness and deflection were taken from the resulting force/deflection curves (Mølster et al. 1982). Maximum load was taken as the strength of the bone at the fracture site, and stiffness was calculated from the initial linear slope of the force/deflection curve. Stiffness of the nails was tested in a similar way.

After mechanical testing, the fragments were repositioned, fixed in formaldehyde, decalcified in formic acid, dehydrated and embedded in paraffin. Longitudinal 6 μ m sections were stained with eosin and haematoxylin.

Osteotomies without signs of bridging callus on X-rays, gross instability after removal of the nail, and the osteotomy gap filled with fibrous tissue on histologic examination, were classified as non-unions, regardless of presence or amount of bone resorption or hypertrophy of bone ends.

Statistical evaluations were performed by the Wilcoxon test for paired samples (Wilcoxon signed rank test).

RESULTS

Of 35 animals with the nail *in situ* at the time of sacrifice, nine showed non-union of the tibia (Table 1). Two of the tibias with non-union (at 12 and 16 weeks) revealed nearly free rotation of the fragments on the rigid nail, and a significant amount of bone resorption in the pseudarthrosis, while no bone resorption was seen around the nail in the medullary cavity (Figure 1).

The development of non-union was evident in the early X-ray controls, and progressing union never reversed to a lower state of consolidation.

The results of mechanical testing of the remaining tibia (Figure 2) are summarized in Table 1. The development of the different parameters over time is shown in Figure 3. Stiffness reached normal values at 12 weeks, and remained unchanged at 16 weeks. Strength followed the development of stiffness, with a corresponding reduction in deflection until 8 weeks postoperatively, when all parameters reached about half of their normal values. After that time, the strength

Table 1. Results of mechanical testing

	Weeks	<i>n</i>	Operated side median (range)	Unoperated side median (range)	Paired differ. median (range)	Level of significance	Non- unions
Stiffness (N/mm)	4	6	5.9 (2.9–143)	376 (317 –477)	371 (–174 –436)	0.05	2
Strength (N)		7	3.9 (1.8– 41)	144 (130 –167)	129 (126 –164)	<<0.005	
Deflection (mm)		6	0.7 (0.4– 1.9)	0.7 (0.5– 0.9)	0.1 (–1.4– 0.5)	>0.1	
Stiffness	8	6	292 (29 –476)	459 (42 –528)	172 (–427 –498)	>0.1	4
Strength		6	109 (15 –211)	186 (53 –226)	88 (–158 –172)	>0.1	
Deflection		6	0.5 (0.3– 0.5)	0.8 (0.5– 1.8)	0.4 (0 – 1.3)	0.05	
Stiffness	12	4	510 (255 –559)	501 (427 –569)	12 (–69 –265)	–	2
Strength		5	98 (44.2–167)	220 (132 –250)	137 (–2.9–177)	>0.1	
Deflection		4	0.2 (0.2– 0.4)	0.5 (0.5– 0.7)	0.3 (0.1– 0.5)	–	
Stiffness	16	8	363 (69 –662)	400 (275 –599)	46 (–206 –439)	>0.1	1
Strength		8	95 (30 –206)	201 (132 –250)	81 (20 –164)	<0.01	
Deflection		8	0.3 (0.2– 0.6)	0.7 (0.6– 1.1)	0.5 (0.1– 0.9)	<0.01	

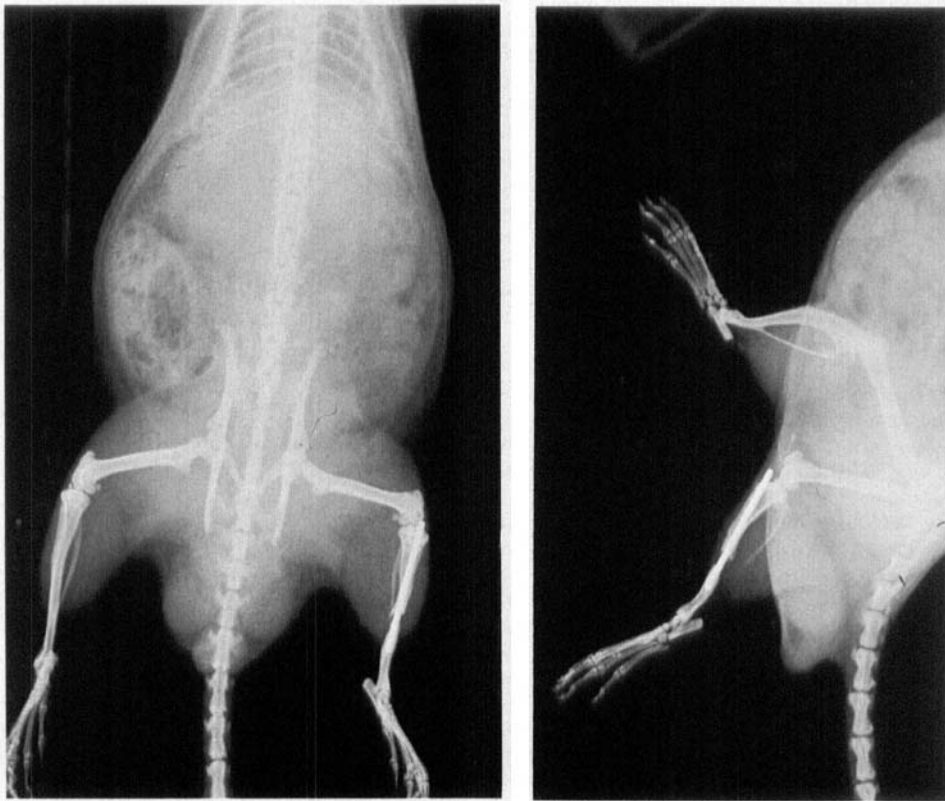


Figure 1. Case with a high degree of rotational instability between the fragments of tibia at 16 weeks. Gross bone resorption in the osteotomy area.

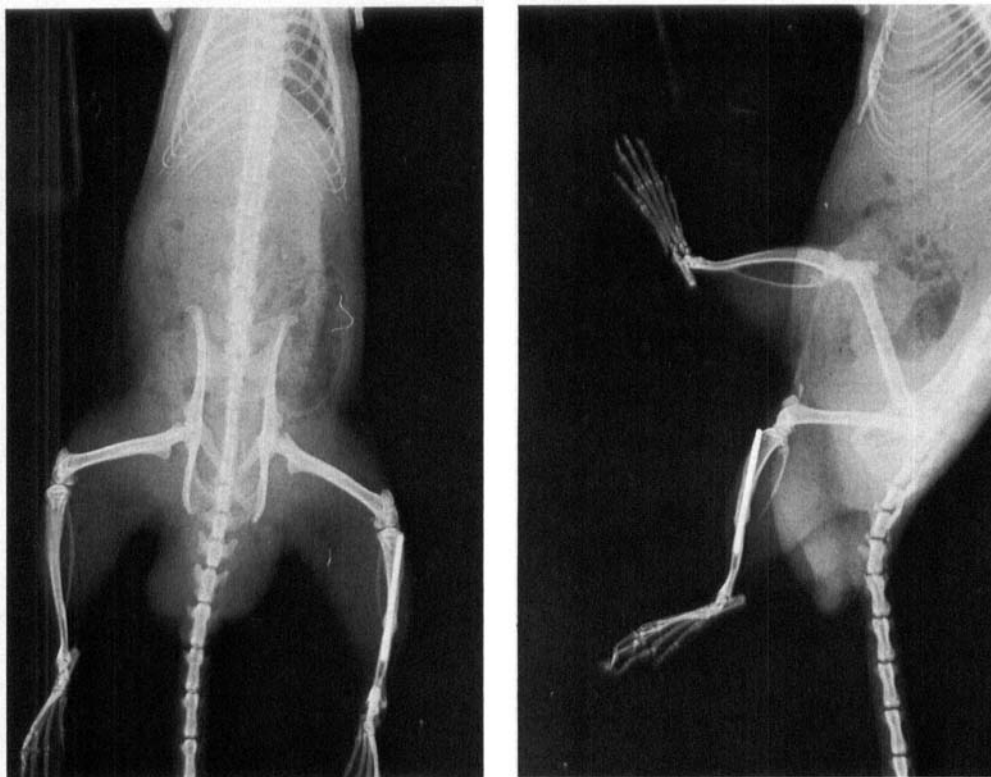


Figure 2. Healing osteotomy at 16 weeks. The diameter of tibia at the osteotomy site is still larger than normal. The end of fibula is atrophic.

and deflection ceased to change and remained approximately half the values of the corresponding unoperated tibia; the difference being sig-

nificantly different from the unoperated side at 16 weeks ($P < 0.01$).

The median values of cross-sectional areas of

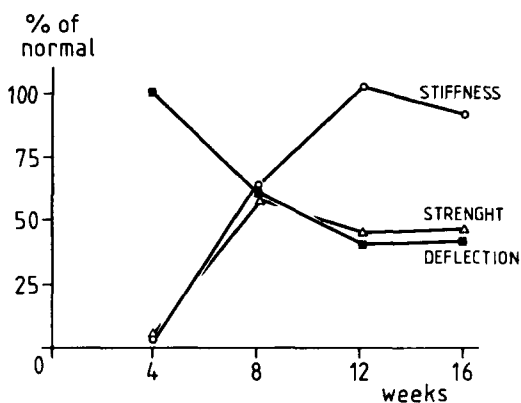


Figure 3. Mechanical properties of healing osteotomies at different time intervals expressed as percent of the values at the unoperated control side. Nails removed.

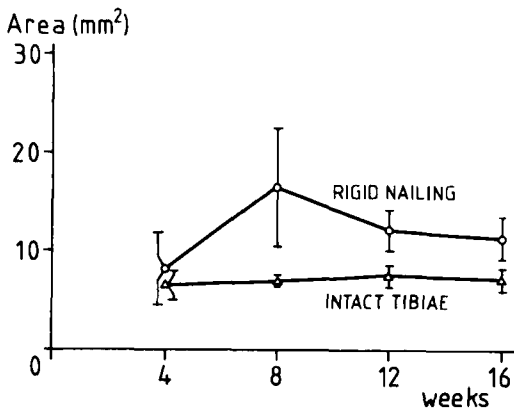


Figure 4. Cross-sectional area of callus as measured from X-rays. Bars represent standard deviations.

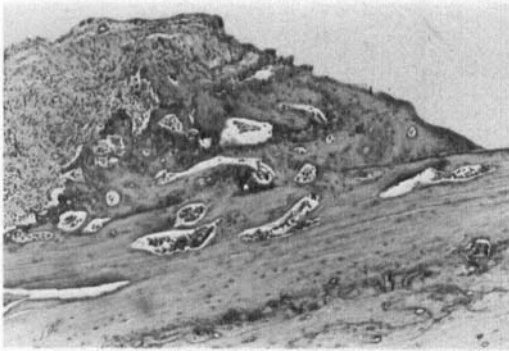


Figure 5. Peripheral part of callus at 4 weeks. Calcified, woven bone with anchoring osteons penetrating into preformed lamellar bone in the lower part of the figure (H&E $\times 90$).

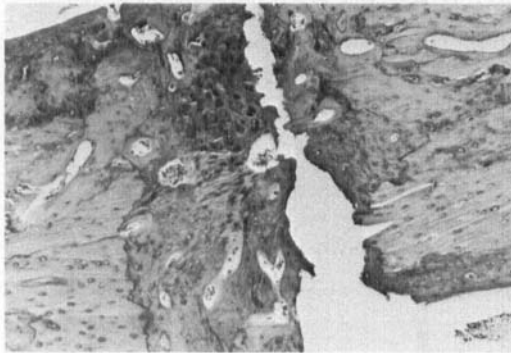


Figure 6. Osteotomy site at 16 weeks, with fracture after testing. Remnants of necrotic bone ends, newly formed, un-oriented bone and cartilage. Demarcation between original and new bone is visible in left portion of the figure (H&E $\times 90$).

callus tissue (Figure 4) were higher compared to the corresponding areas of unoperated tibiae, with a maximum at 8 weeks, but still more than 50% above normal values at 16 weeks.

Histologic examination showed that fracture during the bending test regularly occurred at the osteotomy site. At 4 weeks necrotic bone near the osteotomy was found in both fragments. A moderate amount of callus tissue had developed, with calcification of woven bone in the areas remote from the osteotomy line and with anchoring osteons into pre-existing cortical bone (Figure 5). Gradual resorption and substitution by new bone were taking place over 8 and 12 weeks, with some

remnants of necrotic bone next to the osteotomy area, while cartilage was observed in the gap within the original bone and in the extension of the osteotomy line into the callus outside the surface of the original cortex. At 16 weeks, new bone partly connected the two fragments, but a considerable amount of cartilage was still present in the osteotomy gap. Longitudinal orientation of the bone structure had taken place in the most remote parts of callus, while a haphazard arrangement of bone lamellae and osteons was still evident at the osteotomy site (Figure 6).

Two of the fibulae were healed with moderate amounts of callus after 12 weeks. In both rats there were some shortening of the tibiae bringing the fragments of fibula into contact. All other fibulae showed atrophic non-unions (Figure 2).

No infections were observed.

Thirteen nails dislocated in a proximal direction leaving the osteotomy without fixation; these animals were excluded from the study (Figure 7). Due to technical errors during testing, values for stiffness and deflection were not obtained in two cases, giving different *n* for strength from that of stiffness and deflection at 4 and 8 weeks.

DISCUSSION

The mechanical situation of the osteotomy after nailing is one of reduced stress and movements in bending and *ad latus*. As the proximal end of the nail protrudes outside the bone, protection against axial stress will not be anticipated. The observed tendency for the nails to back out from the distal part of tibia may support this interpretation. This situation is in contrast to that in the study of Brown & Mayors (1980) who found a bony cap over the proximal end of their metal nails inside the medullary cavity. The high friction between bone and metal in some of our animals may, however, cause some axial stress protection. Friction, together with the obliquity of the osteotomy, provides rotational stability. The resistance to rotation is difficult to assess during the course of the experiment, as friction probably changes with time, and stability caused by the oblique osteotomy also depends on the muscle

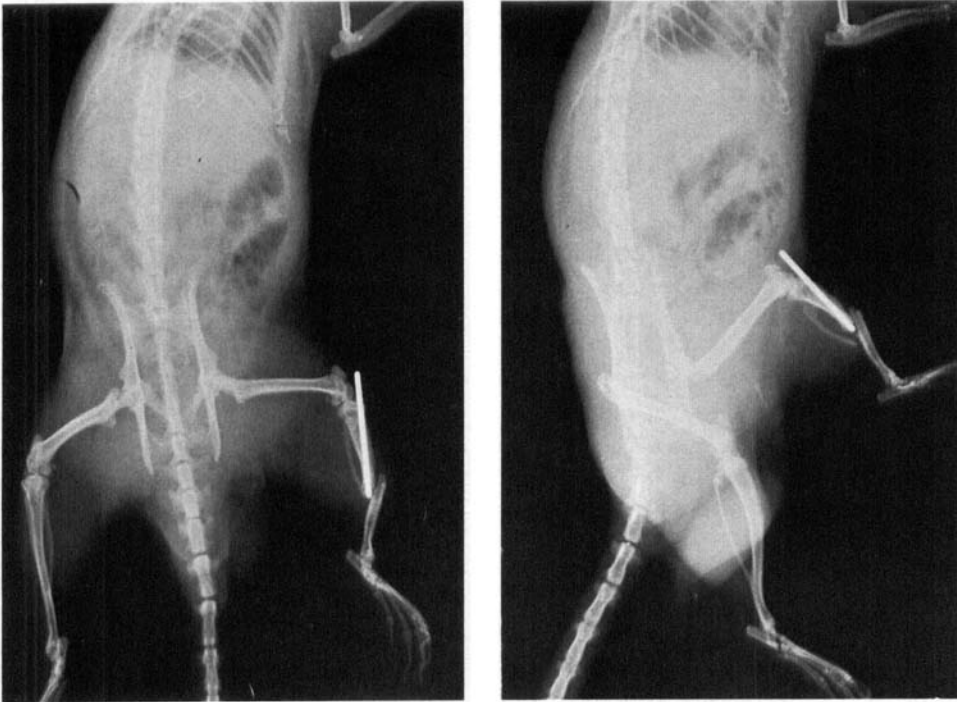


Figure 7. A case where the nail has dislocated in the proximal direction (6 weeks).

tone in the leg. The finding of non-unions with gross bone resorption (Figure 1) in two tibiae with almost free rotation may indicate that rotation is an etiological factor in the development on non-unions in this otherwise stable situation. It may be speculated that the relatively small diameters of callus in rigid nailing may be less efficient in withstanding rotational forces compared to the greater callus produced by a bending instability. Further experiments are presently being carried out in our institution to differentiate between the effects of bending and rotational instability.

The variations in consolidation are believed to be mainly due to variations in the stability of osteosynthesis, and further work is in progress to improve the model. Variations of body weight are probably of less importance, as the corresponding variations in dimensions of the bones will be in the cross-sectional area, giving only about 5% increase in cortical thickness in a 25% increase in body weight.

We found that fracture at testing regularly oc-

curred through the line of osteotomy, even at 16 weeks. The three-point test tends to concentrate energy at the middle point. Therefore, the mechanical properties were tested predominantly in the newly formed tissues of healing, while any weakening of pre-existing bone may not have been revealed. Classification in stages of healing can not therefore be made (White et al. 1977). According to previous reports on pre-existing cortical bone after stress protection, the finding of weak and brittle callus tissue in the cases with rigid nailing might be explained by the presence of a mature bone substance in amounts smaller than normal and arranged so that the outer bone limits are close to normal (Uthoff & Dubuc 1971, Matter et al. 1974, Strømberg et al. 1975, Tonino et al. 1976, Paavolainen et al. 1978, Uthoff et al. 1981). The increase in callus area in our study compared to that of normal bone implies an increase in area moment of inertia that would give abnormally high values for stiffness and strength if the callus consisted of qualitatively normal bone. Therefore, findings at microscopic

examination might have been anticipated: while the mechanical properties reached a stable level at 8 to 12 weeks, the histological appearance at this stage was certainly not one of maturity. Even at 16 weeks, remnants of cartilage and a quite haphazard arrangement of bone lamellae and osteons at the osteotomy site were found.

Our experiments have thus not created absolute stability, which makes primary union possible (Perren 1979). Independent of stability, healing appeared to progress at a rather constant rate during the first 8–12 weeks. Incomplete recovery of strength and deflection at fracture after that time was most likely due to the support from the intramedullary nail. Because there was no basic change in mechanical properties later than 12 weeks, the tibia with its nail can be regarded to have regained its mechanical state at this time. In this sense, healing was completed. However, the tissues at the osteotomy site was clearly not completely matured, even at 16 weeks. Maturation into qualitatively stronger bone substance from approximately 12 weeks was associated with corresponding regression of callus. These two processes balance each other out in such a way that the mechanical properties are maintained on a level determined by the mechanical environment in accordance with Wolf's law (Wolf 1892). The rate of remodelling appears to be slow (McKibbin 1978). Functional capability of healing fractures can therefore not be judged solely from the degree of maturation of callus tissues, as differences in geometry must also be considered. In the experimental situation, the result of qualitative and geometric factors is best tested mechanically for functional evaluation.

It is interesting to compare the healing pattern in our study with that of unprotected closed fractures in the same species. Ekeland et al. (1982) found in adult rats fracture healing as measured mechanically to be completed in about 12 weeks. This healing pattern corresponds to the one revealed in our study, supporting the view that the arrest in a primarily normal development of strength and deflection at about 8 weeks is caused by the presence of the rigid nail.

Atrophic non-unions of the fibulae were anticipated. Even without defects there is a tendency in a rigid situation for fibula fractures to give

atrophic non-unions (Aro et al. 1982, Mølster et al. 1982). There is, however, data indicating that defects in fibula heal with great callus formation when the tibia is supported by a flexible nail (Mølster et al., unpublished data).

In conclusion, after reaming and rigid intramedullary nailing, healing in the mechanical sense is completed at approximately 12 weeks, with a near normal stiffness, but low values for strength and deflection at fracture. The stable level of mechanical properties is in the early stages produced by "immature" callus tissues in a geometric arrangement giving a high moment of inertia. Maturing of the healing tissues into normal bone in later stages seems to be compensated for by a reduction in area moment of inertia.

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