Muscle contraction increases the strength of healing tibial fracture in the rat

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Tibial fractures in 7-week-old rats were fixed with intramedullary nails. After 25 days of healing the nails were removed and the tibiae loaded in vivo with intact soft tissues until refracture. The animals were tested in three-point anterior cantilever bending either during muscle contraction (n 8) or with relaxed muscles (n 8). Muscle contraction increased the ultimate bending moment by 84 percent, energy absorption by 108 percent, bending stiffness by 21 percent, and ultimate deflection by 49 percent.

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The positive effect of muscle function on the healing of fractures has been documented in the rat (Sarmiento et al. 1977, Grundnes and Reikerås 1991). The effect of muscle contraction during loading, however, has not been reported. In intact tibiae, mechanical testing with soft tissues has been shown to increase the ultimate bending moment and the energy absorption by 40 percent and 85 percent, respectively (Nordsletten and Ekeland 1993b), and muscle contraction further increased these values substantially (Nordsletten and Ekeland 1993a).

We report the effect of muscle contraction on the strength of healing tibiae during loading until refracture.

Material and methods

26 male Wistar rats (Møllegård, Copenhagen, Denmark) with a median weight of 203 (199–207) g, were used. The animals were anesthetized with a combination of Hypnorm (fluanisone 5mg/mL-fentanyl citrate 0.16 mg/mL, Jansen Pharmaceutica BV, Beerse, Belgium) and Dormicum (midazolam 2.5 mg/mL, Hoffmann La Roche, Basel, Switzerland). The subcutaneous dose was 0.2 mL/100g body weight both at induction of fracture and for testing. The animals were given standard laboratory pellets and tap water ad libitum. The experiments conformed to the Norwegian Council of Animal Research Code for the Care and Use of Animals for Experimental Purposes.

Fracture

The fracture and fixation technique has been described in detail (Nordsletten et al. 1992). The animals were operated on under sterile surgical conditions. The right lower leg was shaved, and a longitudinal incision was made parallel to the anterior margin of the tibia. An 18 G cannula was inserted through the patellar ligament into the medullary canal. 4 mm distal to the tibial tuberosity the anterior cortex was sectioned with a scalpel, and the fracture completed by manual breaking of the posterior cortex, leaving the fibula intact. The cannula was advanced distal to the fracture until it jammed in the medullary canal. 2 cannulae–21 G and 25 G–were inserted inside the first, and both were advanced past each other until jamming in the distal fragment. The cannulae were cut flush with the bone at the insertion site, and the wound was closed in two layers. Postoperatively, the animals were given buprenorphine (Temgesic, Reckitt & Colman, Hull, England), 0.2 mg/kg b.w. at 12-hour intervals for 2 days. 4 animals were housed in each cage.

The rats resumed weight-bearing within a few days, and none developed infection. 1 animal died during anesthesia at fracture induction. On Day 24, when the rats weighed 331 (324–341) g, they were anesthetized and radiographed. 5 rats had malalignment of the fracture due to insufficient advancement of the intramedullary nails. These were excluded before randomization. The remaining animals were randomized into 2 groups. On the following day, the animals were again anesthetized, the nails were removed, and the healing lower legs with intact soft-tissues were tested until refracture in three-point anterior cantilever bending. One group was tested during tetanic muscle contraction, the other group with relaxed muscles. Removal of the intramedullary nail caused physiolysis proximally in the tibia in two animals in each group. 16 rats were left for in vivo testing, 8 in each group.

Healing tibiae

The test apparatus (Engesæter et al. 1978) and the in vivo testing procedure for intact tibiae have been described previously (Nordsletten and Ekeland 1993a,b). Before testing, the intramedullary nails were removed through a short incision, which was closed with one suture. The sciatic nerve was dissected free on the thigh and a bipolar electrode ligated to the nerve. The electrode was connected to a nerve stimulator (Pulsar 6i, Frederick Haer, Brunswick, ME, U.S.A.).

The skin incision was closed and the rat was suspended in a coat leaving the test leg free. A clamp was fixed to the distal part of the lower leg with suspension under the foot, and the rat was placed in the modular test apparatus. The lower leg was deflected in three-point anterior bending at a rate of 5.43°/s. The load was transferred to the leg by a cam mounted on the rotating disc of the test apparatus. The cam engaged the soft tissues posteriorly to the tibial condyle during in vivo testing. A fulcrum positioned anteriorly to the callus was the third point of force application. The sciatic nerve was supramaximally stimulated during testing with 0.5 ms square pulses of 80 Hz with an amplitude of 6 V to induce tetanic contraction in all muscles of the lower leg.

A load cell connected by an amplifier to a personal computer measured the load in the test apparatus. The load/deflection curve was recorded on-line in WorkBenchMac (Strawberry Tree Incorporated, 160 South Wolfe Road, Sunnyvale, CA, U.S.A.). Ultimate bending moment, ultimate energy absorption, bending stiffness and deflection could be read directly or calculated from the recorded load/deflection data (Nordsletten and Ekeland 1993a). Representative load/deflection curves are shown in Figure 1.

The other group was tested without nerve stimulation and after section of the sciatic nerve.

Intact tibiae

After testing, the animals were killed, and both tibiae removed. The tibiae were kept wet during all handling. The distance from the malleolar plane to the fracture was measured with sliding calipers in the test tibiae, and the fracture position was marked on the contralateral tibia. The intact tibia was then loaded in the same way as the test leg with the fulcrum placed over the fracture mark, and served as each animal's reference value.

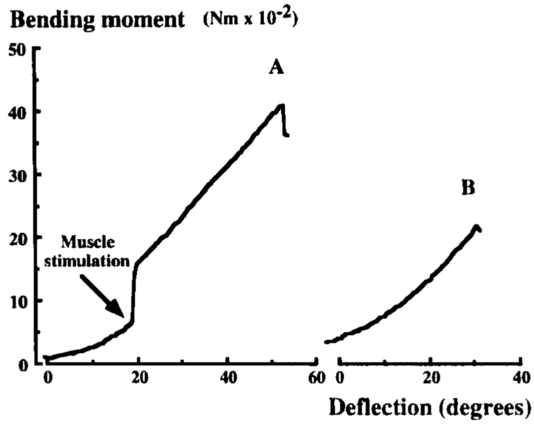

Figure 1. Representative load/deflection curves for three-point ventral bending of 25-day-old healing tibial fracture with intact soft-tissues during muscle contraction (A) and with relaxed muscles (B). Arrow shows start of muscle contraction.

Statistics

The median tibial fracture distance from the malleolar plane was 17 mm, with no differences between the groups. All healing tibiae refractured through the callus. Results are presented as medians, with 25 and 75 percentiles. Differences between healing and intact legs in each group were evaluated with the Wilcoxon's signed rank test. Differences between groups were evaluated with the Mann-Whitney U-test. Differences were considered significant when $P < 0.05$.

Results

Muscle contraction group

The ultimate bending moment was higher in the healing than in the intact leg in five animals, with no significant difference (Table 1). Energy absorption was 71 percent higher in the healing leg than in the intact tibia. Bending stiffness was reduced to 40 percent of the value for the intact leg. Deflection at refracture in the healing leg was 134 percent higher than deflection at fracture in the intact tibia.

Relaxed muscle group

The ultimate bending moment was 41 percent lower in the healing leg than in the intact leg (Table 1). Ultimate energy absorption was not different, while bending stiffness was 69 percent lower in the healing than in the intact leg. Deflection at refracture was 46 percent higher in the healing leg than in the intact tibia.

Table 1. Mechanical results for healing (healing tibial fractures with soft tissues) and intact lower legs (contralateral resected tibia). Healing legs in the muscle contraction (MC) group were loaded until refracture during muscle contraction, while the legs in the relaxed muscle (MR) group were tested after section of the sciatic nerve. Median and 25–75 percentiles

	Ultimate bending moment ($Nm \times 10^{-2}$)		Ultimate energy absorption ($J \times 10^{-2}$)		Bending stiffness ($Nm/^{\circ} \times 10^{-3}$)		Deflection (°)	
Group	Healing	Intact	Healing	Intact	Healing	Intact	Healing	Intact
MC	41^{b}	39	$16.0^{b,c}$	7.7	8.3^{c}	22.9	$49^{a,c}$	20
	36–46	33–40	13.9–17.2	7.3–9.6	7.9–10.7	19.6–25.6	41–52	18–22
MR	22^{c}	40	7.7	9.4	6.9^{c}	24.6	33^{c}	23
	22–25	37–41	6.9–8.7	8.4–10.8	6.2–7.4	20.4–26.3	31–39	20–26

Group MC–MR differences ^{a}P 0.01, $^{b}P < 0.001$. Healing-intact differences ^{c}P 0.01.

Group differences

The healing leg in the muscle contraction group had an ultimate bending moment which was 84 percent higher than the healing leg in the relaxed group. Energy absorption in the muscle contraction group was 108 percent higher than in the healing leg in the muscle relaxation group ($P < 0.001$). Bending stiffness was 21 percent higher in the muscle contraction group than in the relaxed muscle group. Deflection at refracture was 49 percent higher in the muscle contraction group than in the muscle relaxed group.

Discussion

The fracture technique gave a standardized, slightly oblique fracture line, equally positioned in the 2 groups. The in vivo testing procedure has previously been validated for testing intact lower legs (Nordsletten and Ekeland 1993a,b), and in the present study it proved to be a reliable method for testing the contribution of muscle contraction to a healing fracture.

Muscle contraction increased the ultimate bending moment by about 80 percent. The energy-absorbing capacity of the callus with soft tissues was doubled by muscle contraction. Latta et al. (1980) found that the soft tissues carried over 80 percent of the load when they instrumented fracture braces on patients with fresh fractures of the tibia and fibula. Sarmiento et al. (1974) and Latta et al. (1980) concluded from their experiments that the brace and the soft tissues acted together as a hydraulic cylinder, which gave strength and stability to the fracture. They did not study the muscle-contracting contribution per se. Some of the effect of muscle contraction found in our study might have been the result of raised intramedullary and intracompartmental pressures, but as the legs were loaded in anterior bending we believe the posterior shift of the neutral rotation axis due to muscle contraction was the most important factor. Jerosch et al. (1991) recorded intracompartmental pressures during walking and running in humans of 57 and 68 mmHg, respectively, with unloaded pressures about 40 mmHg. In functional fracture treatment with a brace, it is possible that the pressure difference between unloading and loading during muscle contraction is higher. Posival (1973) found the load-carrying capacity of an instrumented brace with strain gauges applied on a normal subject to be 17 percent of the total load carried by the extremity. Furthermore, he concluded from his results "that only small bending moments are taken in the brace. This casts doubt on the bone stabilization effects of the brace". Muscle contraction inside the brace could have a direct strengthening effect on the callus, as shown in the present study for fractures without brace.

The presence of intact soft tissues increased the structural capacity of the lower legs in rats compared to testing of the dissected tibia (Nordsletten and Ekeland 1993b). Muscle contraction further increased the strength compared to testing with relaxed muscles by 22 percent in bending moment and 73 percent in energy absorption (Nordsletten and Ekeland 1993a). By muscle contraction, the neutral axis of rotation is shifted posteriorly, and tensile stress in the tibia is neutralized by compressive stress (Nordin and Frankel 1989, Nordsletten and Ekeland 1993a). The cross-sectional area of the callus is bigger than that of the intact tibia, and changing the neutral axis of rotation posteriorly will thus theoretically increase the strength relatively more, as shown in this study. Furthermore, muscle contraction can increase the intramedullary pressure up to 60 mmHg in rats (Kumar et al. 1979), thereby possibly strengthening the intramedullary part of the callus by increased hydraulic pressure.

The soft tissues are of great importance in fracture treatment. Undamaged soft tissue contributes to the stability of fractures treated with casting or bracing (Sarmiento et al. 1974), and is of importance for the development of the bridging callus (McKibbin 1978). Functional treatment with braces is a reliable method for treating fractures of the tibial and humeral diaphysis when the fracture and soft tissues together have a certain degree of internal stability (Young et al. 1989, Sarmiento et al. 1989, 1990, den Outer et al. 1990). Muscle contraction during loading of the fracture is probably an important part of this internal stability, and its contribution may vary, depending on the type of fracture and the degree of soft tissue damage.

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