Measurement of bone lengthening forres; an experimental model in the lamb

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ABSTRACT

Objective. To obtain the mechanical behaviour pattern of the lengthening process.
Design. In vivo measurement of forces during bone lengthening in lambs.
Background. A series of parameters of a mechanical and biological nature have a bearing on all lengthening processes, and most of them are not fully understood.
Methods. A strain-gauge-monitored unilateral fixator was designed and used to obtain data about the changes which took place in the forces of elongation at a rate of 1 mm/day in four lambs while a 3 cm progressive lengthening of the left tibia was being performed, analysing how these forces behaved from day to day, and how they changed in the course of a single day.
Results. The maxirnum forces in all the animals each day occur after distraction, and the forces reach their greatest magnitude between days 21 and 25 after surgery, attaining values of slightly over 8 kg (40-50% of the animal's weight). The maximum daily force starts to drop 1 h after distraction, and continues to decrease gradually throughout the day until it reaches a value slightly greater than the initial force on the previous day.
Conclusion. This pattern is due to the distraction of soft tissues which gradually adapt to their new situation, thereby reducing the leve) of stress.

RELEVANCE

In the daily bone lengthening procedure, the greatest forces are produced in a short period of time immediately after lengthening. They could be reduced to decrease pain in the patient and loads cm the device by performing lengthening over a greater number of steps or using dynamic equipment able to absorb these forces.

KEY WORDS

Bone lerigthening, external fixation, extensiometry, stress, soft tissue, instrumentation.

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INTRODUCTION

Bone lengthening is a surgical technique which allows the long bones to be lengthened by means of osteotomy or distraction of the growth cartilage followed by sudden or gradual separation of the fragments, and finally consolidation by natural healing. Progressive lengthening is a form of treatment which has been used extensively in orthopaedic surgery to replace earlier methods which required a larger number of operations and a much longer period of confinement to bed.

A series of parameters of a mechanical and biological nature have a bearing on all lengthening processes, and most of them are not fully understood. Thus we still lack information concerning the best rate of lengthening, the type and position of the osteotomy, that is, whether it should be open or closed, metaphyseal or diaphyseal[1-3], and whether lengthening should be commenced immediately or delayed for a few days[4,5]. Nor is the role played by the vessels in the lengthened callus known[1,6-8], or the influence of the rigidity of the external fixator on the forces transmitted through the external fixator during lengthening[1]. The effects of lengthening on the soft tissues and the articular and physeal cartilage likewise remain to be established, from both a clinical and an experimental point of view[9].

The quantity and quality of the newly-formed bone depend on four factors: the damage caused during the osteotomy, and any wounding of the periosteum and nutrient artery; the velocity of distraction; the frequency of the daily distraction and the mechanical conditions of the distraction device[10].

We used an instrumented unilateral fixator to monitor the changes that take place in the distraction forces at a distraction rate of 1 mm/day in four lambs, analysing how these forces behaved from day to day, and how they changed in the course of a single day. This method provided us with information about the forces transmitted via the fixator immediately after distraction, enabling us to observe how they varied over one day, and find out the maximum, minimum and mean forces on every day of lengthening.

The aim of this work was to find out about the mechanical behaviour of the lengthening process, and to discern whether any characteristic pattern is followed.

METHODS

Four 2- to 3-month-old lambs of 13-15 kg weight were operated on, by performing a 3-cm progressive lengthening of the left tibia. The animals were looked after throughout by a team of veterinary surgeons, and the study was performed with the approval of the Ethical Committee.

All the lambs were operated on with the same technique. The surgical procedure was performed under general anaesthesia without intubation. Five-millimetre-diameter pins were attached to the bone at the proximal and distal metaphysis of the tibia, using an image intensifier. A longitudinal incision 2 cm in length was performed on the lateral side at the middle third of the posterior leg. After identifying the periosteum, it was opened and a transversal osteotomy of the diaphysis was carried out using a pneumatic saw and a guide. With this homogeneous technique the medullary vessels and periosteum were not preserved.

Distraction was performed at the same time on 6 days each week in four lambs which were kept in isolated cages. The lengthening was carried out at a rate of 1 mm/day in one step and the lengthening procedure commenced 1 week after the operation.

A unilateral external fixator prototype was fitted to the tibia which had been specially designed for work with lambs (Monotube®, Jacquet Ortopedie, Howmedica, Geneva). Strain gauges were incorporated into the external fixator by replacing a section of the lengthening bar with a sensor consisting of a metal piece in which were placed four strain-gauges to form a complete Wheatstone bridge. The sensor has to be small to fit into the bar of the fixator, capable of measuring forces of between O and 20 kg, and rigid in order not to detract from the original rigidity of the fixator. The force transductor has very good linearity (considering the effects of repeatability, and crosstalk, the error is less than 2%), can be perfectly adapted to the geometry of the fixator, and does not detract from the frame's rigidity[11] (Figure 1).

The fixator was connected by means of a cable to a computer with an .A/D converter for the acquisition and processing of data (Lab View 2, National Instruments, Austin, TX, USA). This was equipped with an amplifier (San-ci, N9224, AC Strain Amplifier, Tokyo, Japan) to pick up the microvolts transmitted through the bar of the fixator every 20 min for 24 h a day, equivalent to 80 readings a day. For each reading, the program performed an average mean of 500 data points taken in 1 s, then transformed the information into the corresponding value in kilograms. This measurement was carried out without interruption over the lengthening procedure, and always at the same time of day (10 a.m.)

The measurement system was checked every day before the lengthening was carried out. When a technical problem was detected, the experiment was stopped. Lengthening procedures performed for less than 3 weeks were not included in the results.

RESULTS

Figures 3, 5, 6, and 7 show the forces obtained before and after lengthening for all animals. In lamb no. 1, (Figure 2) the forces began to increase around day 11, and were clearly higher once the third week after surgery had been reached, that is, after the bone had already been lengthened for a week. The forces continued to rise until day 21, to a value of over 8 kg. A drop in forces was then noted (Figure 3). The same phenomenon was observed in the second lamb. After some compression testing of the instrumented fixators in computer-controlled material testing apparatus (Instron, Model 4502, UK) it was determined that this fact was due to the existence of some free play in the fixator itself, possibly in the pin holders, which place into definitive position when the muscular forces reach a particular level and a tilting of the bone fragments can be observed (Figure 3) (Figure 5).

In lamb no. 2 forces of up to 10 kg were attained after lengthening had been carried out (Figures 4, 5).

The mean forces during lengthening were distributed as follows, the pattern being one of a gradual increase (Figure 6) which was also seen in lamb no. 4 (Figure 7). In lamb no. 3 measurements were carried out over a longer period of time. The range in force before and after distraction in lamb no. 4 was higher than in the other three, probably because this was the oldest animal.

None the less, the most interesting aspect is the analysis of how these forces vary in the course of one day. We can thus see from the graphs how the force increases each day, rising dramatically after lengthening, then slowly falling until it reaches a value slightly greater than the final force on the previous days.

DISCUSSION

The use of engineering techniques to measure strains occurring in various types of implant offers valid information which is useful from both a clinical and a research point of view. Strains can be measured by means of mechanical, optical, pneumatic, acoustic, or electrical gauges[12]. External fixation makes it possible to place instruments within the apparatus in order to measure the forces which are transmitted through it, with the advantage that it is not necessary to implant the gauges inside the organism. This makes it an extremely useful method for determining the rigidity of the fracture callus [13-16] which some authors recommend to monitor the course of fracture healing[17-19].

Another aspect that has received little attention, but which is nevertheless important, concerns the forces which have to be exerted on the osteotomy in order to separate the fragments by 1 mm.

Various authors have performed clinical studies of the forces produced when physeal distraction or lengthening is carried out, but always at a given point in time; they were not able to establish a continuous behaviour pattern. While the growth plate is broken, the forces of distraction reach 80-150 kp[20] or 244-580 N[21]. Spriggins et al.[22] performed a study of the forces of physeal distraction using instrumented fixators in rabbits, and discovered two behaviour patterns. In one group the forces increased to maximum values of 20-32 N, then fell until the next distraction; the authors believe that this indicates a break in the growth cartilage and associated hyperplasia. In the other group the forces were found to be smaller, 6-18 N at the end of the period of distraction, which is evidence of hyperplasia without bone fracture.

The behaviour of the forces in progressive lengthening with a diaphyseal or metaphyseal osteotomy is different, as daily distraction is performed and the forces vary throughout the day and from day to day with the increase in length. The soft tissues, muscles, aponeuroses, fasciae, tendons, and skin oppose lengthening, as these tissues present different degrees of elasticity, which explains why the readings during lengthening vary from author to author, ranging from approximately 100 to 400 N[23,24]. Wolfson et al.[25] using a circular fixator, report forces of approximately 5 kg, 6 days after surgery, which rose to 23 kg by day 27, depending on the patients` age, aetiology, and sex.

For this reason the magnitude of the forces also varies in experimental studies, depending on the animals used and their characteristics. It should therefore come as no surprise that the maximum forces obtained in lengthening processes in dogs reached values of between 150 and 250 N when an increase in length equivalent to 15-25% of the bone length was achieved[3] while in our study the maximum force attained was between 80 and 100 N, when a progressive length increase of 3 cm was reached. None the less, due to the relaxation effect, the force required to maintain a given tissue length will decrease with time[26]. The force obtained after 1 mm distraction decreased by 43% during the 24 h after distraction. We found that the maximum forces each day occur immediately after distraction, and reduced progressively during the next 24 h which is in agreement with Kenwright et al.[27] who, on the basis of discontinuous readings in patients undergoing lengthening, maintain that 20 min after the bar of the fixator had been increased by 1 mm, the load diminished by 80%, and continued to fall over the subsequent 24 h.

We have found that forces, with different magnitudes, follow a common pattern in every case: the maximum daily force starts to drop 1 h after distraction, and continues to decrease gradually throughout the day until it reaches a value slightly greater than the initial force on the previous day; the mean daily force thus increases little by little. Leong et al.[24] found that the maximum force during clinical practice was 14.2 kg for an increase of 1 mm. In their opinion the behaviour pattern could be due to the mechanical properties of the lengthening callus, the behaviour of which is that of a viscoelastic tissue which is stretched, and then relaxes over 24 h until the next distraction is applied. In our opinion this cannot be so because in that case the forces obtained during the first days of distraction should be the greatest, since once the osteotomy was performed we waited 1 week before beginning the lengthening, which gives time for granulation tissue to form and it would be this callus which would offer most resistance to reaction, while they are the lowest of the whole process.

During the following weeks we found that mean forces increase, and this cannot be explained with the theory of Leong elt al.[24], because it is known that callus properties do not vary substantially while lengthening is performed, but during the maturation period that usually follows. The only sensible explanation is that the measurents obtained show the forces applied by the soft tissues, not by the callus. The progressive increase obtained is therefore just the result of distracting the soft tissues.

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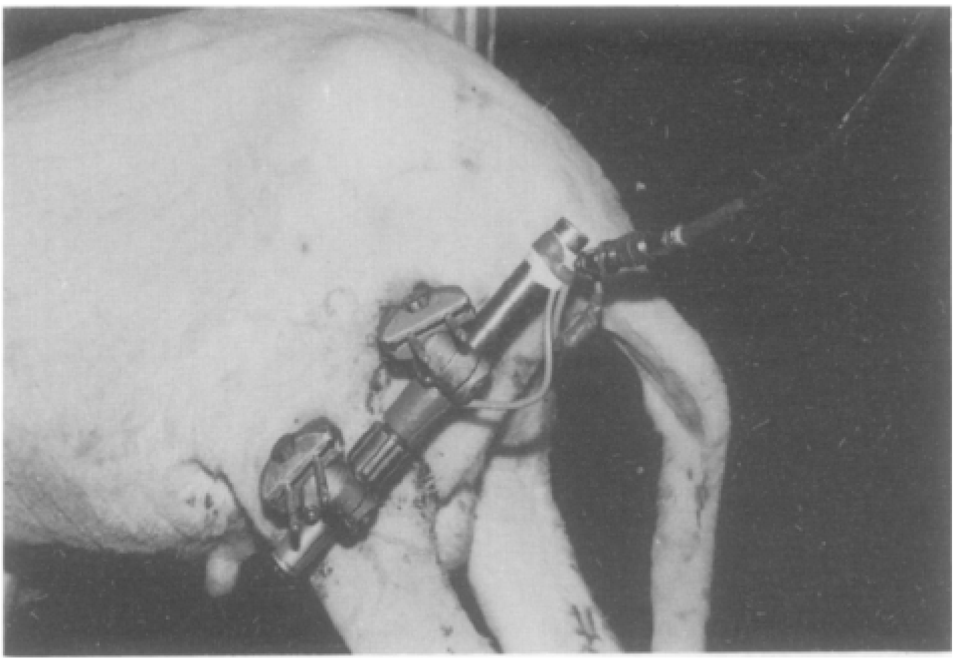

Figure 1. Unilateral external fixator with the strain gauge system.

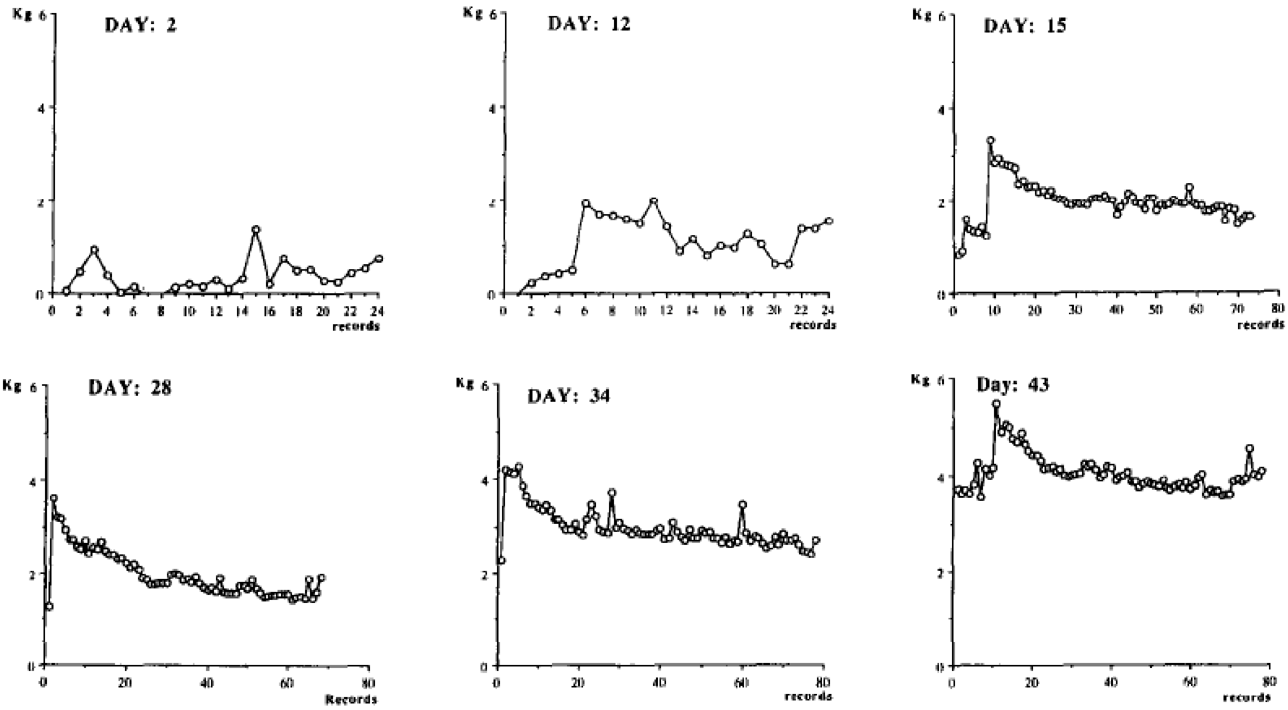

Figure 2. Lamb no. 1. Forces during the lengthening process on different days,

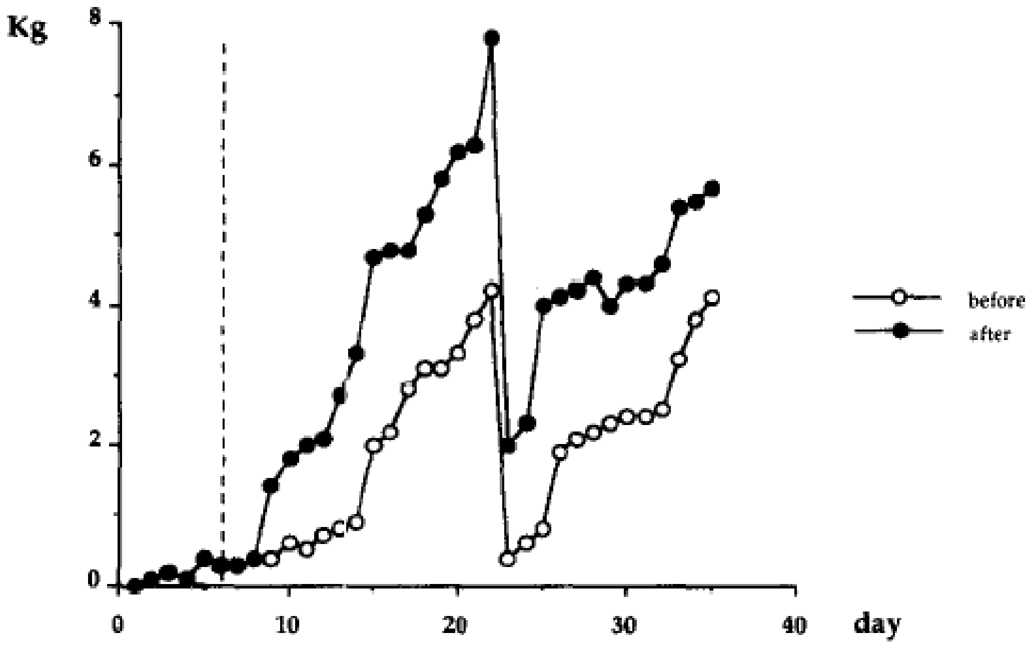

Figure 3. Daily forces registered in Lamb no. 1, before and after external fixator 1 mm lengthening. Dashed line indicates the beginning of elongation.

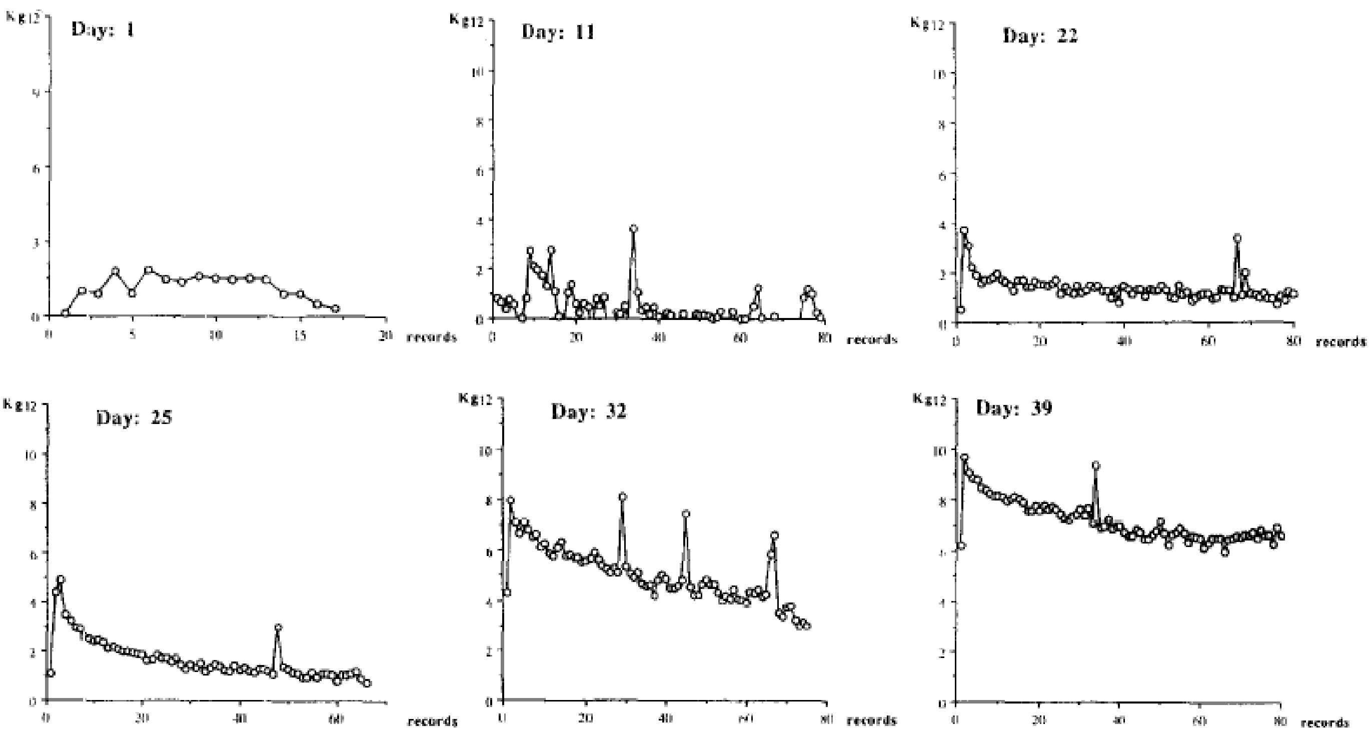

Figure 4. Lamb no. 2. Continous registration of data on 6 different days during the lengthening process.

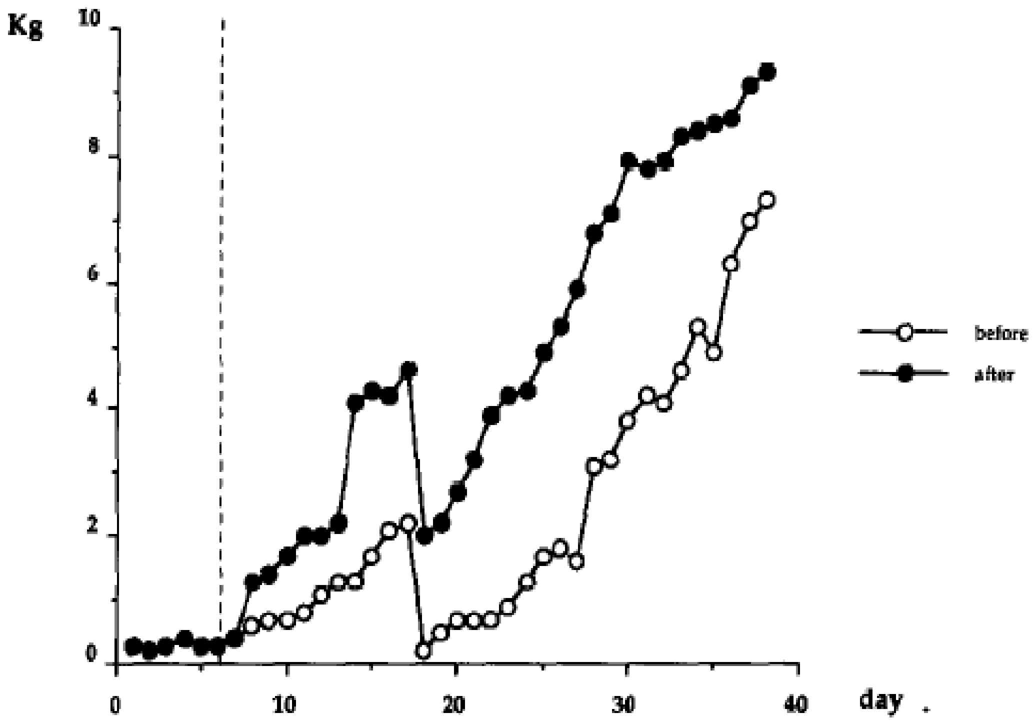

Figure 5. Daily forces registered in Lamb no. 2, before and after 1 mm of lengthening. Dashed line indicates the beginning of elongation.

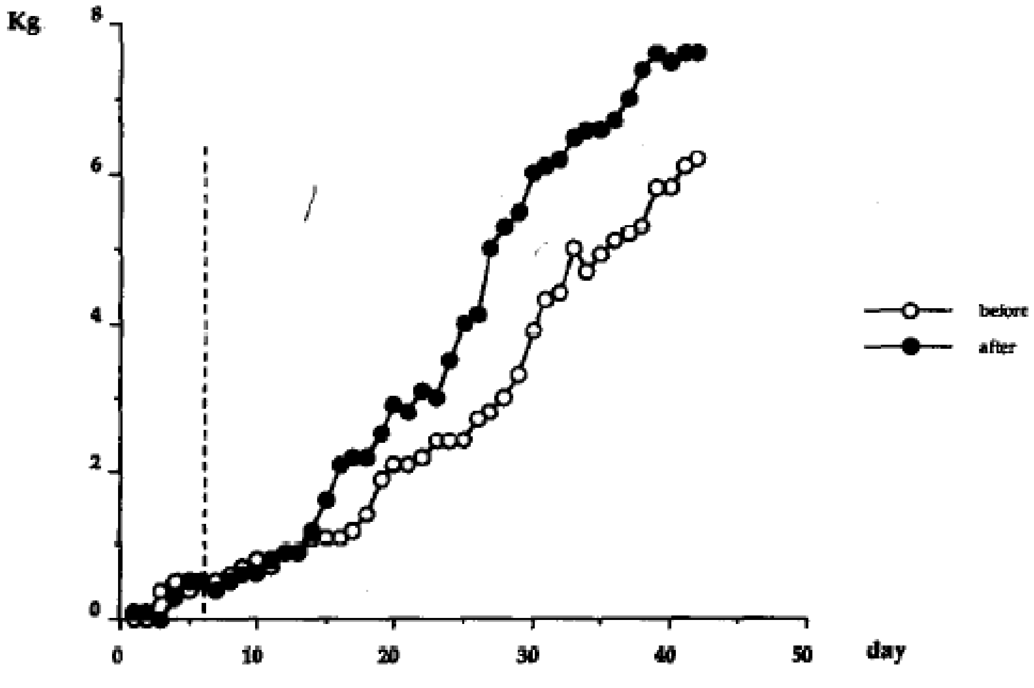

Figure 6. Daily forces registered in Lamb no. 3, before and after 1 mm of lengthening. Dashed line indicates the beginning of elongation.

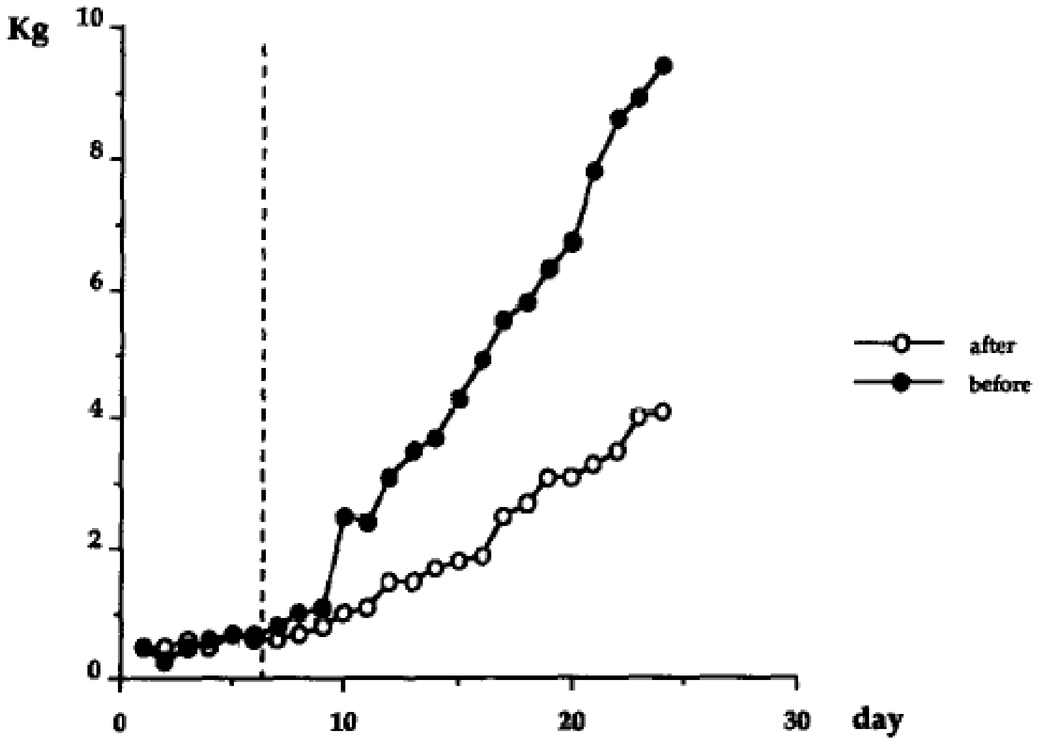

Figure 7. Daily forces registered in Lamb no. 4, before and after 1 mm of lengthening. Dashed line indicates the beginning of elongation.