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EXPERIMENTAL RUPTURE OF THE ACHILLES TENDON

Comparison of Various Types of Experimental Rupture in Rats

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Previous authors attempting to induce tendon rupture (Sallefranque 1887, Blix 1895, Loos 1901, McMaster 1933, Lindblom 1939, Fink & Wyss 1942, Stucke 1951, Davidsson 1956, Viidik 1968) have used different methods: injury to the tendon (ligation of its vessels, crushing or partial cutting of the tendon), stimulation of the muscle, training of the experimental animals, and a different speed of the attempted rupture.

Apart from the injury experiments, the experiments on the bone-muscle-tendon-bone chain have rarely resulted in tendon rupture (Sallefranque 1887, Lindblom 1939).

In a previous study the present author (Barfred 1971 c) described the influence of the animal's age, sex, and conditions of living upon a standardized rupture experiment. It was concluded, among other things, that a rupture of the Achilles tendon could be induced at a distance of 0–2 mm from the calcaneus in recently captured large, wild rats by an oblique, quick traction on the intact bone-muscle-tendon-bone unit with simultaneous tetanic stimulation of the muscle. The tendons exhibited no histological signs of degeneration (Barfred 1971 a).

The frequency of tendon rupture was found to be the same in 3 groups of rats—females weighing 250–300 g, females weighing more than 300 g, and males weighing more than 300 g. It was also the same

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when the material was divided into two halves, large and small rats. In the present paper the three weight groups will be considered together as a control group against variations in the experimental procedures on rats fulfilling the same weight criteria.

The variations studied by previous authors, speed of traction, and traction with and without stimulation, were also studied in the present series. To this were added experimental conditions which might be imagined to influence the occurrence of human subcutaneous tendon rupture, viz. exhaustion of the muscle, changes in its initial length, and changes in the direction of traction.

MATERIAL AND METHOD

The experimental animals were large, wild, brown rats subjected to the experiments not later than two weeks after being captured. Table 1 gives their distribution by sex and weight.

Table 1. Distribution of recently captured wild rats by sex and weight in the various groups of rupture experiments.

Type of rupture experiment Group	Average weight g	Total	No of investigated legs ♂ > 300	♀ 250–300	♀ > 300
Control	338	42	13	14	15
Slow traction	395	13	6	1	6
Straight traction	392	16	7	1	8
Exhausted	370	13	6	1	6
No stimulation	360	16	9	1	6
Short initial length	335	14	4	3	7

The experimental procedure has been thoroughly described in a previous paper (Barfred 1971 c). For each experiment (each leg) the body weight, foot length, muscle-tendon length, initial length, excursion, separation force, elongation at rupture, $L_{2.0}$, and $\triangle L_{1.5}$ were investigated. (*Foot length:* distance from heel to longest toe. *Muscle-tendon length:* distance from muscle origin to tendon insertion with extended knee and maximum dorsal flexion of the ankle. *Excursion:* the difference between the above-defined muscle-tendon length and the length of the muscle-tendon when the knee flexion and the ankle plantar flexion are maximal. *Initial length:* length of muscle-tendon group at commencement of the loading experiment. $L_{2.0}$: elongation at increase in tension to twice the isometric force. $\triangle L_{1.5}$: elongation from $L_{1.5}$ to $L_{2.0}$).

The choice of the type of experiment was fortuitous for each leg. The variations were as follows:

1. Control group in which the footplate and thereby the calcaneus was in a 30° angle in relation to the long axis of the tendon in the frontal plane. The elongation was performed quickly, with simultaneous stimulation of the muscle. The initial length was the length of the muscle-tendon group at 90° flexion in the ankle and approx. 40° flexion in the knee.

2. Slow traction, the elongation of the muscle-tendon group being performed appreciably more slowly than in the control group.

3. Straight traction, with the footplate and thereby the calcaneus in a neutral position instead of 30° angulation.

4. No stimulation, when the loading experiment was done without stimulation of the muscle.

5. Exhausted, when the muscle, during a period of 3–5 min, was exposed to tetanic stimulation until exhausted, so that the contraction force fell to 5 per cent of the maximum isometric force. Thereafter, the stimulation was interrupted, and the next moment the loading experiment was performed.

6. Short initial length means that the initial length corresponded to the shortest possible length of the muscle-tendon group in the intact leg + 25 per cent of the greatest possible excursion.

All the parameters were entered on paper tapes, and the material was analysed in a GIER computer.

Unless otherwise stated, the linear regression equations were determined for the parameters and compared between the groups.

The groups were compared with the control group, but as the body weight and sex ratio were extremely varied (Table 1), and as many of the relations were found to change with increasing weight, especially in the case of the largest rats (Barfred 1971 c), the control group was divided into a large and a small subgroup which, as already mentioned, showed the same distribution of ruptures. To exemplify the dependence of the parameters upon weight, the separation force-muscle force relations are shown in Figure 1 for the small and the large control sub-group.

In stating the results below, the comparison against the entire control group has been checked by comparing with the large control sub-group and, if indicated, by comparing males or females from the variation group with the corresponding sex in the control group.

A significant difference from the control group was rejected if the fractionated comparison was insignificant, unless there was still a distinct tendency to the named difference.

Comparison between the right and left leg and comparison between the leg first exposed to experiment and the second leg were done by applying the t-test to the difference.

For comparing the distribution of the site of rupture in the various groups the approximate χ^2 test was used.

Differences were considered significant when $p < 5$ per cent.

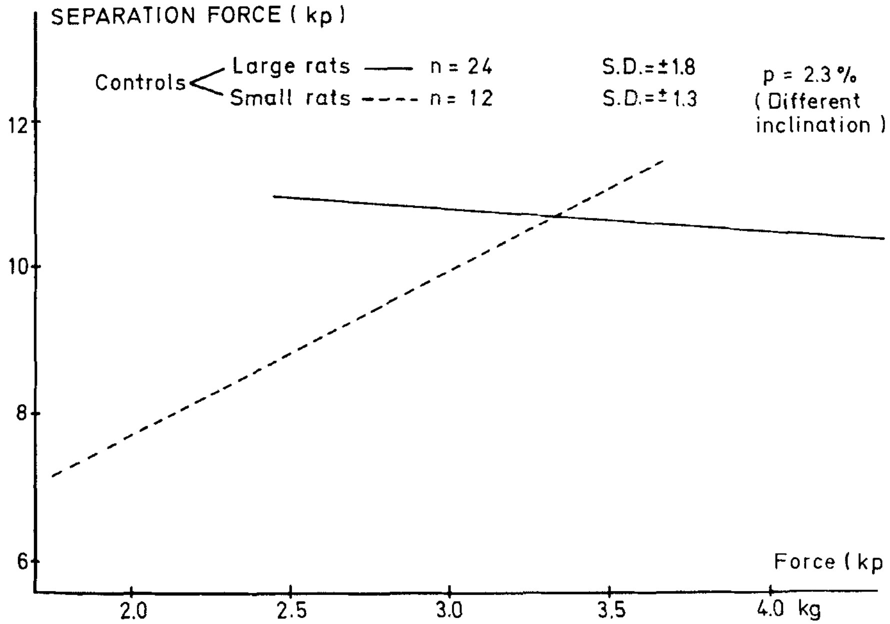

Figure 1. Correlation between separation force and muscle force in recently captured large, wild rats. The broken line represents the regression equation for the 18 smallest rats, the solid line the regression equation for the 24 largest rats. The difference between the inclination of the lines is significant. Force unit: Kp = 9.81 × 10⁵ g cm/sec² = 9.81 N (Newton).

RESULTS

The distribution of the site of rupture in the various groups is divided in Figure 2 into 4 types: fixation ruptures, tendon ruptures, muscle ruptures, and other ruptures. The latter signifies ruptures at tendon insertion or muscle origin with avulsion of a bone fragment from the calcaneus or condyles and also includes ruptures at the muscle-tendon junction.

The number of experiments on right and left legs was approximately the same in all groups. The right leg experiments corresponded to pronation and the left leg ones to supination of the foot. No significant difference was found between right and left legs from rats on which the same procedure was used on both sides.

The duration of anaesthesia might also have influenced the experimental results, *inter alia* because some of the rats went into shock. However, a comparison between the first and second leg on rats having the same type of experiment on both sides showed no signifi-

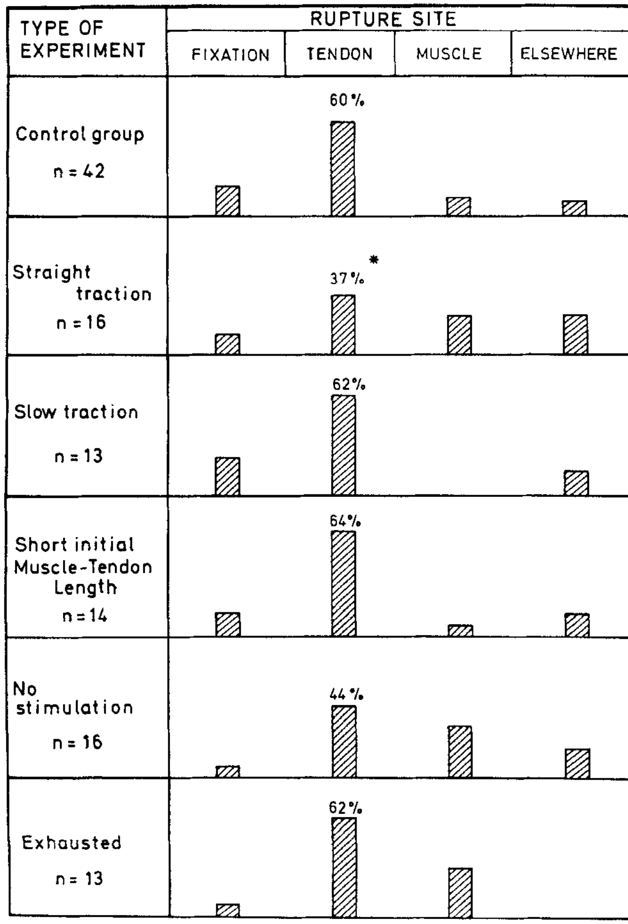

Figure 2. Dependence of distribution of rupture site upon type of experiment on recently captured large, wild rats. The height of the columns is determined by the percentage number of ruptures.

* *On comparison with the tendon ruptures in the control group p = 13 per cent.*

cant difference. The duration of the anaesthesia had been approx. half an hour longer for the second than for the first leg.

Straight traction. The only change in procedure in this group as compared with the control group was that the calcaneus was in a neutral position. The incidence of tendon rupture (Figure 2) dropped to 37 per cent (p.= 13 per cent). At the same time the number of muscle ruptures increased from 5 out of 42 (12 per cent) to 4 out of 16 (25 per cent). Although the values are not finally convincing, the straight traction appears to have distributed the risk of rupture to all parts of the bone-muscle-tendon-bone group, whereas the oblique traction appears to concentrate the risk on the tendon.

The elongation-muscle-tendon length relations as well as the separation force-muscle force relations differed significantly on comparison between the straight traction and the control group. Both relations showed that the regression line was steepest for straight tractions, so that elongation and separation force were less than in the control for the smallest rats, whereas no major difference was found between the large ones. Otherwise, there were no differences between the groups.

Slow traction. The incidence of tendon rupture and the distribution of the ruptures were the same as in the control group. The change made in this group was that the speed of traction was slower, an average of 94 per cent/sec, as compared with the control group in which the elongation averaged 257 per cent/sec (stated as per cent of muscle-tendon length).

On comparison of the various parameters, no difference from the control group was detected.

Short initial length. In the control group the initial length was the length of the muscle-tendon group when the foot was in 90° flexion and the knee in about 30° flexion. This length was about 2 mm shorter than the greatest possible length of the muscle-tendon group (called muscle-tendon length). As a short initial length the author chose the shortest length that the muscle-tendon group could have (maximum flexion in the knee joint and plantar flexion of the ankle) + 25 per cent of the excursion. The excursion was almost 10 mm, the length of the muscle-tendon group about 50 mm.

This procedure did not alter the distribution of the type of rupture (Figure 2). The separation force, in relation to muscle force and body weight, as well as $\triangle L_{1.5}$ in relation to muscle-tendon length, was the same in both groups. In relation to muscle-tendon length both $L_{2.0}$ and elongation were significantly greater in "short". In absolute figures the average elongation in the control group was 13.2 mm and in the "short" group 16 mm. The difference in the initial length was 4.9 mm. Thus, the final length (initial length + elongation) of the muscle-tendon group obtained at rupture was 1.9 mm less in the "short" than in the control group. The final length-muscle-tendon length relation showed this difference to be significant.

In this connection it must be mentioned that the final length was never less than the muscle-tendon length. As mentioned in the previous paper, the lower leg was cut except for the Achilles tendon before the rupture experiment. In one rat of those which had been kept in a run (Barfred 1971 c) the elongation at tendon rupture was only 3.3 mm, corresponding to a final length of 1.3 mm more than the muscle-tendon length. If this experiment had been performed with a short initial length, the final length might have been presumed to be 1.9 mm shorter, and thus the tendon rupture could have taken place without exceeding the muscle-tendon length. In this case the heel region was oedematous, but the tendon itself was normal, grossly as well as microscopically.

In 6 legs the final length, corrected as above, was less than 3.5 mm greater than the muscle-tendon length. Of these 6 legs 3 were from the control group, 2 from the straight traction group, and one from the group kept in a cage for 3 months after being captured (Barfred 1971 c). These tendons showed no gross or microscopic changes in

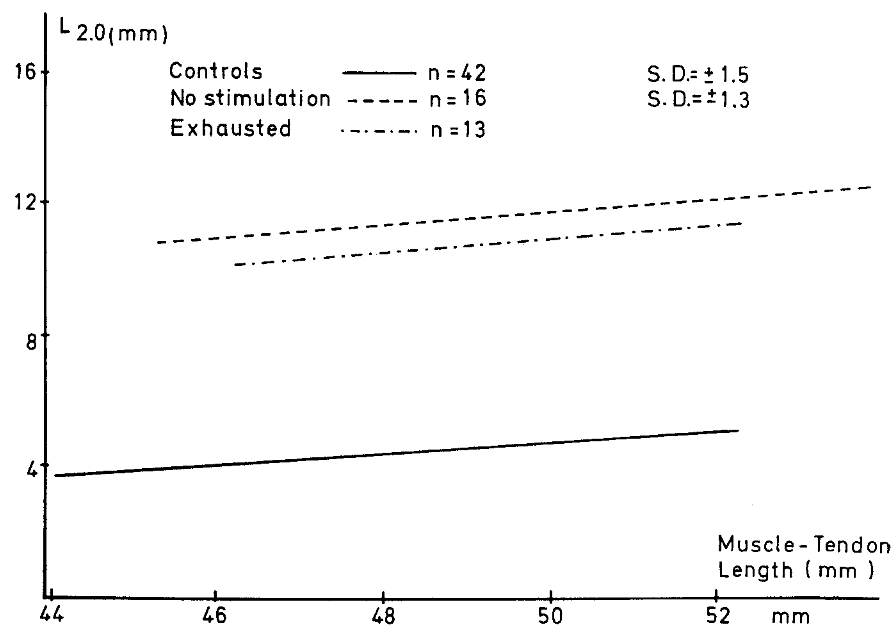

Figure 3. Correlation between $L_{2.0}$ and muscle tendon length. $L_{2.0}$ is the elongation at the tension which corresponds to 2 × the maximum isometric force. The lines represent the regression equations for the control group, the no stimulation group, and the exhausted group. The difference between the control and the exhausted group is significant ($p = 0.0$ per cent), whereas that between the exhausted group and the no stimulation group is not significant ($p = 8.4$ per cent).

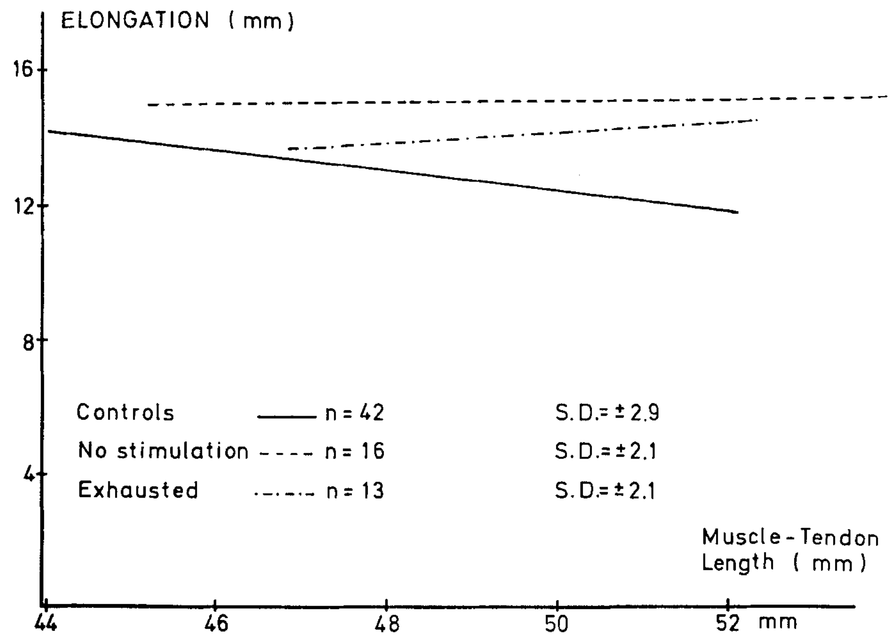

Figure 4. Correlation between elongation at rupture and muscle-tendon length for the control group, no stimulation group, and exhausted group. The lines represent the respective regression equations. The difference between the control group and the no stimulation group is significant (p= 1.1 per cent). Otherwise, no significant difference between the groups.

explanation of the short elongation at rupture. The 7 legs just mentioned were from 4 groups totalling 84 experiments.

No stimulation. In this group the incidence of tendon rupture fell from 25 out of 42 (60 per cent) to 7 out of 16 (44 per cent). The difference was not significant. There seems to be a tendency to a larger number of muscle ruptures in this group.

The elongation-muscle-tendon length as well as $L_{2.0}$ -muscle-tendon length relations disclosed that elongation and $L_{2.0}$ were significantly greater than in the control group (Figures 3 and 4).

The separation force was significantly less, in relation to force and to log. weight.

$\triangle L_{1.5}$ was significantly less in the control group, corresponding to a greater inclination in this part of the length-tension diagram.

Exhausted. The incidence of tendon rupture was exactly like that in the control group. At the same time, there seemed to be a tendency to a larger number of muscle ruptures, just as in the no stimulation group.

Figures 3 and 4 show that the elongation and $L_{2.0}$ in relation to muscle-tendon length were greater than in the control group, but the difference was significant only for the $L_{2.0}$ -muscle-tendon length relation.

Just as in the no stimulation group $\triangle L_{1.5}$ was significantly lower in the exhausted group than in the control group.

Neither the separation force-muscle force nor separation force-log. weight relations were different from those in the control group.

Comparison between no stimulation and exhausted did not show any significant difference between any of the named relations, but the values for exhausted were always between those for control and no stimulation.

The elongation-muscle-tendon length relation (Figure 4) exhibited a difference which might indicate that an exhausted muscle was stiffer than a non-stimulated one, but $p = 14$ per cent.

As already mentioned, the rupture experiments in both these groups were performed without stimulation, but those in the exhausted group had been immediately preceded by 3–5 min tetanic stimulation which exhausted the muscle so much that its force was less than 5 per cent of the maximum isometric force.

Comparison Within the Groups

The site of rupture in the bone-muscle-tendon-bone chain is determined to some extent by the animal's conditions of living and by the experimental procedure. Furthermore, it could be expected that properties in the individual animal might influence the site of the rupture.

A comparison of muscle and tendon ruptures within the control group showed that the muscle force appears to have a major influence upon the type of rupture (Figure 5). The comparison was performed as muscle force-log. weight and muscle force-muscle-tendon length relation with the same result. The 5 muscle ruptures occurred among the rats which were rather small (250–345 g), had a fairly short muscle-tendon length, and significantly less muscle force than the entire control group. From the same figure it is apparent that these criteria were not tantamount to the result of the rupture experiment being a muscle rupture.

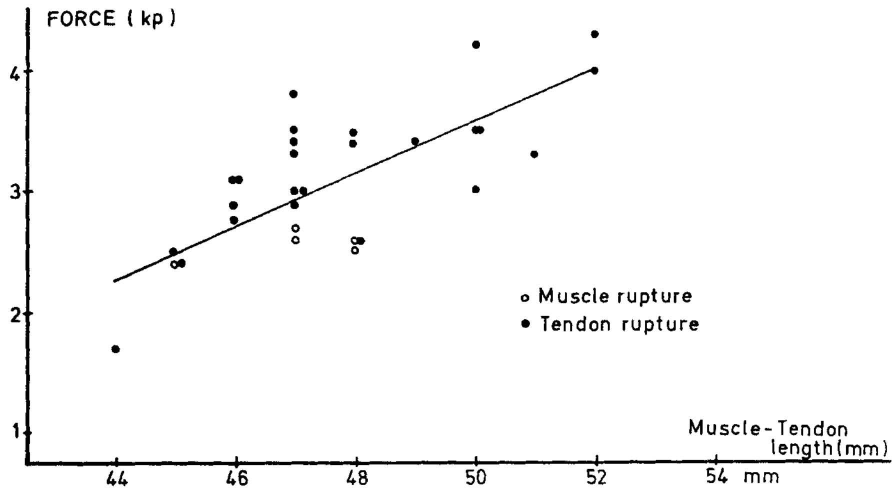

Figure 5. Correlation between force and muscle-tendon length. The line represents the common regression equation for muscle and tendon ruptures in the control group. Muscle rupture (n = 5) and tendon rupture (n = 25) are marked differently. SD ± 0.1 and ± 0.4 respectively. The difference between muscle rupture and tendon rupture is significant (p = 1.1 per cent).

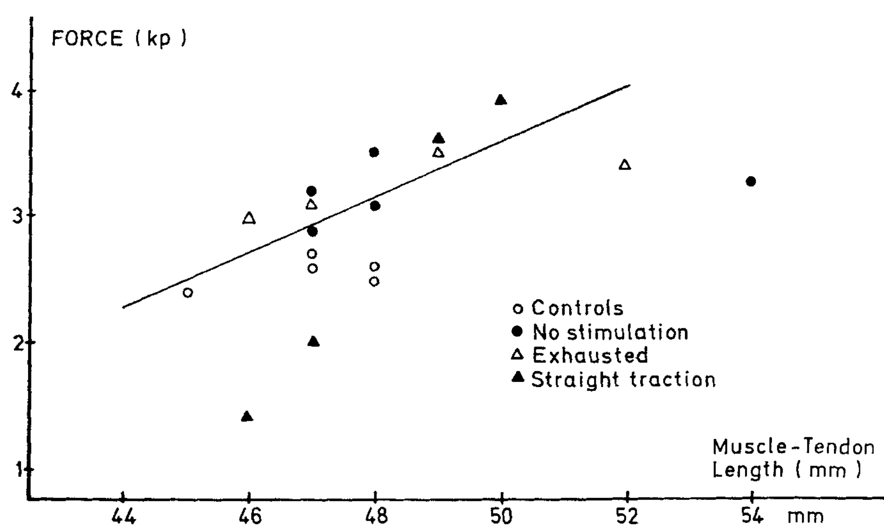

Figure 6. Correlation between force and muscle-tendon length for muscle ruptures in the control group, no stimulation group, exhausted group, and straight tra tion group. The line represents the common regression equation for muscle and tendon ruptures in the control group.

The slow group was not represented in the "danger zone" with respect to muscle rupture, and indeed no muscle ruptures occurred. The group short initial length was represented by one leg in this zone. The result was muscle rupture, the only one occurring in the group.

In three groups: no stimulation, exhausted, and straight traction 5, 4, and 4 muscle ruptures occurred (Figure 6). All the muscle ruptures in the exhausted and in the no stimulation group occurred in large rats with a fairly great muscle-tendon length and significantly greater muscle force than those showing muscle ruptures in the control group. These two groups are not represented by more than one leg each in the zone in which the muscle ruptures of the control group occurred. In both cases the result was tendon rupture.

Within the groups no stimulation and exhausted there was no difference between the muscle force-muscle-tendon relations for muscle rupture and for tendon rupture.

In the straight traction group 2 legs were in the "danger zone". Muscle ruptures occurred in both. In addition, 2 muscle ruptures occurred in rats with muscle force exceeding the average. This makes the inclination of the regression line for the muscle force-muscle-tendon length relation significantly steeper for muscle ruptures than for tendon ruptures in this group and at the same time significantly steeper than for muscle ruptures in the control group. This occurrence of muscle ruptures in strong rats was not observed in the control group (oblique traction) and supports the previously mentioned impression that straight traction distributes the risk of rupture to all parts of the muscle-tendon group.

In the control group the elongation, when muscle rupture occurred, was significantly greater than at tendon rupture. The same tendency was found in the straight traction, no stimulation and exhausted groups. The separation force in these three groups did not differ for tendon and muscle rupture, neither in relation to force nor to log. weight.

DISCUSSION

Lindblom (1939), by traction on an abducted shoulder (in a anatomical preparation), could induce tendon rupture of the supraspinatus tendon. He emphasized that by this direction of traction the articular part of the tendon was strained (tightened) first, and at this time the acromial part of the tendon was relaxed, with undulating surface. He could have produced even greater differences in the strain on various parts of the tendon by external or internal rotation of the shoulder.

All tendons passing one or more joints with axes of movement at right angles to each other may be exposed to oblique traction, for instance the Achilles tendon, the supraspinatus tendon, and the biceps brachii tendon. A tendon inserting immediately distal to a hinge joint may, even though it is flat, be exposed to overstrain of its convex side, e. g. the finger extensor passing the distal interphalangeal joint.

If a human Achilles tendon 1.5 cm wide is exposed to traction with 30° supination of the calcaneus, it may be calculated that the fibres on the convex aspect are elongated by 10 per cent before straining of the fibres on the concave side occurs. This 10 per cent corresponds approximately to the values stated for the elongation of tendons at rupture (Stucke 1950: 7.3 per cent, Rollhäuser 1951: 11.5–13.5 per cent, Viidik 1968: 12–13 per cent).

By exerting oblique traction, then, it might be possible to strain a small part of the tendon and induce rupture by less force. The above calculation presupposes, erroneously, that the tendon is homogeneous. Mollier (1937) and Altmann (1963) have described the complicated structure of the tendon which in their opinion affords the best possibilities of transmitting the muscle traction to bones assuming various positions as needed. The tendon fans out at the insertion, and the juxtaskeletal part is stiffer than the remainder of the tendon because of its conversion into cartilaginous tissue. In this way the tendon is protected from oblique traction just as the stiff cuff fitted on a flex close to an electric iron prevents breaking of the flex.

At the free end of the tendon the fibres are twisted and bound to each other by interdigitation of parts of the fibres. Between the fibres there is the ground substance which permits a certain displacement and thereby lends the tendon the properties of a laminated material.

Cummins et al. (1946) found that the human Achilles tendon was pronated 30–150°. At the same time they noted that the separation of the individual fractions of the tendon derived from the soleus, medial and lateral gastrocnemius was more difficult to effect the less the pronation. Thus, the interdigitation of the fibres appears to be alternative to rotation. This perhaps contributes to determining the site of rupture, so that marked rigidity and fan-shape at the insertion, together with marked interdigitation of the tendon fibres, afford a more homogeneous tendon and more proximal ruptures, whereas the reverse causes more distal ruptures.

In the rat Achilles tendon there was pronation, as in man, of about 60°. At the same time, it was very easy to separate the components of the tendon. Moreover, at its insertion the tendon did not fan out as in man, being collected mainly into 2 small facets laterally and medially on the posterior surface of the calcaneus. Indeed, the ruptures in this experimental series were localized close to the insertion, although often there was a longer tendon remnant on one side (Figure 7, Barfred 1971 c). Even during straight traction the level of the rupture may be determined by the structure of the tendon. Rotation of the human tendon gives rise to crossing of the fibres 2–5 cm from the insertion (Biro & Tarsoly 1967). Christensen (1954) pointed out the possibility that one part of the tendon (gastrocnemius) may damage the other part (soleus) by a saw-like action at the site of crossing.

In the present experimental series the incidence of tendon rupture fell from 60 to 37 per cent when the traction was straight instead of oblique. This was not significant, but considering the previously mentioned risk of rupture in all parts of the bone-muscle-tendon-bone chain on straight traction, it seems reasonable to assume that the oblique traction weakens the tendon in a selective way. It might be imagined that the oblique traction had also caused a lower rupture limit, but the reverse was found, and no reasonable explanation can be advanced. It seems more reasonable that the elongation at rupture was less with straight than with oblique traction.

That the incidence of tendon rupture was the same in the slow group and in the control group (quick) ought to indicate that a fairly rapid movement (as in the slow group) entails the same risk to the tendon as an ultra-rapid one (control group). Nevertheless, the latter must be considered more dangerous, as it does not allow the organism time for instituting protective measures, e.g. relaxation of the muscle.

In the group short initial length, where the incidence of tendon rupture was the same as in the control group, the elongation was significantly greater, whereas the final length was nevertheless significantly less than in the control group. Thus, the elongation which may involve a danger to the tendon is easier to attain when the position of the joints at the onset of the trauma creates the shortest possible muscle-tendon length.

Fatigue has been stated as a contributory cause of Achilles tendon rupture (Hunter 1835, Debrunner 1950). It may be fatigue of the proprioceptive system (Debrunner 1950), i. e. a more central phenomenon, but it may also be local changes in the muscle in the form of increased rigidity of the myofibrils, if the process of restitution cannot keep pace with the process of contraction (Lindhard 1931, Merton 1956). The present investigation indicates that the local phenomena are essential, as the values for separation force, elongation, $L_{2.0}$, as well as $\triangle L_{1.5}$ in the exhausted group were between those for the control group (with stimulation) and the no stimulation group.

The incidence of tendon ruptures in the exhausted group was found to be of the same magnitude as in the control group, whereas in the no stimulation group this incidence fell to 44 per cent, which is not significantly different from the control group. Although this difference is not convincing, the fact that the elongation was significantly greater than in the control group gives the no stimulation group less chance of obtaining, within the normal excursion, the elongation which is needed for inducing rupture in the muscle-tendon chain.

In the exhausted as well as in the no stimulation groups the muscle appears to be weakened in relation to the stimulated muscle, muscle ruptures being more common and the separation force lower. This is significant for the no stimulation group. In addition, it was found that muscle ruptures occurred in the control group when isometric muscle force was low. The contractile tissue in the muscle appears to be highly contributory to determining the site of rupture as well as the separation force and, as previously mentioned, the elastic stiffness.

The problem whether elongation to the rupture limit is possible at all in a healthy human muscle-tendon has so far been unheeded (Barfred 1971 b).

It has been mentioned above that the length at rupture in the present experimental series always exceeded the muscle-tendon length. In a few cases this difference was so slight that if a larger number of experiments had been carried out, the final length might sometimes have been less than the maximum muscle-tendon length.

SUMMARY AND CONCLUSION

The bone-Achilles tendon-muscle-bone unit in anaesthetized large, wild rats was tested in a material testing machine. The method has been described in detail in a previous paper (Barfred 1971 c) in which the author disproved the claim that a healthy tendon never ruptures. The rupture experiment was performed rapidly during tetanic stimulation of the muscle, using an oblique traction and an initial length corresponding to the elastic equilibrium length.

To ascertain the importance of the individual factors, it was endeavoured in the present study to alter only one of the named experimental conditions at a time.

The findings were as follows:

(1) The incidence of tendon rupture was the same with slow and quick traction.
(2) An oblique traction on the calcaneus appeared to concentrate the risk of rupture on the tendon in experiments comprising the bone-tendon-muscle-bone unit.
(3) Muscle ruptures occurred mainly when the isometric muscle force was below average.
(4) The resting muscle appeared to be weaker than the tendon.
(5) An exhausted, non-stimulated muscle occupied a position intermediate between stimulated and non-stimulated muscle as far as the parameters of the rupture experiment were concerned.
(6) The incidence of tendon rupture was the same in the exhausted and in the control group.
(7) The possibility of inducing tendon rupture without exceeding the maximum muscle-tendon length in the leg was slight, but
(8) this possibility would be greatest at a short initial length.
(9) Elongation was less when the rupture experiment resulted in tendon rupture than when it caused muscle rupture.

It may be concluded that subcutaneous rupture of the Achilles tendon in the rat is conceivable in nature, although presumably it is very rare. The greatest possibility of tendon rupture is present when the loading on the tendon is oblique, when the muscle is in maximum contraction, when the muscle is exhausted, and when the initial length is short.

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