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A METHOD FOR RECORDING TENDON STRAIN IN SHEEP DURING LOCOMOTION

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Although more than a hundred reports have been published over the last century from experiments in which tendons have been artificially stressed to determine their physical properties, the authors are aware of only two reports of measurements of the mechanical behaviour of these structures during life (Shaw 1968, Barnes & Pinder 1974).

The importance of knowing how organised collagen behaves *in vivo* prompted this investigation to determine the mechanical strain imposed on a single tendon, and to correlate it with the activity of its muscle belly.

METHOD

The tendon of the forelimb lateral digital extensor of the sheep was used in these experiments. The transducer (Figure 1) was a strain gauge "bridge" made from a 30 mm $\times$ 3 mm strip of soft stainless steel 0.05 mm in thickness. At each end 5 mm were bent back and a piece of 0.1 mm sprung stainless steel held between the two layers of thinner metal by epoxy resin. The resultant structure consisted of two firm ends for attachment to the tissue and a flexible "bridge" between them. A foil resistance strain gauge was bonded to the concave surface of the "bridge".

The strain gauge transducer was connected to form one arm of the Wheatstone Bridge circuit of an A. C. transducer meter. The recorder was an ultra-violet direct writing recording oscillograph. The transducer was calibrated immersed in water at 38° C before implantation and after removal.

To attach the transducer to the tendon an incision was made on the lateral aspect of the right forelimb along the metacarpus. All loose connective tissue over the tendon was cleared, its surface swabbed dry and cleaned with ether and the transducer then placed in position. Braided stainless steel sutures were laid at each corner but not tightened. Isobutyl 2-cyanoacrylate was applied between the proximal transducer flange and the tendon. This bond was then held securely for 1 minute before being checked for adhesion, after which the sutures were tied. The distal flange was attached in the same way (Figure 1). The length of the flexible "bridge" was measured. Lead wires from the transducer ran subcutaneously to a small skin incision over the animal's rib cage. The incision accommodated a skin

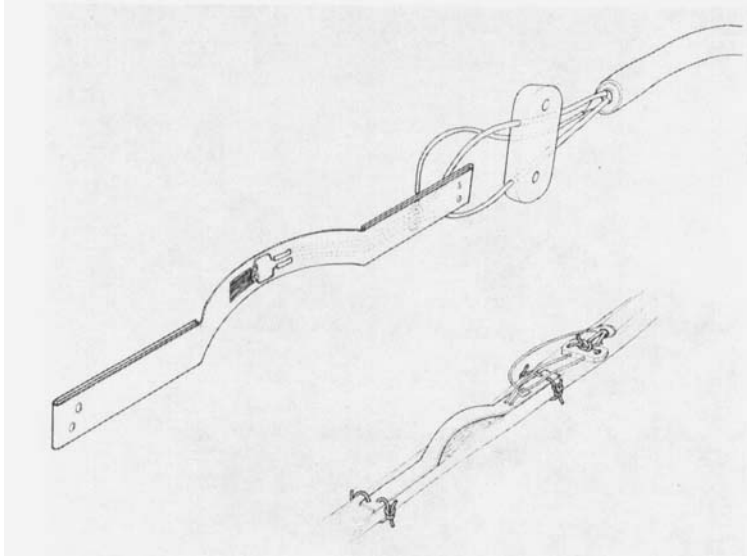


Figure 1. The upper diagram shows the transducer used to record tendon strain. A foil resistance strain gauge was bonded to the concave surface of the flexible metal "bridge". Either end of the "bridge" was glued and sutured to the tendon as shown in the lower diagram. A small epoxy resin flange holding the lead wires was sutured close to the transducer.

socket similar to that described by Lanyon (1971 a). A hard-rolled 0.15 mm stainless steel cover screwed to the metacarpus protected the instrument from skin pressure.

Daily recordings were taken from 14 animals. Limb position was recorded on slow motion film (64 frames per second) and by a variable inductance linear accelerometer, as used by Lanyon (1971 b). In five cases simultaneous recordings of electromyographic potentials were made using fine wire electrodes implanted in the lateral digital extensor muscle (Kear & Smith 1972).

At the end of each experiment, with the animal anaesthetised, the tendon was dissected out and the transducer checked qualitatively to ensure it was still functioning correctly. The muscle was also electrically stimulated and a transducer record made. In one case the humerus was securely fixed and the distal end of the tendon was connected to a force transducer and recordings taken from both instruments as the muscle was stimulated.

In every case a postmortem histological examination was made of the tissue to which the instrument had been attached.

RESULTS

The recordings were very similar, both between animals and from the same animal at different speeds.

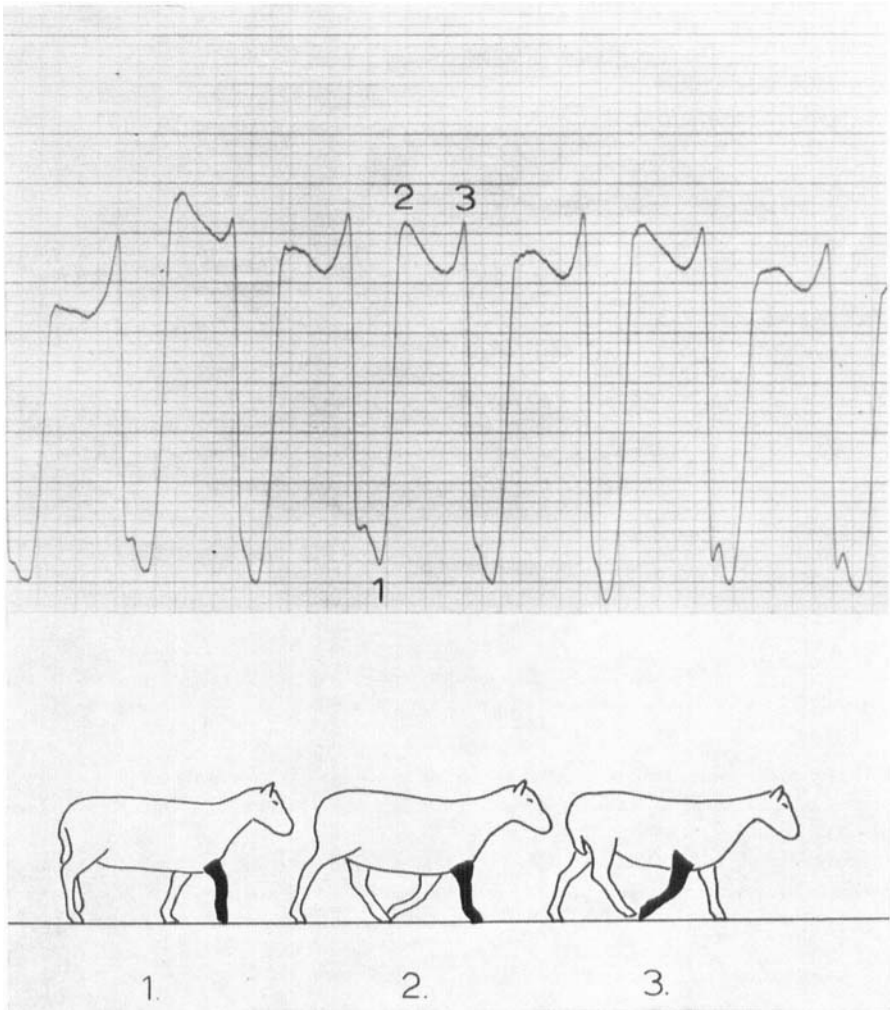


Figure 2. Part of a trace recorded from a walking animal which had a strain gauge transducer attached to the lateral digital extensor tendon. Each strain change cycle represents one stride, during which three points can be recognised. Between points 1 and 2 there is a sharp increase in tendon strain as the foot is placed on the ground and weight taken on it. A slight reduction in tension is recorded as the body swings forward but strain is transiently reimposed at point 3 when the foot leaves the ground.

A typical recording is shown in Figure 2. An increase in length of the transducer is indicated by an upward deflection of the trace and a decrease in length by a downward deflection. Each stride was marked by a strain change cycle. Three distinct points could be identified in each cycle and these are indicated with the corresponding limb position. When the foot was placed on the ground and weight taken on it, there was an apparent tension in the tendon. As the body swung forward this tension was slightly reduced, transiently reimposed and then completely released.

The height of each trace indicates the degree of extension of the transducer and from this an estimate could be made of the strain which occurred in the tendon at each stride. The tendon strain varied from animal to animal and to a lesser extent in the same animal on different days, but in each case strain tended to increase with the speed of locomotion. Ten strides were measured on each day at each of four speeds and the resultant mean strains and standard deviations for each animal over the experimental period are given in Table 1.

Table 1. The mean tendon strain (per cent) for each animal over the experimental period.

Animal	Slow walk	Med. walk	Fast walk	Trot
1	1.2±.4	1.2±.4	1.5±.5	2.0±.7
2	0.8±.4	1.1±.7	1.3±.4	1.4±.6
3	0.8±.3	0.7±.3	0.9±.3	1.1±.6
4	1.5±.3	1.5±.3	1.8±.5	2.4±.8
5	1.1±.6	1.7±.7	2.1±.5	2.2±.6
6	1.7±.7	1.8±.9	2.0±.5	2.6±.5
7	1.6±.4	1.7±.3	1.9±.4	----
8	0.5±.1	0.3±.0	0.6	0.6
9	1.1±.3	1.4±.5	1.0±.3	1.0±.3
10	0.8±.3	0.9±.3	1.1±.6	1.0±.3
11	0.7±.5	1.1±.4	1.3±.5	1.5±.4
12	0.5±.3	0.6±.3	0.6±.3	0.8±.6
13	0.6±.2	0.8±.2	0.9±.1	1.4±.1
14	0.8±.2	1.0±.2	1.1±.3	1.7±.3

The rate at which the tendon was strained during each cycle varied from nil to a maximum shown in Table 2. However, these maximum rates were recorded for only about one-tenth of a second during each stride, as the animal walked fast or trotted.

Table 2. Maximum strain rates recorded for each animal.

Animal	Maximum recorded strain rate (per cent per second)
1	29.9
2	17.2
3	15.0
4	43.8
5	26.1
6	31.4
7	25.8
8	5.4
9	9.0
10	10.9
11	10.2
12	11.4
13	13.4
14	21.4

Figure 3 shows a typical record from an animal during a trot with a strain gauge transducer attached to the tendon and two sets of electromyographic electrodes implanted in the muscle. The strain change pattern shown here is similar to that shown in Figure 2. The bursts of muscle activity occurred mainly during two phases of each stride. The most consistent period of activity occurred during the main tension phase in the tendon as the leg was protracted and the foot extended to be placed on the ground. The second burst occurred as the foot was lifted from the ground about the time when there was also a slight increase in tendon strain.

At the end of each experiment, stretching the tendon either manually or when the muscle contracted, produced a normal record from the transducer.

When the force transducer was used, a load of 4.5 kg was recorded simultaneously with a tendon strain of 2.3 per cent, imposed at a rate of 11.5 per cent per second. Strains of a similar size and rate had been previously recorded from the transducer during normal locomotion.

At postmortem examination the tendon did not appear to have been grossly damaged, although the whole area under examination was covered by a gelatinous pad of inflammatory tissue. This may in fact have helped to protect the instrument. There was however a very slight cellular infiltration between tendon fibres in a few places, notably

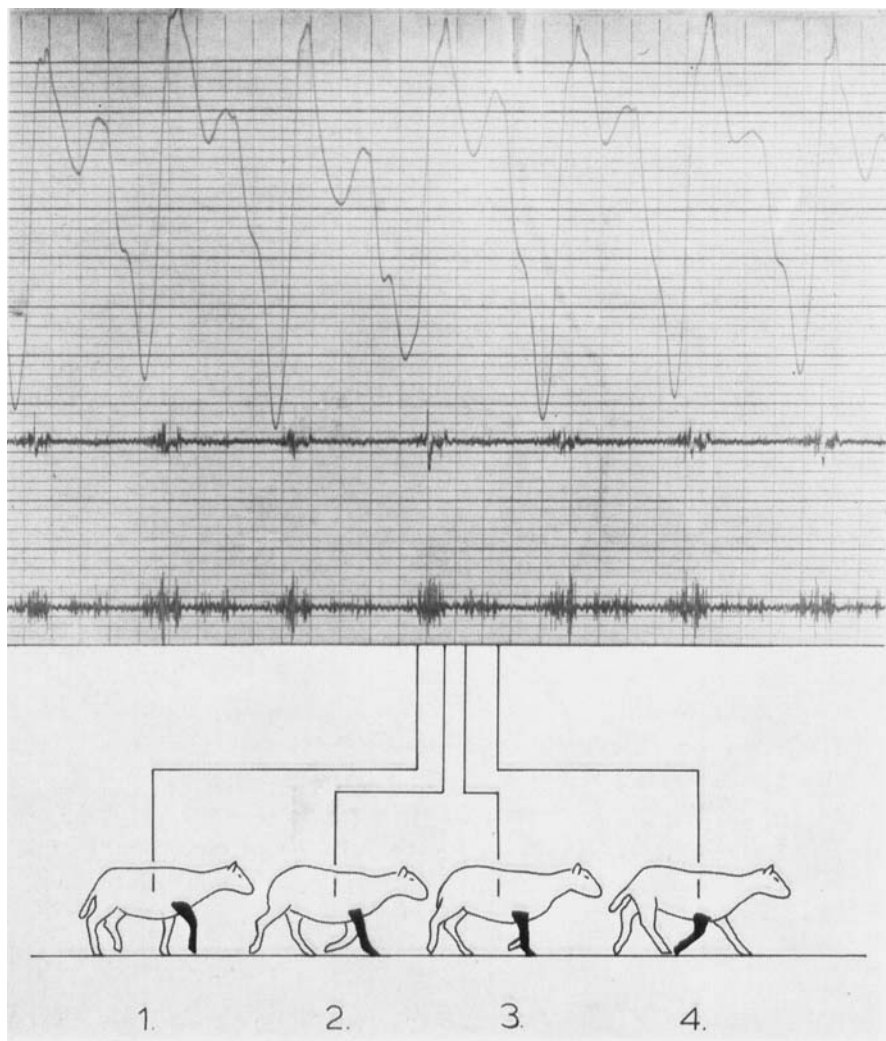


Figure 3. Part of a recording taken from a trotting animal in which both a strain gauge transducer and electromyographic electrodes had previously been implanted. Muscular contraction occurred mainly during one particular phase of the stride, during the period of tendon stretching as the foot was placed on the ground (between points 1 and 2). There was a second less consistent period of activity as the foot was lifted from the ground (between points 3 and 4).

around the sutures. In some cases there was a small amount of infiltration between the surface of the tendon and the layer of adhesive, although this did not appear to be related to the length of time the instrument had been implanted or to the size of the strain which had been recorded.

DISCUSSION

This series of experiments was fraught with many problems that could have affected the accuracy of the results.

It is unlikely that the bond between transducer and tendon did transmit 100 per cent of the change in length which occurred, especially as in some cases cells had found their way between the glue layer and the tendon surface.

It is possible that sometimes when the transducer indicated a shortening the tendon may have bowed slightly without actually decreasing its length. While the limb was being lifted forward during the swing phase (between points 4 and 1 in Figure 3) there was an apparent rapid and marked shortening of the tendon. It is possible that in this flexed position tendon bowing may have occurred.

It was assumed in taking simultaneous electromyographic and strain readings that the instrument lag on the two systems was identical. This is probably justifiable but may not have been absolute.

It seems likely that the cause of the periods of tendon stretch was due, at least in part, to muscular contraction and electromyographic potentials were recorded during both these periods of tendon strain.

A more detailed explanation of muscle activity as related to limb position and tendon strain would require simultaneous recordings from several muscles.

However, although far from ideal this technique did produce reasonably consistent results from a number of animals and in this respect it is an advance on those previously reported. Shaw (1968) did not measure tendon strain but tendon load and this he accomplished by substituting a strain gauge for a section of the superficial digital flexor tendon in a dog. He obtained a peak load of 0.6 kg while the animal was standing and 1.0 kg as it walked. It was suggested that these values were lower than normal as the animal was not putting full weight on the leg. Barnes & Pinder (1974), also wishing to measure tendon tension, attached a buckle transducer to the common digital extensor tendon in a single horse. They published a trace of tension measured in

the tendon during four strides. The tension appeared to increase during the period in which the foot was extended and brought to the ground. It reached its highest point just after impact. The tension then declined and remained at a relatively low level throughout the support phase, to be re-imposed as the limb was protracted. The maximum tension was 170 N (17.3 kg) but the normality of gait was somewhat suspect.

It is difficult to decide whether or not the results from this work support previous *in vitro* studies, as the conditions found *in vivo* are quite different from those used in most of the *in vitro* work. Harkness in 1968 considered the rate of tendon stress *in vivo* to be very rapid, and this type of loading of tissues under experimental conditions has been little studied. Only the properties of tendon found when forces are applied slowly over a discrete period of time have been well documented. These experiments have been carried out without particular regard to physiological conditions, despite the considerable effect that experimental conditions have been shown to produce (Chvapil et al. 1962, Rigby et al. 1959). A typical stress/strain curve produced in such experiments (Elliott 1967) has an initial "toe" portion where the tissues are easily extensible. It is in this region that Harkness (1961) and Stucke (1950) believe that tendon reacts in life. With an increase in stress, the "toe" is followed by a straight portion over which the tendon is elastic. Abrahams (1967) and Rigby et al. (1959) believe it is in this region that tendon normally reacts *in vivo*. Beyond the proportional limit the tissue begins to creep and finally ruptures.

If one can relate such *in vitro* studies to circumstances in life, the absolute limit of strain which could normally occur without permanent damage to the tendon must be the proportional limit. This appears to be between 2 and 5 per cent strain (Abrahams 1967, Elliott 1967, Gratz 1937, Gratz & Blackberg 1935, Rigby et al. 1959, Stucke 1950). Harris et al. (1964) consider that tendon is probably never stressed, *in vivo*, to greater than one-fourth its ultimate strength. They consider the limit of stress *in vivo* to be 2.5 kg/mm². According to their experiments, elongation is 2.5 per cent at this level of stress.

From the work described in this paper the maximum strain recorded in the lateral digital extensor tendon was 2.6 per cent while the sheep was trotting. This would agree with expectations. However, any use of these findings in a consideration of tendon degeneration and rupture should take into account that these occur almost exclusively in flexor tendons whose mechanical circumstances may be very different from those of the extensors.

SUMMARY

Strain change in the lateral digital extensor tendon of sheep was measured during locomotion by means of a small metal strain gauge transducer. The strain pattern was correlated with the activity of the muscle and the position of the limb.

The main period of tendon strain occurred immediately following a phase of muscle activity as the foot was placed on the ground. A second period of tendon tension occurred as the foot was lifted from the ground. This was again usually associated with a muscular contraction.

Daily recordings were taken from 14 animals for about 10 days after implantation of the transducer.

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