THE ELASTIC PROPERTIES OF THE ANTERIOR CRUCIATE LIGAMENT OF THE RABBIT

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INTRODUCTION

In most current anatomical literature joint ligaments which do not contain a large proportion of elastic fibres are described as inelastic, and they are sometimes contrasted with structures such as nerve trunks and small arteries which are termed elastic. Clearly, in such descriptions, the term elasticity refers to that property of gross and reversible extensibility in response to small tensile stresses which is characteristic of thin rubber and weak springs. However, although this usage is common, the word elasticity is also used to denote a physical property which is only loosely related to the 'springiness' implied by its colloquial use, and it is in this technical sense that the word is used in this communication.

When any body is affected by a tensile stress, its length is altered, the extensibility varying in amount from substance to substance. If, when the stress ceases, the body returns to its original length it is elastic to a stress of that magnitude, whereas if it fails to do so it is inelastic or viscous. Each elastic body has an 'elastic limit': if the tensile stress is less than the elastic limit the body reacts elastically, whereas if it is greater the body fails to recover its original length when the stress ceases. Thus in determining whether a body is elastic or inelastic to a particular tensile stress, its complete return to its original length on release is the only relevant factor: the degree of temporary extension which the stress produces is of no significance. For example, steel and rubber are both elastic to tensile stresses of certain values. The elastic limit of steel is much greater than that of rubber, whereas the extension caused by a particular tensile stress is much greater in rubber than in steel.

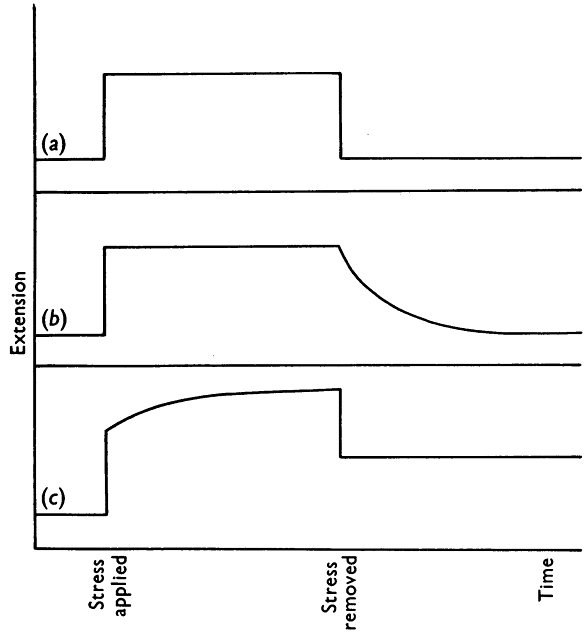
This simple definition of elasticity takes no account of the duration of the tensile stress to which the body is subjected. Bodies which are elastic to a momentary stress of a certain magnitude may react in one of three different ways to a stress of the same magnitude which is maintained at a uniform value for some time.

In the first type of reaction the body is extended when the tensile stress is applied, retains its new length while the stress is maintained, and regains its original length immediately the stress is removed. A body which reacts in this way is elastic to stresses of the magnitude and duration used in the experiment, and the reaction may be shown graphically, as in Text-fig. 1*a*.

The second type of reaction is similar to the first, except that when the tensile stress is removed, the original length is regained over a period of time, the duration of which is proportional to the duration of the preceding stress. A body reacting in this way is elastic, but shows the phenomenon of 'elastic after-effect' (Text-fig. 1*b*).

In the third reaction, the body is extended as tensile stress is applied to it, and the extension then gradually increases while the same stress is maintained. The body may eventually rupture: on the other hand, if the stress is discontinued before rupture occurs, the body fails by a greater or lesser measure to regain its original length. A body reacting in this way is inelastic or viscous to stresses of the duration and magnitude used in the experiment (Text-fig. 1*c*).

Thus in the examination of the reaction of any body to a tensile stress, two dimensions of the stress—those of magnitude and duration—are both of fundamental importance.



Text-fig. 1. The reaction of elastic bodies to prolonged tensile stress.

THE LITERATURE

Annovazzi (1928), whose investigations were carried out on the knee joints of dogs immediately after death, found that the joint ligaments were appreciably extensible under load and that, within certain limits, they were also elastic, as they completely regained their original length when the load was removed. Furthermore, he demonstrated that the elastic limit (i.e. the maximum momentary load to which the ligament would react elastically) was less in ligaments containing elastic fibres than in those consisting entirely of collagen fibres. In keeping with Annovazzi's findings is the fact that joint ligaments which are both extensible and elastic are inherent in the concept of the 'Schnappgelenke' mechanism elaborated by Palmgren (1929) and Fick (1931), and discussed recently by Haines (1951). In contrast, Hardy (1951) came to the conclusion that the joint ligaments which he examined did not extend under load, but it is considered that his observations did not fully justify such a conclusion. The method which was used to determine the non-extensible nature of the cat's ligamentum patellae was not described, and furthermore, the fact that the greatest lengthening of the human spring ligament which was observed was not mathematically significant, did not permit the assumption that no lengthening occurred.

Structures which are histologically similar to joint ligaments may be surmised to possess similar physical properties, and therefore the elastic properties of such structures are of some interest. Thus Wertheim (1847) and Hill (1951) have shown that the tendons of muscles are extensible and elastic. Gratz (1931), in his well-known study of human fascia lata, found that it was appreciably extensible and that it was elastic with a high elastic limit. And Dick (1951), working on human fascia lata and dura mater, observed 'that white collagenous fibres by themselves respond to distension as does rubber'.

It seems probable, therefore, that joint ligaments in common with other predominantly collagenous structures, extend when subjected to load, and that this extension is reversible within certain limits. However, information is incomplete, especially on the relationship of the reaction of a ligament to the duration of the load, and the present investigation was carried out mainly in an endeavour to elucidate this aspect of the problem.

MATERIAL

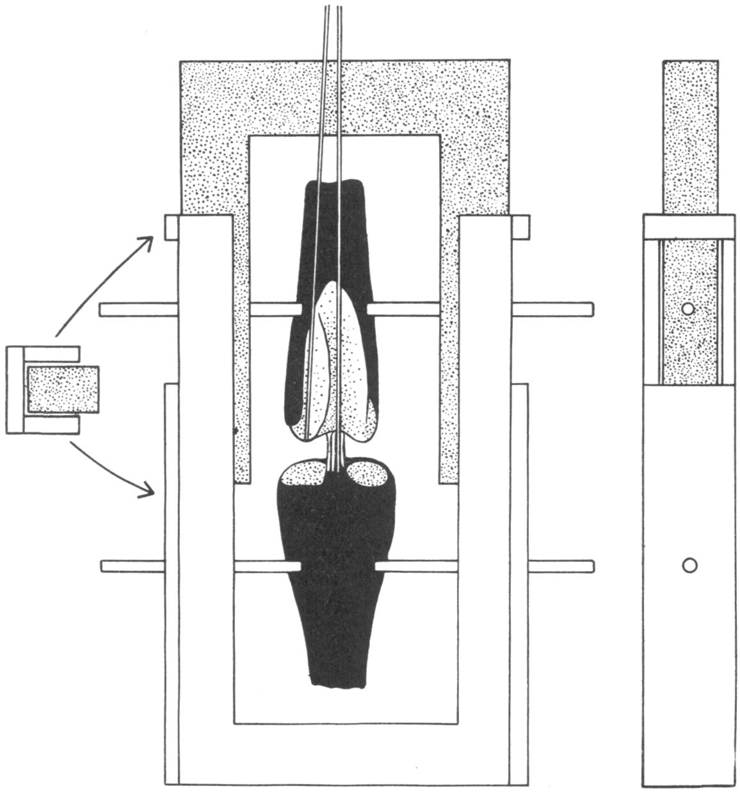
The investigation was carried out on the anterior cruciate ligaments of young rabbits of between 2 and 6 lb. body weight. This ligament was chosen for study, for the following reasons. Histologically it consists solely of collagen fibres and is devoid of elements showing the specific form and staining reaction of elastic fibres (Pl. 1, figs. 1, 2). The ligament is longer and stronger than most of the other ligaments of the rabbit, so that its use tends to reduce the percentage error in measurements of elongations and assessments of breaking loads. Furthermore, the ligament is attached centrally to the ends of the femur and tibia rather than marginally, a feature which assists considerably in the attachment of loads (*vide infra*), and lastly, it is discrete from the capsular ligament of the knee joint, so that the dissection required to isolate it leaves it undisturbed.

Annovazzi (1928) noted that the physical properties of ligaments change rapidly after general or local death. In my own experience ligaments become less readily extensible (Young's Modulus increases) and react elastically to greater loads (the elastic limit increases): the change becomes apparent within an hour of death and is progressive thereafter. The preparation of each ligament for examination was therefore always completed as quickly as possible, and no observations were considered valid unless they were made within 30 min. of death.

METHOD

In each experiment the animal was first weighed and then killed. The knee joint, with an inch or so of bone on either side, was immediately excised, and all connexions between the tibia and the femur except the anterior cruciate ligament were divided. A steel pin was then driven through the shaft of each bone from side to side, and the pins were attached to stirrups. The upper stirrup was fixed to a cross-bar, and to the lower one the necessary load was applied.

This method of loading a joint ligament has certain advantages over the method by which loads are attached to the isolated ligament by means of clamps, but it can be used only when, as in this case, the ligament has central rather than marginal bony attachments. One advantage of the method is that there can be no slipping of the clamps, but an additional and more important advantage is the fact that the whole of the ligament, including its attachment to bone, is examined. Ham (1953) has observed that the histological appearance of the intermediate part of a ligament differs from that of the same ligament at or close to its attachment. Near the attachment the fibroblasts become rounded and encapsulated and there is a considerable



Text-fig. 2. The interlocking stirrups. The stirrups with a knee-joint ready for examination are shown in the centre. On the right is a side view, and on the left a cross-section through the parts indicated.

increase in the amount of amorphous intercellular substance. The difference is shown in Pl. 1, figs. 3 and 4. The possibility has to be recognized, therefore, that the elastic properties of different parts of a ligament may vary; for this reason examination of part of a ligament gives no certain assessment of the properties of the whole structure.

As the anterior cruciate ligament passes from the tibia to the femur, it twists through 90°, as if the femur had been rotated medially to that extent upon the tibia. For this reason, when all other connexions between the tibia and femur are divided, tension on the ligament tends to undo this twist with a consequent elongation of the ligament which is not due to extension of its fibres. To obtain a correct assessment of the actual lengthening of the ligament under load, rotation of one bone on the other must be prevented. This was done by interlocking the two stirrups as shown in Text-fig. 2, so that although they could approach or recede they could not twist or tilt in relation to one another. Although some friction must occur between the two stirrups it was considered that because of the relatively large loads used in the investigation, it could be safely discounted.

OBSERVATIONS

The relation of the breaking load of the anterior cruciate ligament to the weight of the rabbit

The breaking load of a ligament is that which causes rupture of the ligament as soon as it is applied. In the case of the anterior cruciate ligament of the rabbit the rupture constantly occurs at its attachment to the tibia, and a flake of bone is always torn away.

The breaking loads of twenty-seven ligaments have been examined by the method described below. Each specimen was fitted into interlocked stirrups and a counter-poised metal drum was suspended from the lower stirrup. The drum was rapidly filled with water from the tap until the ligament ruptured, when the tap was immediately turned off. The drum, still counterpoised, was weighed to the nearest quarter of a pound by means of a spring balance, and this weight was taken as the breaking load of the ligament.

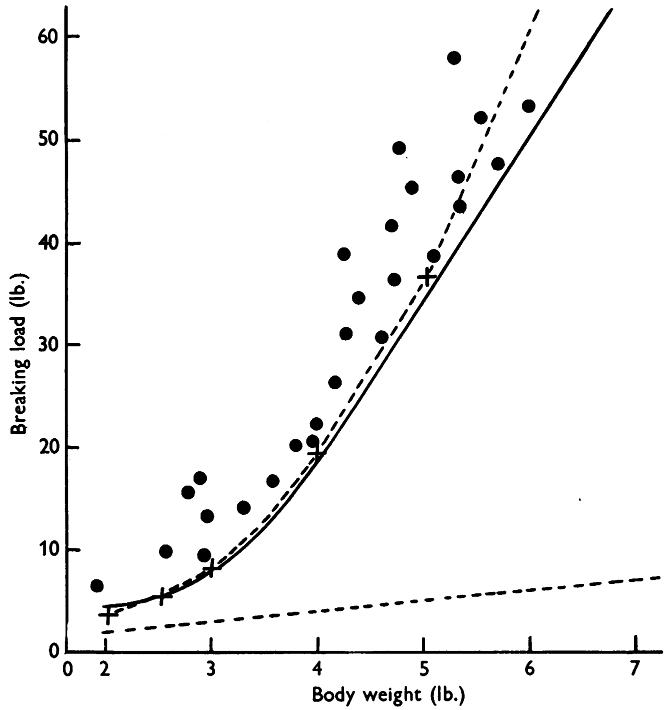
The results which were obtained are shown in Text-fig. 3, in which the breaking load of the anterior cruciate ligament is plotted against the body weight of the animal. Although there is considerable individual variation, the breaking load of the anterior cruciate ligament is approximately proportional to the cube of the body weight. The upper dotted line in Text-fig. 3 expresses the equation:

$$3{\cdot}4\ (\text{breaking load}) = (\text{body weight})^3.$$

The relationship is not sufficiently uniform to permit the calculation of the breaking load of a given ligament, but on the other hand, it makes it possible to estimate the greatest load which can be applied to the ligament of a rabbit of known weight without risking its rupture. Such a load will be referred to subsequently as the submaximal load and it is indicated by the continuous line in Text-fig. 3.

The effect of load on the length of the ligament

Each specimen was prepared and fitted into the interlocking stirrups as described above. When a load is applied through the lower stirrup to the tibia, the tibia moves downwards but because the upper stirrup and pin and the other apparatus fixing the femur are themselves distorted by load, the femur will also move downwards. Thus the actual change in length of the ligament due to a load is equal to the difference in the downward displacements of the tibia and femur. For this reason cotton threads were attached to both the tibia and the femur as closely as possible to the areas of attachment of the ligament to those bones, and the threads were led off and attached to two magnifying arms which drew tracings on a smoked drum. In all the kymographs shown here the upper tracing represents the femoral attachment of the ligament, and the lower tracing the tibial attachment. Vertical displacement of either end of the ligament is indicated by a proportionate deviation of the corresponding tracing in the opposite direction. Thus when a load is applied to a ligament both tracings ascend and any elongation of the ligament is shown by a proportionate decrease in the distance between the two tracings: when a load is removed, both tracings descend and any contraction of the ligament is indicated by



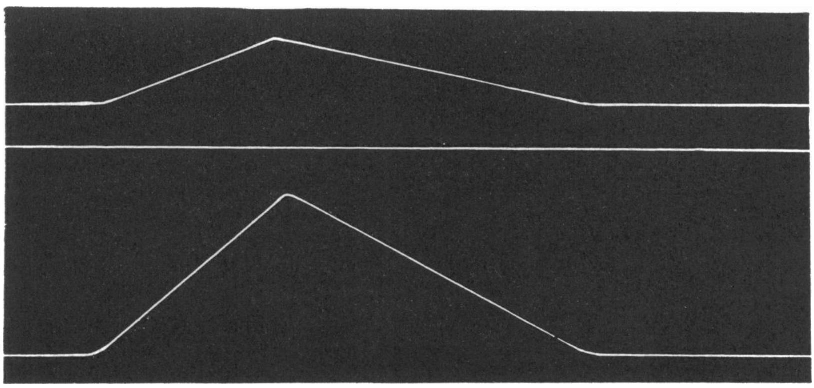
Text-fig. 3. The relationship of the weight of the animal to the breaking load of the anterior cruciate ligament. The upper dotted line represents the equation 3·4 (breaking load) = (body weight)^3; the continuous line indicates the submaximal loads, and the lower dotted line denotes loads equal to the body weight.

proportionate increase in the distance between them. The magnifying arms were so arranged that the actual change in the length of the ligament was magnified more than ten times. The distance between the tracings was measured by calipers which were accurate to $\frac{1}{100}$ in., so that a change in the length of the ligament was measured correct to $\frac{1}{1000}$ in. In the several kymographs shown in this paper, the initial distance between the tracings and the speed of the tracings both varied, and in the final reproduction the reduction differs in each case.

Experiment 1

Six ligaments were subjected to loads which in each case increased at a rapid and uniform rate to the appropriate submaximal value indicated in the graph in Text-fig. 3 and then similarly decreased to zero. The load was increased by filling the counterpoised drum already mentioned with water from the tap, and decreased by removing the water from the drum by a suction pump.

In the experiment illustrated in Text-fig. 4 the ligament was taken from a rabbit of 5 lb. body weight. The two tracings approach one another as the load is applied, indicating a proportionate elongation of the ligament, and return to their original relationship as the load is removed, indicating the recoil of the ligament to its original length. Thus it is apparent that under these circumstances, the ligament is both extensible and elastic.



Text-fig. 4. Rapid loading and unloading of the anterior cruciate ligament.

The tracings produced while the ligament was loaded and unloaded are straight lines, and because the load was applied and removed at uniform rates, it follows that the extension of the ligament was always proportional to the load. The response of the ligament thus conforms to Hooke's Law for elastic bodies, i.e. strain $=$ C $\times$ stress, where C is the modulus of elasticity.

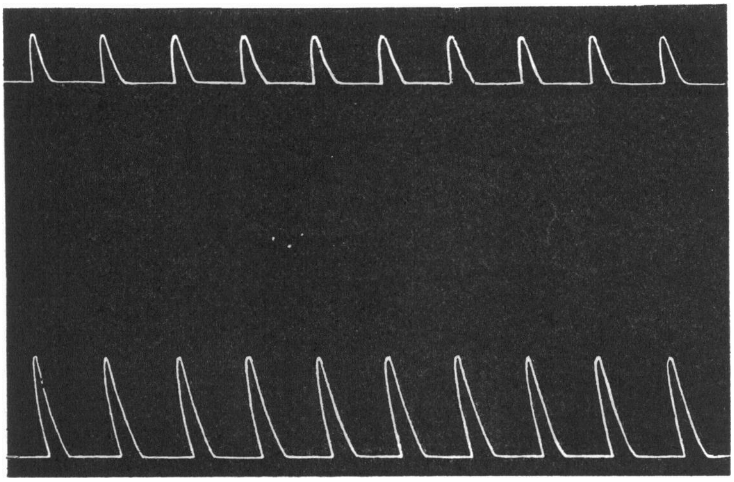
The actual extension of the ligament in the experiment illustrated in Text-fig. 4 was $\frac{82}{1000}$ in., and the approximate average length of the fibres of the ligament was about $\frac{1}{3}$ in. These measurements indicate that the ligament was temporarily extended by the submaximal load more than 20 % of its original length. The extension of ligaments by full submaximal loads varied from specimen to specimen, but it was always easily appreciable even by naked eye examination. Pl. 1, fig. 5, is a photograph of a specimen fixed in the extension apparatus, and the area outlined by the dotted lines indicates the area shown in the three photographs in Pl. 1, figs. 6–8. In fig. 6, the load on the ligament was 2 lb., in fig. 7, it was 25 lb., and in fig. 8, it was 48 lb.; the progressive extension of the ligament, as measured by the separation of the stump of the posterior cruciate ligament from the lateral femoral condyle, is readily apparent.

Experiment 2

Six ligaments were subjected to repeated submaximal loads at 1 min. intervals, the load being applied and then immediately removed on each occasion. Text-fig. 5 shows the tracings from such an experiment when a load of 42 lb. was applied

10 times to the ligament of a 5½ lb. rabbit. The two tracings approach each time the load is applied, but return to their original relationship each time the load is removed. This indicates that the ligament lengthens with each application of load but retains its original length at the end of the experiment.

The anterior cruciate ligament is therefore elastic to a submaximal load of short duration, even if this load is repeated several times at short intervals.



Text-fig. 5. The effect on the anterior cruciate ligament of intermittent submaximal loads of momentary duration.

Experiment 3

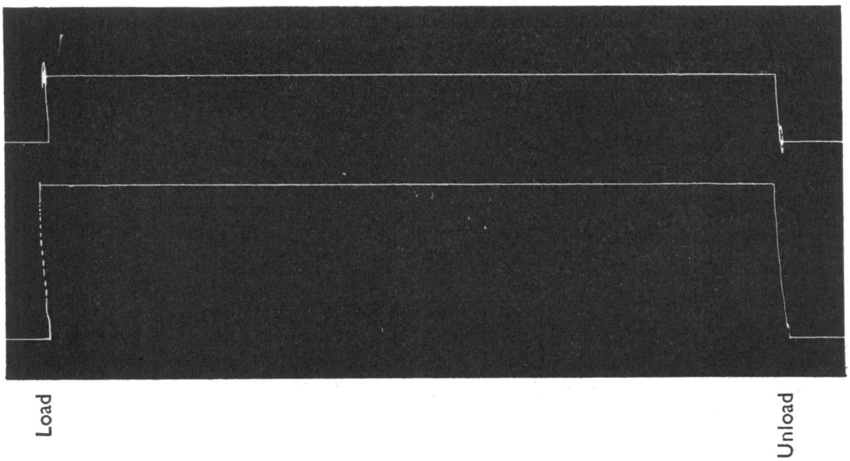
Six ligaments were subjected to loads equal to the body weight of the animal from which they were obtained, for a long period arbitrarily fixed at 5 min. A typical experiment is illustrated by Text-fig. 6. The tracings separate as the load is applied, remain parallel while the load is constant, and return to their original relationship as soon as the load is removed. The form of the tracings indicates that the ligament extends as the load is applied, remains of uniform length while the load remains constant and returns to its original length when the load is removed.

Thus the anterior cruciate ligament is elastic to a load of the order of body weight, even if this load is maintained for a considerable time.

Experiment 4

Six ligaments were subjected to submaximal loads for a period of 5 min. It was found that the ligament extended rapidly as the load was applied, and then continued to extend more gradually while the load was maintained. In some of the experiments the ligament ruptured before the completion of the period of 5 min., and such a case is illustrated by the tracings shown in Text-fig. 7*a*. The initial approach of the tracings is due to the elongation of the ligament on application of the load. The subsequent more gradual approach of the tracings indicates a progressive extension of the ligament occurring while the load was constant at the submaximal value.

In other cases the ligament was still intact at the end of 5 min., and such an experiment is illustrated in Text-fig. 7*b*. The ligament extended as the load was applied and then continued to extend while the submaximal load persisted, as indicated by the gradual progressive approach of the two tracings. When the load was removed the tracings separated but did not achieve their original relationship. The permanent reduction in the distance between the two tracings signifies a proportional permanent elongation of the ligament. Subsequent histological examination of the ligament in this experiment showed no rupture of the fibres, and it is to be presumed that the permanent elongation is related to the fibres themselves. Thus the anterior cruciate ligament is not elastic to a submaximal load of long duration, but acts, in those circumstances, as a viscous body.

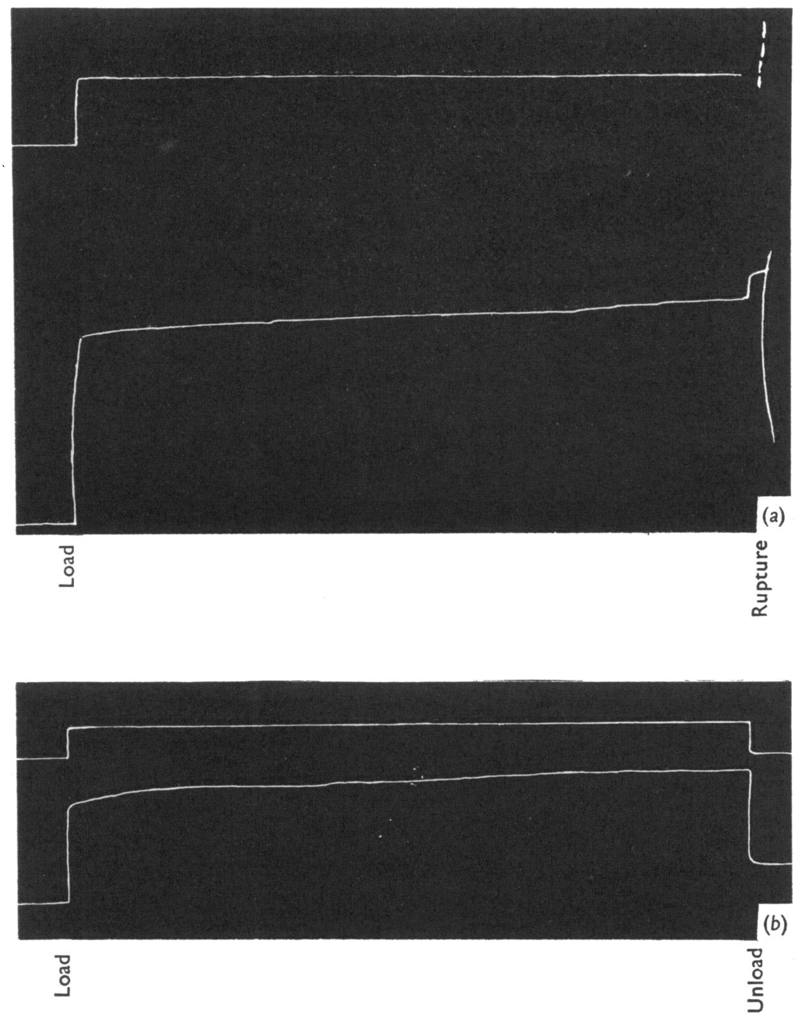


Text-fig. 6. The effect on the anterior cruciate ligament of a prolonged load equal to the body weight of the animal.

DISCUSSION

The observations which have been made during this investigation show that the anterior cruciate ligament of the rabbit is an appreciably extensible structure. Furthermore, the ligament is elastic to loads of the order of body weight, and this property is independent of the duration of the load within the limits likely to be experienced during life. The ligament is also elastic to what has been described as submaximal loads, either single or repeated, provided that each load is of a very short duration. A load may be outside the elastic limits of the ligament either because of its magnitude alone, or because of the combination of its magnitude and its duration. In the former case, the load is equal to or greater than the breaking load and the ligament ruptures as soon as it is applied. In the latter case, the load is less than the breaking load, but if it is prolonged, the ligament will either rupture after an appreciable interval or will remain elongated after the load has been removed.

The magnitude and duration of the stresses which affect the joint ligaments of a living experimental animal, vary with the posture and activity of the animal. When the animal is stationary, the stresses are usually of small magnitude, but may persist continuously for some time. The average duration of stress would appear to vary in different animals and in different parts of the same animal, but it is usually



Text-fig. 7. The effect of prolonged submaximal loading of the anterior cruciate ligament. *a*, rupture of the ligament after 4 min.; *b*, load removed after 5 min.

of the order of 1 min.; in the case of the trunk and lower limbs of man it has been shown (Smith, 1953) that the average duration of immobility during standing is 30 sec. It has been demonstrated that the anterior cruciate ligament of the rabbit is elastic to a load equal to body weight, maintained for as long as 5 min., and it is therefore suggested that this ligament is elastic to the stresses which may affect it when the animal is stationary.

During movement, it is doubtful whether joint ligaments are subjected to any considerable stress, as long as progress continues on a smooth surface, and in an intended direction, because in those circumstances, the joint is under full muscular control. Nevertheless, unexpected joint displacements frequently occur during movement, and if they take place with a force or a speed too great for the defensive muscular mechanism, the joint ligaments are subject to a stress which may be very large, but which persists for a very short time. The stress may be sufficiently large to rupture the ligament at once, but if rupture does not occur, the observations recorded in Exp. 2 would indicate that the joint ligament will react elastically even if the stress is repeated several times.

SUMMARY

1. The elastic properties of the anterior cruciate ligament of the rabbit have been studied within 30 min. of the death of the animal.

2. The breaking load of the ligament is related to the weight of the animal.

3. The ligament can be temporarily extended by as much as 20 % of its original length.

4. The ligament is elastic to a load of the order of body weight maintained for 5 min.

5. It is elastic to submaximal loads of short duration.

6. It reacts as a viscous body to submaximal loads of long duration.

My thanks are due to Prof. R. Walmsley for his interest and advice. I am also indebted to Mr J. Brown who prepared the photographs and photomicrographs in the plate.

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EXPLANATION OF PLATE

Fig. 1. The anterior cruciate ligament of the rabbit. Weigert's elastin stain. (× 250.)

Fig. 2. One of the genicular arteries. Section from same block as that in fig. 1. Weigert's elastin stain. (× 250).

Fig. 3. The intermediate part of the anterior cruciate ligament of the rabbit. Haematoxylin and eosin. (× 250).

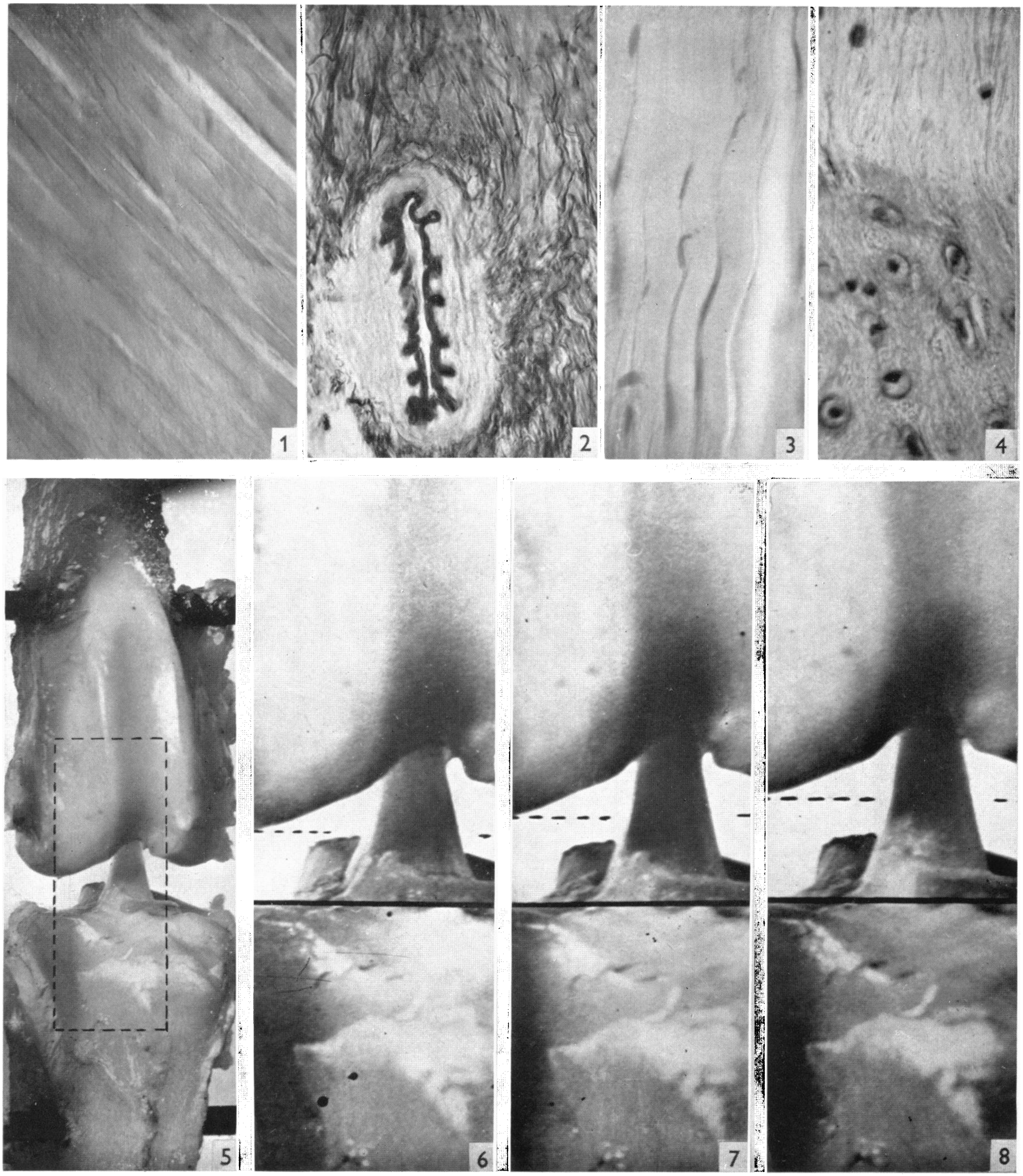
Fig. 4. The attachment of the anterior cruciate ligament of the rabbit to the tibia. Ligament above, bone below. Haematoxylin and eosin. (× 250.)

Fig. 5. Rabbit's knee joint with all connexions between the femur and tibia divided except the anterior cruciate ligament. The area enclosed by the dotted line is that shown in figs. 6–8. (× 1·3.)

Fig. 6. The anterior cruciate ligament under a load of 2 lb. (× 3.)

Fig. 7. The same ligament under a load of 25 lb. (× 3.)

Fig. 8. The same ligament under a load of 48 lb. (× 3.)



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