

THE GROWTH OF TENDON STRENGTH

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In the foetal rabbit the tendon of peroneus brevis is thinner than that of tibialis anterior but it grows at a faster rate so that, in the adult animal, it has become the thicker tendon. If the strength of a tendon is related to its thickness then the factors which determine the tendon's rate of growth and its thickness when mature will be relevant to any consideration of injury to the healthy tendon.

Leonardo da Vinci described tendons as mechanical instruments which carry out as much work as is entrusted to them. The passive transmission of the tendon developed by a muscle is the principal function of tendon but certain secondary functions have been described by Clark (1958) and Lockhart (1960). For instance, the tendon enables the bulk of the muscle belly to be at a convenient distance from the joint over which it acts. The tendon concentrates muscular power, if need be, onto a relatively small area of bone. Retinacula can alter the course of a tendon and thus enable a muscle to act over more than one joint. Finally, Hill (1951) suggested that the elasticity of mammalian tendon has an important protective function as a mechanical buffer during sudden and unexpected stress.

These functions of tendon are made possible by the mechanical properties of the dominant constituent, collagen, a strong, flexible, fibrous protein which is relatively inextensible and which behaves as an imperfect elastomer which is almost perfectly elastic at physiological tensions.

The tendon is a long glistening cord composed almost entirely of longitudinal bundles of collagenous tissue within a sheath of looser connective tissue, the paratenon, or, where a change of direction or increased friction demands efficient lubrication, within a tubular sheath of parietal and visceral layers continuous through the mesotenon and containing synovial-like fluid (Mayer, 1946, 1952; Bunnell, 1956; Nisbet, 1960). Through its opened sheath the tendon gives an appearance of watered silk (Schafer, 1912) with alternative light and dark transverse bands about 70 microns wide (Heringa and Lohr, 1924). These disappear when tension is applied and reappear with relaxation (Nauk, 1931) and are thought to be due to the intrinsic helical or wave form of the collagen fibrils. The epitenon, a delicate layer of loose connective tissue covering the tendon, continues into its interior as the endotenon intervening between the component fibrous bundles and carrying with it small blood vessels, nerves and lymphatics.

The structural unit of the tendon is the collagen fibre or primary tendon bundle. This may be defined as the coherent bundle of collagenous fibrils lying between rows of fibroblasts and encircled by their anastomosing processes (Sobotta, 1930). Its diameter is very variable and depends on the number rather than the size of its constituent fibrils (Jacobson, 1953) but in tendon may be up to 300 microns (Bear, 1952; Verzar, 1957a). The

diameter of the fibrils increases with the age of the individual (Jackson, S.F., 1953, 1957; Banfield, 1955) and falls within the range 500 to 5000Å in mature tissues (Bear, 1952; Gross, Highberger and Schmidt, 1954) a trimodal distribution occurring in tendon (Borysko, 1963) which may be due to an anastomosis of fibrils (Harkness, 1961). Inconsistent use of terminology has confused the argument on the arrangement of fibrils within a collagen fibre but the evidence supports the conclusion that the fibrils are orientated parallel to the long axis with some intrinsic waviness (Rigby, Hirai Spikes and Eyring, 1959; Kuhnke, 1962; Borysko, 1963) rather than in a series of helices (Lerch, 1950; Keller, 1951, Verzar, 1957a, b.). The fibre bundles are grouped into fasciculi, or secondary tendon bundles, and these into larger tertiary bundles. This arrangement varies not only in different tendons but also within the length of one tendon as lesser bundles pass to and fro between the larger one (Keller, 1951). Thus successive cross-sections of a long tendon show progressively changing patterns (Walls, 1960). The arrangements of the larger bundles is more complex and the interweaving is such that muscular tension is distributed equally to all parts of the insertion whatever the position of the joint (Mollier, 1937; Altmann, 1963). By analogy to the difference which exists between the stress-strain curves of nylon thread and nylon stockings (Bull, 1957) it is possible that the arrangement of the component bundles could influence the ultimate strength of a tendon.

A muscle and its tendon act together as a functional unit and a study of the muscle-tendon junction with an electron microscope reveals the intimacy of the relationship between contractile and connective elements (Elliott, 1965b). The essential unity of a muscle and its tendon suggest that there should be a correlation between muscle and tendon size during growth. A certain relationship is, of course, found in a study of their rates of longitudinal growth. The growth in length of the tendon depends not only on bone growth and the distance between the muscle belly which might be due to a change in its relative range of movement or some re-arrangement of its internal architecture. The longitudinal growth rate of the muscle belly of the rabbit tibialis anterior is greater than its tendon and the mature belly can achieve the same relative excursion as the younger belly but with a smaller percentage contraction of its belly length (Alder, Crawford and Edwards, 1956). Thus the final length of the tendon in the mature animal must, in some way, be determined by the functional requirements of its muscle.

The factors which may determine the final thickness of a tendon are not so easy to define. That the growth of tendon and the development of its strength are the natural consequences of the tensions acting on it was a hypothesis put forward by Sir Charles Bell (1828). Roux (1895) postulated that for the growth of all connective tissues the prime stimulus was mechanical force, compressive for bone, shear for cartilage and tensile for collagen. It was not until later that this was supported by experimental evidence when Weiss (1929) showed the growth response of fibroblasts to

regional tensions in tissue culture and Stearns (1940 a, b) demonstrated a similar effect in the transparent chamber in the rabbit's ear. However it is known that stress is not the only factor to determine connective tissue growth. For instance, it has been shown that the isolated femur of the chick embryo continued to grow and to develop trochanters when cultured in vitro and in the absence of mechanical forces (Fell, 1956) and that the trabeculae within the neck of the foetal femur trace the lines of force of tensions which have not yet been transmitted (Evans, 1957). Furthermore the absence of any simple quantitative relationship between muscle growth and tendon strength is implied by the observation (Inglemark 1945, 1948) that there is a threefold increase of the Achilles tendon of the rat but that the weight of its muscle increases by as much as fivefold during the same period. In the adult rabbit there is, in fact, no simple relationship between the strength of muscles in the hind limb and the thickness of their tendons. The thickest tendon, both in absolute size and relative to the cross-sectional area of its muscle, belongs to semitendinosus, a red muscle with prolonged postural activity (Elliott and Crawford, 1965 a). This suggests that the duration of muscle tension might be important factor in the growth of tendon thickness, a concept which is quite different from that of muscle hypertrophy which is considered to be stimulated only by the development of a maximal tension, however brief (Hettinger, 1961).

When the growth of tendon is related to the cross-sectional area of its muscle (Elliott and Crawford, 1965 b) it can again be seen that the rate of growth of peroneus brevis tendon is greater than that of tibialis anterior. However during growth there is a diminution of cellular density and water content and it can also be seen that, within any one muscle, the growth in thickness of the tendon's collagen is more closely related to the growth of muscle cross-sectional area, and thus muscular strength, than is the growth of tendon thickness itself. In fact, whereas there is no significant difference in the three-week old rabbit between tibialis anterior and peroneus brevis in their value of tendon collagen thickness per unit cross-sectional area of muscle, they diverge during growth so that this value increases in peroneus brevis but decreases in tibialis anterior.

The further growth of tendon after maturity is possible by athletic training. Inglemark (1945, 1948) exercised mice and rats daily on an endless belt and found an increase of up to 25% in tendon cross-sectional area, proportionate to a similar increase of muscle bulk. Under similar experimental conditions Wrete (1950), by a histochemical technique, demonstrated an increase of mucopolysaccharides in the tendon. Rollhauser (1954 a, b) found, after an initial diminution, an increase of up to 12% in tendon tensile strength. This was associated not with hypertrophy but with an improved birefringence which implies an improvement of the tendon's internal architecture.

The evidence of some experiments on the growth of tendons has been reviewed recently. It was shown that, after denervation of muscle in the three-week old rabbit, the girth of the muscle belly grew to less than 30% but the thickness of the tendon grew to more than 75% of their normal values at maturity, and that even after complete excision of muscle belly from the three-week old rabbit the subsequent growth of the tendon to 85% of normal was dependent on the amount of passive tension to which it was subjected (Elliott, 1965 a). In general these and other experiments support the conclusion that the final thickness of a tendon's collagen may be a measure of the total tension transmitted during growth. It is certainly true that the final thickness of a tendon and its collagen is not proportional to the maximum isometric tetanic tension which its muscle can exert.

The relationship between the mechanical properties of a tendon and the strength of its muscle is therefore indirect. Tendon behaves as an imperfect elastomer and its biomechanical characteristics are a function of its thickness, and thus, when mature, of its collagen content. The tensile strength of tendon is not easily estimated because of the fact that tendon must rupture at its weakest point which is where it attached to the measuring apparatus or where it has been previously weakened. Most estimates of the ultimate strength of tendon lie in the range 5 to 10 Kg/mm² (Elliott, 1965 b). This variation is large enough to suggest that there is room for a difference in strength between the collagen of several groups of tendons just as there is (Harkness, 1961) between tendon and uterine collagen. However, it has been shown that, in fact, there is no significant difference in certain of their mechanical properties between tendons of fusiform muscles, which exert the greater maximum tension per square millimetre cross-sectional area of tendon, and those of penniform muscles which transmit less (Elliott, 1967). The mechanical properties which may be measured include the elimination of the wave-form appearance of tendon (Elliott, 1967) and the working capacity of tendon, the point beyond which the tendon is no longer so easily extensible (Stucke, 1950). The proportional limit of the tendon's stress-strain relationship has also been measured (Gratz, 1937), but, like tensile strength, this takes the tendon into the range in which semi-plastic change will occur. Wave-form is eliminated by a tension of 0.2 Kg/mm² and the working capacity of tendon is 0.9 Kg/mm² whereas the maximum tension which can be transmitted is 1.5 Kg/mm² by a rabbit penniform muscle or 2.5 Kg/mm² by a fusiform muscle. If the maximum isometric tetanic tension is never exerted during the normal activity of a muscle then it remains possible that the normal range of tensions fall within the tendon's range of relatively easy extensibility, the "toe" of the stress-strain curve. There is a more than sufficient reserve of tensile strength in healthy tendon for the greatest possible muscular stress.

It is therefore for the pathologist to provide the aetiology of Achilles tendon rupture. Besides the hypotheses of derangement of tendon blood supply (Nisbet 1957) and disorders of the paratenon (Williams, 1966), a biochemical and pathological study is needed of the constituents

of tendon ground-substance. In lathyrism (Levene and Gross, 1959) and again in the foetal membranes of the end of pregnancy (Harkness and Harkness, 1956) there is a loss of connective tissue strength with no loss of collagen content, and it has been suggested that the mucopolysaccharides may have an important cohesive role in normal tendon (Day, 1947; Jackson, D.S., 1953).

Thus in a study of the normal tendon we find that growth in thickness, and hence the development of tendon strength, is in some way related to the function of its muscle but that its final strength, which should be more than adequate for the strongest forces which will act upon it, is not directly proportional to the strength of its muscle.

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