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Tensile properties during tendon healing

A comparative study of intact and sutured rabbit peroneus brevis tendons

by

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CONTENTS

INTRODUCTION

The healing of severed tendons is a problem of great practical importance. Consequently, numerous studies have been undertaken since the middle of the 19th century, in order to elucidate the processes leading to the healing of a cut tendon. The majority of these studies has been directed towards the morphological aspects of tendon healing, as revealed in the light and electron microscope. Other authors have described metabolic changes in healing tendons. Several papers deal with functional impairment from adhesions, both in clinical and experimental series.

Comparatively little has been written on the biomechanics of the healing tendon as compared to the normal tendon. The purpose of the present investigation has been to find at least a partial answer to the following questions:

1. What are the tensile properties of tendons during healing, as compared to intact tendons?
2. Do different suture techniques alter the tensile properties of healing tendons?

REVIEW OF LITERATURE

The normal tendon

Morphology

The dominating constituent of a tendon is the collagen fibril. Under an ordinary light microscope the fibrils reveal a cross-striation, which is a reflection of the structural units composing the fibril. This basic unit is the so-called tropocollagen particle, composed of three amino-acid chains (not chemically identical) twisted into a left-hand coiled superhelix, with a pitch of 28.6 Å (Ramachandran & Kartha 1955, Rich & Crick 1955). The dimensions of the tropocollagen particle are estimated to be 15 Å x 2.900 Å and with a molecular weight of roughly 340.000 (Boedtker & Doty 1956).

In native collagen the cross-striation of the fibrils is quite regular and with an interval of approximately 640 Å in the unstrained state. The interval can be accounted for if the tropocollagen particles are arranged with a special type of overlapping (Hodge et al. 1965).

The tropocollagen particle has a high tendency to fibril formation. The reason for this tendency has not been satisfactorily explained. It may be that mechanical stress induces anisotrophy in a collagen solution (Lerchenthal 1968).

Other factors, such as the presence of mucopolysaccharides and glyco-proteins, have also been suggested to influence fibril formation (Wood 1960).

The fibrils are arranged parallel to each other and assembled into bundles. The bundles are separated by a thin layer of delicate connective tissue, the endotenon. The surface of the tendon has a glistening white, synovia-like appearance. This is due to the epitenon, which is a thin membrane adherent to the tendon. A straight tendon is usually surrounded by loose areolar tissue, the paratenon. Where a tendon bends, it is surrounded by a specialized paratenon, the tendon sheath. Within the sheath, the mesotenon, constructed in much the same way as the mesentery of the gut, carries important blood vessels to the tendon (Nisbeth 1960).

Situated between the fibre bundles are the cells of the tendon, the tenocytes. The immature tenocyte is called a tenoblast and is believed to be derived from undifferentiated fibroblasts. The tenocytes are long, slender and few in number.

The tendon is a relatively avascular tissue. Within the sheath, the tendon has three sources of vascular supply: via the musculo-tendineal junction, via the junction of tendon to bone, and via the vessels of the mesotenon. Mesotenial vessels perforate the tendon in a segmental fashion, all on the same side of the tendon. These vessels are continuous with an, in the main, longitudinal system of vessels found in narrow spaces between the fibre bundles in the tendon. The longitudinal system is connected to the vessels, which enter the tendon at each end. The longitudinal vessels are small arteries

and accompanying veins. There are several transverse anastomoses (Biesalsky & Mayer 1916, Edwards 1946, Brockis 1953, Nisbeth 1960, Smith 1965, Bergljung 1968, Schatzker & Brånemark 1969). The tendon capillaries are of three types, long ones mainly parallel to the collagen bundles, shorter ones also parallel to the bundles, and very short straight ones more of the type of arterio-venous shunts (Schatzker & Brånemark 1969).

Outside the sheath the tendon has the same vascular arrangement as inside it, except that there is no specialized mesotenon and the segmental vessels can reach the tendon from any part of its circumference.

Chemistry and metabolism

The fibroblast is responsible for the production of the basic unit in collagen, namely the tropocollagen particle (Branwood 1963, Porter 1964). The particle is probably assembled within the cell and then excreted (Fitton Jackson 1965). Whether the fibroblast loses its ability for collagen production when differentiated into a tenocyte, is a question which as yet is not definitely settled.

The general structure of the tropocollagen particle, as revealed by chemical and X-ray diffraction studies, suggests that the sequence of amino-acids is glycine-proline-x (Hannig & Nordwig 1967, Ramachandran 1967). The composition of collagen is the same throughout the animal kingdom (Gross 1963).

The bonds between the chains in the tropocollagen particle are hydrogen bonds (Rich & Crick 1955, Ramachandran 1963).

The collagen in tendons (and other tissues) can be divided into three main groups according to different solubility characteristics:

1. Neutral salt soluble collagen. This fraction consists of newly formed collagen and is thus found in relatively large proportions in growing tissues.
2. Acid salt soluble collagen. This fraction is soluble in a solution of buffered citric acid. The amounts are larger than the neutral salt soluble collagen.
3. Insoluble collagen. This is the largest group. The explanation for the increasing insolubility of collagen fibres with increasing age is thought to be an increased amount of cross-links between the macromolecules (i.e. the tropocollagen particles). This is an important part of the phenomenon called collagen maturity (Gross 1958).

The tendon also holds a small amount of ground substance, which is a complex of proteins and polysaccharides. The polysaccharides are hyaluronic acid and chondroitin-sulphates. The sulphated polysaccharides are believed to regulate water content, and in complex with proteins to contribute to the rigidity of non-calcified tissues. Hyaluronic acid probably acts as a lubricant between collagen bundles (Hall 1961).

The metabolic turnover in a mature tendon is low. It can be assessed in different ways.

Autoradiographic methods using tritium labelled isotopes of proline, hydroxyproline or glycine have shown that the half-life of these amino-acids is comparable to the entire life-span of the adult animal. In the young animal the turnover is elevated, and may in the very young one reach the same magnitude as in skeletal muscle (Neuberger et al. 1951).

Oxygen consumption is estimated to be .1 μl of O_2 per mg dried tissue per hour (Peacock 1957).

The blood flow through a tendon (assessed with a method based upon Cr^{52}-labelled erythrocytes) is .10 cm^3 per gram tissue per minute as compared to .16 for bone and .27 for skeletal muscle (White et al. 1964).

Tensile properties

Collagen is the main constituent of the tendon. Collagen can be regarded as a high polymer of specific amino-acids. At low temperatures the mechanical properties of such a polymer are mainly due to its chemical composition, i.e. the local molecular structure. At high temperatures the mechanical properties are more dependent on the molecular architecture. The general mechanical behaviour of a typical amorphous, linear, highly polymerized substance can be coarsely divided into three categories, depending on the temperature. At low temperatures a polymer displays a fast, entirely reversible elastic deformation with a high modulus of elasticity. For intermediate temperatures the properties are becoming time-dependent, reversible and with a lower modulus of elasticity. The time-dependency reflects the internal viscosity. The viscous flow is non-linear, the flow increase being proportionally greater than the stress increase. At high temperatures there is marked plastic deformation, i.e. slipping of the individual chains in relation to each other (Alfrey Jr & Guerney 1957).

Studies of mechanical properties of isolated collagen fibres reveal several characteristic features. The isolated fibre does not follow Hook's law[1]. In a test of tensile properties the stress-strain curve has a toe part in the beginning, followed by an almost linear portion up to the point of plastic flow[2], and later the breaking point (cf fig 10) (Morgan 1960). The mechanical failure of the fibre is due to breaking up of cross-links rather than ruptures in the chains of amino-acids. It has been calculated that breaking up the molecular chain at its weakest point, the C–N-bond, would require a stress in the order of 300 kp/mm^2 (Gustavson 1959), whereas the calculated breaking strength for pure collagen is in the range of 10–15 kp/mm^2 (Harkness 1961).

The stress-strain curve up to the point of plastic flow shows a decreasing convexity towards the abscissa. The curve is exponential (Morgan 1960, Stromberg & Wiederhielm 1969).

Since the deviation from Hook's law is small, an approximate modulus of elasticity can be determined using the stress-strain curve for an isolated fibre, provided the toe-part is excluded. Morgan 1960 found increasing modulus of elasticity with increasing cross-section area and increasing strain rate. The collagen fibre also displays creep and stress-relaxation phenomena[3].

Tanning of collagen fibres alters the mechanical behaviour in a quantitative sense, but not in a qualitative one. The modulus of elasticity, for instance, is increased (Morgan 1960).

The two main factors responsible for the mechanical behaviour of collagenous tissues are the material *per se*, i.e. the collagen, and the spatial arrangement of this material. The mechanical properties of collagen can probably be altered to some

[1] Hook's law states that stresss = constant x strain (stress = force/unit cross-section area; strain = = relative change of dimensions). The constant is denoted modulus of elasticity (E). If a material obeys Hook's law the relation between stress and strain is linear, i.e. it has linear elasticity.

[2] Increased strain at constant stress.

[3] Creep – change in strain for constant stress. Stress-relaxation – change in stress for constant strain.

extent by other substances in close relationship with it, such as elastin, apatite and ground substance (Partington & Wood 1963, Harkness 1968).

Since a tendon is mainly composed of collagen fibres arranged parallel to each other, and subjected only to uni-axial loading in the direction of the fibres, it can be expected that the tensile properties of the whole tendon are rather similar to those of the isolated fibres (Diamant et al. 1972).

Several authors have studied the tensile properties of the normal tendon from different points of view. Most of them agree on the following basic characteristics:

The stress-strain curve is convex towards the abscissa. The convexity is prominent for low stress – the toe part. The portion after the toe part is almost linear (fig 7 page 28). When subjected to cyclic loading the curves are successively displaced to the right, i.e. the deformation increases, but it asymptotically reaches a maximum value for each stress level. The tendon exhibits stress-relaxation and creep (figs 8 and 9 page 29). There is a difference of opinion as to whether the tendon behaves perfectly elastically for strains less than 2–3 % (Rigby et al. 1959, Partington & Wood 1963, Rigby 1964, Abrahams 1967, Diamant et al. 1972, Minns et al. 1973) or whether it shows a plastic deformation for all strain values (Gratz 1931, Rollhäuser 1950, Stucke 1950, LaBan 1962, Viidik 1968, Gross & Arnold 1973). The modulus of elasticity increases with increasing strain rate (McElhaney 1965, Abrahams 1967, Viidik 1968, Welsh et al. 1971, Gross & Arnold 1973, Minns et al 1973).

Several authors have tried to determine numerical values for some of the tensile properties of tendons, such as modulus of elasticity (E) and ultimate tensile strength (UTS) (McMaster 1933, Cronkite 1936, Rollhäuser 1950, Stucke 1950, Rigby et al. 1959, Walker et al. 1964, van Brocklin & Ellis 1965, Harris et al. 1966, Abrahams 1967, Viidik 1968, Blanton & Biggs 1970). The numerical values found differ considerably. There are several reasons for this: different tendons from different animals have been investigated; both fresh and embalmed specimens have been used; tests have been conducted on both dry and wet specimens; the design of the testing apparatus has been different as well as the mode of testing; different methods for calculating cross-sectional areas of tendons have been employed.

Under slight magnification a resting tendon has a wavy appearance, which gradually disappears when low strains are applied to it, indicating that the individual fibres are successively put under stress (Nauck 1931, Rigby et al. 1959, Abrahams 1967, Elliott 1967, Viidik 1968, Diamant 1972). The gradual extension of initially crumpled fibres could account for the toe part in the stress-strain curve. On the other hand, the toe part could also be explained as extension of a helical spring, such as the tropocollagen particle, until it is converted into a "straight wire" (Morgan 1960, Viidik 1968). In electron microsopic studies on resting collagen fibres, the periodicity of the cross-striation is 640 Å (Hodge et al. 1965). It can be increased by straining the fibres (Abrahams 1967, Viidik 1968).

The large plastic flow observed with high stress is probably due to slipping of individual fibres (Rigby et al. 1959, Harkness 1961).

The stress-relaxation and creep phenomena can possibly be explained on the basis of two different mechanisms being at work at the same time:

- deformation of a tendon includes redistribution of water and ground substance, and the redistribution is time-consuming (Harkess 1968).
- collagen is a polymer whose mechanical properties are time-dependent (Alfrey Jr & Guerney 1957).

The importance of the constituents of the ground substance, such as chondroitin-sulphate and hyaluronic acid is shown by the fact that treatment of the tendon with specific enzymes – such as hyaluronidase and trypsin – alter the viscoelastic properties of tendons, without altering collagen specific properties like thermal contraction (Partington & Wood 1963, Minns et al. 1973).

The chemical composition of collagen is in some way altered with increasing age, so-called maturing. It is reflected in the change in solubility characteristics, the insoluble fraction increasing (Gross 1958, Harkness 1961, Peacock 1965, Vogel 1969).

Since the insoluble collagen is thought to have more cross-links between its macromolecules, it is reasonable to expect that such collagen – and therefore tendons from older individuals – should display a higher modulus of elasticity, less strain and higher ultimate tensile strength than tendons from younger individuals. This is in accordance with the findings of Rollhäuser 1951, Anders et al. 1971 and Diamant et al. 1972. The latter found rather large differences which partly could be explained as above, and partly on the basis of different amounts of water and ground substance in the tendons. Diamant et al. 1972 ascribe part of the differences to quantitative alterations in the waviness observed in resting tendons.

The healing tendon

The nature of the processes underlying tendon healing is far from understood. For exellent literature surveys in this field up to 1932 the reader is referred to Hesse 1932 and Mason & Shearon 1932.

Part of the differences of opinion among the authors can be ascribed to the difficulties in interpreting a truly dynamic function with the aid of snapshots (for instance in the form of histological preparations). Tendon healing might also be species specific or even differ between tendons in different parts of the body of the same species (Lipscomb & Wakim 1961).

Cellular reaction

Immediately after dividing a tendon there is slight bleeding and exsudation. The fibrin forms a clot. Many authors believe that the clot promotes healing (for references see Hesse 1932 and Mason & Shearon 1932, and also below under Influence of stress page 14). The tendon stumps become oedematous. There is a fairly abundant amount of inflammatory cells, and mononuclear cells resorbing collagen while invading the stumps (Greenlee & Pike 1971).

Some authors report necrosis among the tenocytes of the tendon (Buck 1953, Skoog & Persson 1954, Potenza 1963, Lindsay & Birch 1964, Flynn & Graham 1965).

Four to seven days after division of the tendon the clot is invaded by cells very much resembling fibroblasts, whose origin is a matter of dispute. The following sources of origin have been suggested by different authors:

Migrating blood cells, tenocytes, fibroblasts from the endotendon, epitenon, tendon sheath or paratenon, and finally undifferentiated mesenchymal cells of no specific localization. Combinations of these different sources are also possible.

Dembowsky 1913 (as quoted by Hesse 1932) placed the origin in migrating blood cells. Exclusive and true regeneration from the tendon proper (i.e. the tenocytes) is suggested in older studies (see Hesse 1932 and Mason & Shearon 1932).

Lindsay & Thomson 1960 and Flynn & Graham 1965 state that fibroblasts can be derived from both endotenon, paratenon, including the sheath, and the tendon proper. There is, however, a dealy in proliferation of the tenocytes until the second week.

Buck 1953 holds much the same views, but excludes the tenocytes from taking part in the proliferation.

Peach et al. 1961, Potenza 1962 a and b, and Lindsay & Birch 1964 moreover exclude cells from the endotenon from taking part in the healing.

Skoog & Persson 1954 and Peacock 1964 regard the paratenon, not including the tendon sheath, as the only source of cell origin.

Finally, Salamon & Hamori 1966, maintain that the fibroblasts are derived from undifferentiated mesenchymal cells in the surrounding tissues.

According to Peach et al. 1961 the fibroblasts, whatever their source of origin, can be divided into a migrating and a synthesizing type. The former is most common on days 4–5, the latter after day 7.

In connection with the problem of cell origin arises the question of whether tendon healing is a true regeneration or if the stumps are joined by scar tissue. The authors excluding tenocytes from participating in healing, consider the junction between the stumps as scar tissue, in many instances distinguishable from tendon proper with the naked eye.

Collagen synthesis

The tropocollagen particle is synthesized in the fibroblasts (Fitton Jackson 1965). The collagen fibrils are polymerized from the tropocollagen particles outside the cell. The fresh collagen is neutral salt soluble, owing to the comparatively few intermolecular bonds it holds. Consequently, the neutral salt soluble fraction shows an increase from the 4th day, reaches a peak around the 21st day and is again normal after the 35th day (Peacock 1962 and 1965). Birdsell et al. 1966 used tritium-labelled proline and found a sixfold increase in the collagen synthesis in sutured tendons, starting after the first week and reaching a maximum after about 4 weeks. Even after three months there was a three to fourfold increase.

Vascular reactions

There is a prompt vascular reaction after division of a tendon. During the first week sprouting buds of capillaries growing in the direction of the tendon wound and coming from the surrounding connective tissue can be demonstrated with micro-angiographic techniques. To a lesser extent capillaries are also derived from the cut stumps.

Successive organization follows, and after 5 weeks the vascular anatomy is practically normal (Bergljung 1968).

Normally the vascular supply of the tendon is covered in the proximal third via vessels from the muscle, and in the distal quarter via vessels from the bone (Peacock 1959). Schatzker & Brånemark 1969 state that disruption of the segmental vascular supply causes cessation of capillary flow, which would if prolonged presumably lead to necrosis. On the other hand Colville et al. 1969 found that the tendon graft survives because new vascular communications via the mesotenon are established within the first 3 or 4 days.

Even if the vascular supply is disconnected at the time of injury, new communications are in general established at the same rate as the adhesions. This leads to an increased vascularity during the first 4–6 weeks (Nichols et al. 1954, Peacock 1959, Bergljung 1968).

Influence of stress

It is generally believed that a moderate amount of mechanical stress exerts a favourable influence on tendon healing, leading to a higher tensile strength of the sutured tendon. When mechanical stress becomes an important factor or how increased tensile strength is attained, however, are questions on which opinion differs. Theoretically, this influence may start on the first postoperative day, and thus affect the fibrin in the clot, or it may be delayed until collagen production is well on its way in the second or third week.

Buck 1953 maintains that the fibrin in the clot is liable to geometrical orientation in response to stress (see also Hesse 1932 and Mason & Shearon 1932).

Weiss 1929 and Stearns 1940 a and b have shown that fibroblasts in tissue cultures do orient as a response to mechanical forces. Rokkanen & Vainio 1971 studied the collagen fibrils in the scanning electron microscope and found them oriented in the direction of the tensile forces right from the start.

Several other authors take the opposite view: the fibroblasts are initially not arranged in the direction of force, but rather in the direction of growth. Consequently, they do not believe in force orientation of collagen fibrils before the third week (Davidsson 1956, Lindsay & McDougall 1961, Peach et al. 1961, Potenza 1962 a and b).

Peacock 1965 states that not only does mechanical stress provoke orientation of collagen fibrils, it is also responsible for what he denotes as remodelling of adhesions (see below). He has shown an increase of salt soluble collagen under continuous stress, which is interpreted as circumstantial evidence for remodelling in the presence of constant total collagen amount.

Adhesion formation

Bunnell 1944 states in his "Surgery of the Hand": "if there is left an 'unsatisfied' end of a tendon . . . that part will grow principally from its epitenon a pseudopodium,

which will reach out and attach itself to the surrounding tissues . . .". In view of more recent studies it is probably more correct to say that fibroblasts grow into the tendon, thus establishing the adhesions. If, as is generally believed today, tendon healing cannot be accomplished without multipotent fibroblasts derived from the surrounding tissues, it is obvious that tendon healing is impossible without some adhesions beeing formed. Several methods of wrapping up a cut tendon in an artifical sheath have been employed to avoid adhesions. Skoog & Persson 1954 and Potenza 1962 b have shown that this leads to delayed healing, which is accomplished by fibroblasts creeping in under the end of the "envelope". The same authors have demonstrated that adhesions are only found where the epitenon has been damaged to allow an ingrowth of fibroblasts.

Peacock 1965 maintains that the early processes in the healing of a tendon wound are exactly the same as in the healing of any other wound. Consequently, he does not believe in "manipulations" that will give a favourable tendon healing without adhesion formation. The fact that adhesions are sometimes not seen after tendon suture can, according to Peacock, be attributed to secondary remodelling of the scar. The adhesions become weak and elastic and the tissue between the stumps strong and stiff. The mechanisms behind remodelling are unknown but Peacock advances two: influence of old collagen and of tensile forces.

Tensile properties

Mason & Allen 1941, from an experimental study on dog tendons, state: "Tendon healing as measured by its tensile strength exhibits three phases:

- phase of rapid diminution, which lasts about five days.
- phase of increasing tensile strength up to a plateau, which it reaches about the 16th day.
- second phase of increasing tensile strength, which probably starts between the 19th and the 21st day and continues for an undetermined period of time."

They relate the increase in tensile strength to observed morphology of tendon repair:

- "phase of exsudation and fibrinous union.
- phase of fibroplasia.
- phase of maturation and organising differentiation."

Other studies of tensile strength both in tendon wounds, skin wounds and artificially produced granulation tissue corroborate these studies (Carstam 1953, Cowan & Courtemanche 1959, Viljanto 1964, Brunius 1968).

Peacock 1965 is of the opinion that wounds can increase their tensile strength for several months in spite of unaltered collagen content. Viljanto 1964 finds that tensile strength of granulation tissue and skin wounds during the first 60 days of healing is strictly correlated to collagen content. He also reports the tensile strength as depending on neutral salt soluble and insoluble collagen in the ratio of 2:3 for the first 4 days and 1:8 or 1:10 from the 12th day.

Both collagen content and remodelling of formed collagen are probably of importance with regard to tensile strength.

The healing of a wound is a lengthy process, and collagen in cicatricial tissues shows changes even after several years (Verzár & Willenegger 1961).

Influence of cortico-steroids

Several attempts have been made in clinical praxis to control tendon healing, specifically the aspect of adhesion formation. The most extensively tried drug for this purpose has been cortico-steroids, which diminishes adhesion formation (Carstam 1953, Wrenn et al. 1954). However, it also lowers the tensile strength of sutured tendons. They were 40 % stronger in a group of untreated animals after 3 weeks' healing (Wrenn et al. 1954).

Influence of immobilisation

Partial immobilisation after tendon surgery is mandatory, or suture insufficiency will ensue. In connexion with separation of tendon ends, an excess of adhesions is found (Mason & Allen 1941, Cowan & Courtemanche 1959). There is a faster gain in tensile strength after the end of the immobilisation (Mason & Allen 1941, Cowan & Courtemanche 1959).

Influence of suture technique

Several studies have been conducted on fresh sutures in different types of tendons from a variety of species. There is unanimous agreement that "plaited" sutures like the Dychno-Bunnell criss-cross suture have the highest tensile strength. At maximum load there is always separation between tendon ends. The separation before total failure is subject to wide variations (Malewitsch 1908, Kimura 1912, Mason & Allen 1941, Flückiger 1952, Cowan & Courtemanche 1959, Schink & Gersbach 1961, Shaw 1968, Glogowsky & Fiebig 1970).

A comparison between tendon-to-tendon and tendon-to-bone sutures shows tendon-to-bone sutures to be the strongest, which is in agreement with clinical experience (Forward & Cowan 1963, Levine et al. 1966).

MATERIAL AND METHODS

Adult rabbits were chosen as the experimental animal. The animals were not purebread, but the majority were of the albino type. Their body weights varied between 1.8 kg and 5.5 kg, with a mean body weight of 2.9 kg and a standard deviation of .6 kg. They were kept in indoor cages two weeks befor surgery and the first 10–14 days postoperatively. Thereafter they stayed in outdoor cages with smooth bottoms in order to avoid damage to the animals' feet. They were all fed standard diets and water ad libitium.

Anatomy of the rabbit hind leg

Muscles and tendons

On the lateral side of the thigh runs the biceps femoris muscle with its two portions. Caput breve inserts with its flat tendon on the lateral margin of the patella, caput longum has a broad insertion on the fascia of the lateral proximal third of the lower leg.

On the lateral side of the lower leg, under the long head of the biceps, runs the soleus and the lateral head of the gastrocnemius muscles. Further laterally and anteriorly one finds the heads of the long toe flexors. In front of the flexors lies the peroneal group of muscles, consisting of the fused heads of peroneus quartus and tertius and the flexor digitorum longus. In front of those is the peroneus longus, beneath which lies the peroneus brevis. This last muscle has origins on both tibia and fibula and the interosseous membrane.

Just in front of the distally very slender fibula and laterally to the tibia, run the tendons from the peroneal muscles. They are kept together within the same tendon sheath. They pass through a groove in the lateral malleolus, and are held in the groove by a retinaculum. On the distal side of the malleolus they are split up in the following fashion:

- peroneus longus (primus) is attached to the reduced first metatarsal. The tendon crosses the plantar side of the foot.
- peroneus brevis (secundus) attaches to the tuberosity at the base of the 5th metatarsal.
- peroneus tertius attaches to the first metatarsal and unites distally with the tendon of the extensor digitorum longus on the phalanges of the digits.
- peroneus quartus attaches to the head of the 4th metatarsal.

Vessels and nerves

On the lateral side of the lower leg runs the lesser saphenous artery, which branches off from the popliteal artery just above the femoral condyles. It passes along the lateral head of the gastrocnemius, continues behind the lateral malleolus and down to the foot. The rest of the popliteal artery divides into two main branches, the anterior and posterior tibial arteries. The anterior branch passes through the interosseous membrane and the origin of the short peroneal muscle, to continue down on the tibia. Proximally it gives off the peroneal artery, also going distally but rather more laterally than the anterior branch.

All arteries have accompanying veins. On the lateral side of the lower leg there is one large superficial vein – the sciatic vein.

The sciatic nerve divides in the middle of the thigh. It gives off the lesser saphenous nerve, which in homo is called the sural nerve. The rest of the sciatic nerve gives off the peroneal and tibial nerves. The latter runs between the heads of the gastrocnemius and eventually reaches the posterior side of the long flexors, along with which it reaches the sole of the foot. It gives off branches to the flexor group of muscles. The peroneal nerve passes between the insertion of the long head of the biceps an the origin of the lateral head of the gastrocnemius. It then perforates first the gastrocnemius and then the fused heads of the peroneus tertius and flexor digitorum longus. When it emerges underneath these muscles it immediately gives off muscle branches to the peroneal muscles, the anterior tibial muscle and the extensor group. Some of these branches pass over the short peroneal muscle in its proximal part at about the same level as the anterior tibial artery, but more superficially. The rest of the peroneal nerve runs distally lying under the long peroneal muscle, passes over its tibial border and joins the peroneal artery. The nerve and the artery reach the back of the foot somewhat medially to the lateral malleolus. (Bensley 1948).

Surgical procedures

Preoperative preparations and anaesthesia

The animals were not starved before operation. One hour preoperatively they were given a premedication of a 25 % urethane solution subcutaneously in the interscapular region. Dosage: 3 ml/kg body weight. Anaesthesia was induced with a solution of 3.5 % pentobarbitalsodium and 10 % barbitalsodium given intravenously into the marginal vein of the rabbit's ear. Dosage: approximately 1 ml/kg body weight.

The rabbit's hind legs were shaved with the aid of an ordinary clipping machine. The leg to be operated was then thoroughly cleaned with a 75 % alcohol solution, and finally draped with sterile textiles.

All surgery was performed by the author personally with the aid of the same assistant. With the exception of the personal improvement they may have made from operating some 300 rabbits, the techniques used have been unaltered throughout the whole study.

Care was taken to handle the tissues as atraumatically as possible, using moistened gloved hands or saline soaked textiles rather than instruments, and when using instruments avoiding, if possible, those with sharp edges. Exsiccation of the tissues was prevented during surgery by dripping isotone saline solution into the wound at frequent intervals.

The overall time for anaesthesia was aproximately two hours, of which the surgical procedures proper consumed 20 minutes per leg. No tourniquet was used and the blood loss was negligible. No hypovolemic shock was recorded. A few animals died during surgery from an overdose of barbiturates.

Choice of tendon for suture

All tendon sutures were performed on the tendon to the short peroneal muscle. There were several reasons for this choice:

- the tendon must have a minimal length of 40 mm, 10 mm at each end for fastening into the clamps of the testing machine, and 20 mm measuring length.

– the tendon should be as thick as possible in order to facilitate surgery.
– the tendon, and its muscle, should be easily accessible from a surgical point of view.

Relaxation of tendon and postoperative immobilisation

Pilot studies on suturing of the peroneus brevis tendon in the rabbit revealed that a successful suture could not be achieved, unless the tendon was at least partly relaxed, and this relaxation maintained with some immobilisation device. It was found that, irrespective of the position of the ankle joints, sufficient relaxation could not be established in the short peroneal tendon.

It was also found that casting of the hind leg in a rabbit is difficult. The cast will be softened by a diversity of fluids, and the rabbit often manages to free itself from the cast.

Immobilisation was instead tried with internal fixation of the ankle joints through insertion of a Kirschner wire from the plantar side of the heel. This method caused too many wound infections and had to be abandoned.

Three other relaxation methods were tried: lengthening of the tendon with the aid of a Z-plasty; neurotomi of the branch leading to the short peroneal muscle; partial release of the origin of the short peroneal muscle. The latter procedure was the most satisfactory and therefore used in combination with two weeks' application of a soft bandage, holding the foot at approximately right angles to the lower leg.

Surgical technique for partial release of the short peroneal muscle

A lateral incision was made from the level of the knee-joint and extending about 3 cm distally. The long head of the biceps femoris was incised in the direction of the fibres. The incision exposed the peroneal muscles. By retracting the long peroneal muscle together with the peroneal nerve anteriorly and the peroneus tertius and quartus posteriorly, direct access was gained to the origin of the short peroneal muscle. The muscle branches from the peroneal nerve were identified and avoided, as was the anterior tibial artery. The short peroneal muscle was then released from its origin. The release was only performed in the proximal 2/3, the distal 1/3 was left intact. The long head of the biceps was sutured with interrupted catgut stitches and the skin closed with running steel wire. A sterile gauze was used as wound dressing and fixed with tape.

Using the muscle release procedure one can relax the tendon to any desired degree. The release of the proximal 2/3 of the origin allows a suture of the short peroneal tendon without any noticeable tension.

The muscle release eventually heals and thereby gradually increases the tension it can exert over the tendon suture. Atrophy of the muscle has been classified at the time of testing (with the exception of 0 and 1 week postoperatively), rather coarsely, into 3 groups: slight, moderate or gross. The atrophy was in most cases classified as slight and restricted to the proximal part of the muscle belly. Distribution of atrophy in relation to surgical procedure and healing time is given in table 1 (page 20).

Maximum isometric tetanic contraction power after muscle release was measured in 4 animals and compared with the intact muscles on the contralateral side of the same animals. The loss of power 4 weeks postoperatively was roughly 30 % (page 56).

Table 1. Assessment of atrophy

Procedure nr	HT weeks	Atrophy, number of specimens with			
		slight	moderate	gross	not known
1	2	5	4	–	2
	4	1	7	1	2
	8	8	2	–	–
	24	7	3	1	–
2	2	5	–	–	–
	4	5	–	–	–
	8	5	–	–	–
3	2	4	1	–	–
	4	10	1	–	–
	8	5	–	–	–
	24	3	–	–	–
4	2	3	2	2	3
	4	4	5	–	1
	8	4	5	–	–
	24	4	1	1	–
5	2	7	4	–	3
	4	4	3	2	2
	8	8	2	1	–
	24	4	2	–	–

The influence of muscle release on the mechanical properties of tendons is described on page 49.

Technique for tendon suture

The suture was made directly after concluding the muscle release. A lateral incision on the distal third of the lower leg was employed. The tendon compartment is located directly under the skin. The tendon sheath was incised for a distance of about 3 cm. The tendon of the short peroneal muscle was identiefied and freed of its accompanying mesotenon for a distance of 2 cm. The tendon was severed with a sharp knife perpendicular to its long axis. The cut was made 1.5–2 cm above the lateral malleolus. The tendon was then sutured with one of two techniques:

– 4 interrupted silk sutures at regular intervals around the circumference of the tendon. Suture material: atraumatic, braided, 8/0 silk on round curved needles. The silk was impregnated with bees-wax to reduce friction and diminish capillary effects. Thread diameter: .038–.051 mm. Minimal breaking strength for one straight thread: .09 kp. (Specifications by the manufacturer Johnson & Johnson, Ethicon product nr 700G). (Fig 1 page 21).

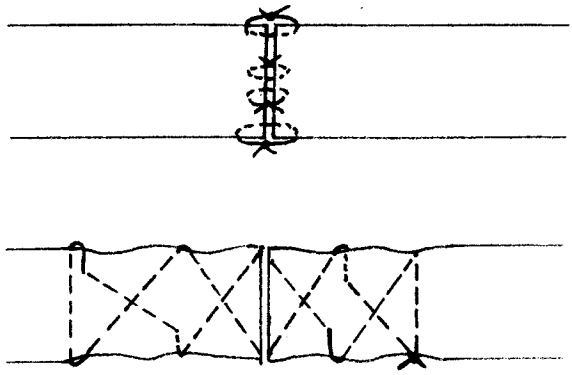

Fig 1. Schematic drawing of techniques for tendon sutures.
Upper fig: 4 interrupted sutures with 8/0 silk.
Lower fig.: Criss-cross suture with 5/0 stainless steel wire.

– Criss-cross suture according to the technique described by Bunnell. The suture consisted of two "loops" proximal to the cut and two "loops" distal to it. Suture material: atraumatic, multistranded, twined 5/0 stainless steel wire on two straight needles with cutting points. The wire consisted of 7 strands, one acting as a core, and the other 6 twined round it. All strands were of the same dimensions. Wire diameter: .142 mm. Minimal breaking strength for one straight wire: .91 kp (Specifications by the manufacturer Johnson & Johnson, Ethicon, product nr 583G.) (Fig 1).

The tendon sheath was not closed. The skin was closed with interrupted stainless steel wire. The wound was covered with a sterile gauze and a soft bandage applied holding the ankle joint in about 90° dorsiflexion.

Adhesion formation

Adhesions were invariably found after tendon suture, whether on divided or undivided tendons. When tendons were removed for testing the degree of adhesion formation was coarsely classified in one of four groups:

– very slight, a few flimsy fibrous bands producing no restraint on tendon excursions
– slight, more dense fibrous structures impairing extreme tendon excursions
– moderate, fibrous bands clearly restraining tendon excursions
– abundant, massive fibrous bands, making tendon excursions impossible

Table 2 page 22 shows the degree of adhesion formation in relation to type of surgical procedure and healing time (with the exception of healing time 1 week). It can be seen from this table that division of a tendon causes increased adhesion formation and also that criss-cross sutures often evoke a stronger tissue reaction than interrupted sutures.

Table 2. Assessment of adhesions

Procedure nr	HT weeks	Adhesions, number of specimens with				
		very slight	slight	moderate	abundant	not known
2	2	4	1	–	–	–
	4	4	1	–	–	–
	8	4	–	1	–	–
3	2	–	3	1	1	–
	4	–	6	5	–	–
	8	1	2	2	–	–
	24	1	1	1	–	–
4	2	–	1	4	2	3
	4	–	3	4	2	1
	8	–	3	5	1	–
	24	–	2	3	–	1
5	2	–	–	6	5	3
	4	–	4	4	1	2
	8	–	2	5	4	–
	24	–	2	3	–	1

Methods of mechanical testing

Testing apparatus

The tensile tests were performed in an Alwetron material tester (Lorentzon & Wettre) (fig 2 page 23). The Alwetron is a highly versatile tester and can produce cyclic loading or tests for relaxation and creep. Thus for relaxation tests the apparatus can be stopped at any desired deformation and kept there without any variations at all (fig 7 page 28). When performing creep tests, that is with constant load, the apparatus oscillates around the desired load level (fig 7). The oscillations are due to the construction of the Alwetron. They were the same in all creep tests and amounted to only a few percent of the applied load.

As the standard version of the Alwetron was considered unsatisfactory with regard to deformation measurements, it was for this purpose fitted with a differential-transformer (Bofors AB, RLK-1, fig 3 page 24).

The signals from the load cell of the Alwetron and the differential-transformer were, via an amplifier (Lorentzon & Wettre) used to drive two X-Y-recorders (Mosely 7005AM, Hewlett-Packard and Houston Instruments Omnigraphic TM X-Y). One recorder was used for force-deformation diagrams, the other for creep or force-relaxation diagrams. The two recorders were used simultaneously.

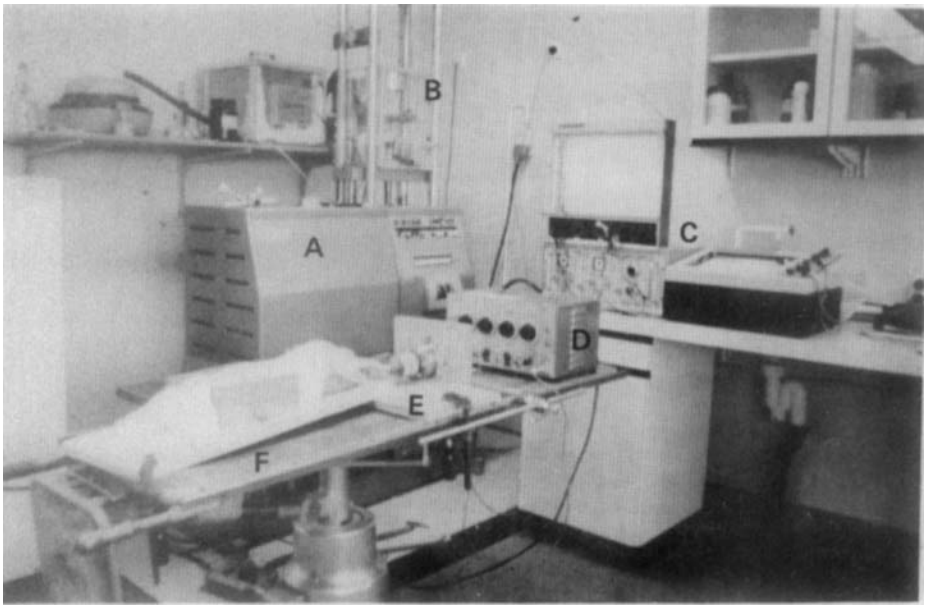

Fig 2. Apparatus used for tensite tests of tendons and measurements of maximum isometric contraction power of the peroneus brevis muscle.
A. Alwetron material tester.
B. Humidity chamber
C. Amplifier and x-y-recorders
D. DC-pulse generator
E. Dismounted load-cell
F. Rabbit being tested for maximum muscle power

Accuracy of measurements

Load cell and amplifier ±1 % with a load of 5 kp.
Differential-transformer and amplifier ±.5 % over a measuring range of ±12 mm. Temperature sensitivity <.02 %/°C. It was used in almost constant room temperature. X-Y-recorders ±.2 % of full scale measurements for force or deformation, ±1.5 % of maximum measuring range for time measurements (used with creep or force-relaxation tests).
(Figures given as specified by the manufacturers.)
All units were calibrated before each individual test.

Fitting of specimens

The standard clamps, delivered with the Alwetron and used for holding different types of test materials, were changed in order to allow a safe grip of a moistened tendon without any detectable slipping when the tendon was being strained. The special

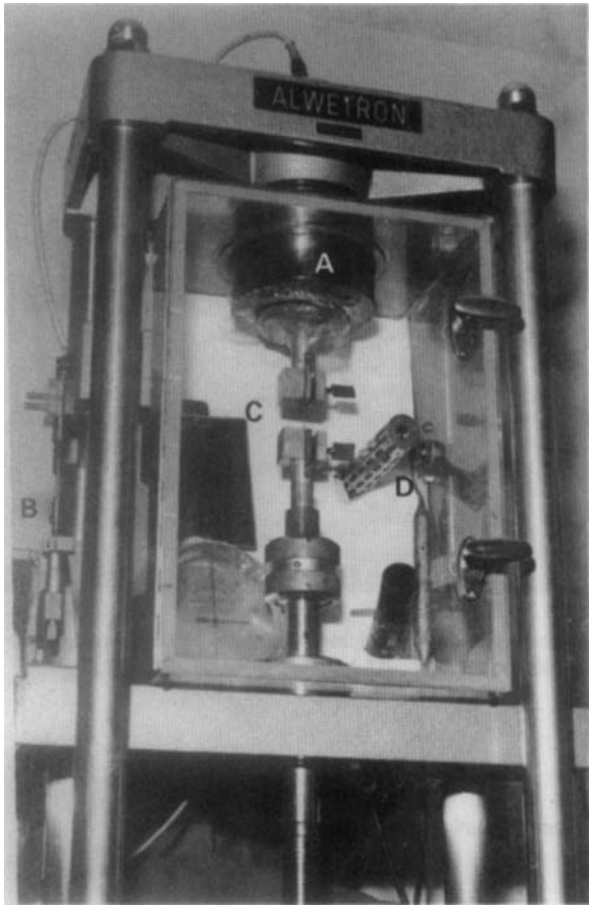

Fig 3. Close-up view of the Alwetron material tester with the humidity chamber for environmental control. A = load cell for force measurements. B = differential-transformer for deformation measurements. C = clamps for holding test specimens. D = thermostat.

clamps manufactured consisted of two parallel steel plates, which could be screwed against each other (fig 3). Water-proof abrasive paper was glued to the inner surfaces of the parallel steel plates, thereby raising the coefficient of friction.

The distance between the clamps when fitting the specimens was always 20 mm.

Slipping of clamped specimens

As is evident from the photograph of the testing machine (fig 3), the deformations measured by the differential-transformer relate to the distance between the clamps. In order to show that these deformation measurements did not include any slipping of the specimens relative to the clamps the following tests were executed:

A tendon specimen was fitted in the clamps and an extensometer (Instron G-51-17M, accuracy ±.25 %, measuring range 10 mm) (fig 4 page 25) was fastened directly on the tendon.

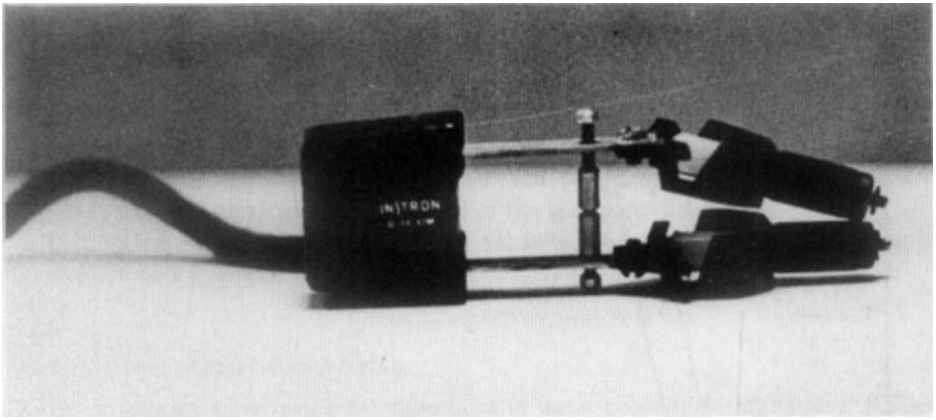

Fig 4. Instron extensometer attachable to tendon specimens.

Both the differential-transformer and the extensometer were connected to the same X-Y-recorder. A deformation roughly equivalent to a load of 5 kp was applied to the tendon. The distance between the clamps was kept constant for 5 min. In the presence of slipping in the clamps the extensometer readings would decrease, while the differential-transformer would be steady. No such drifting was observed in the graphs (fig 5). The curve is fairly linear, which also indicates the absence of slipping.

Experiments were repeated with a registration of load versus deformation measured by the Instron extensometer. A load of 5 kp was applied and kept constant for 5 min

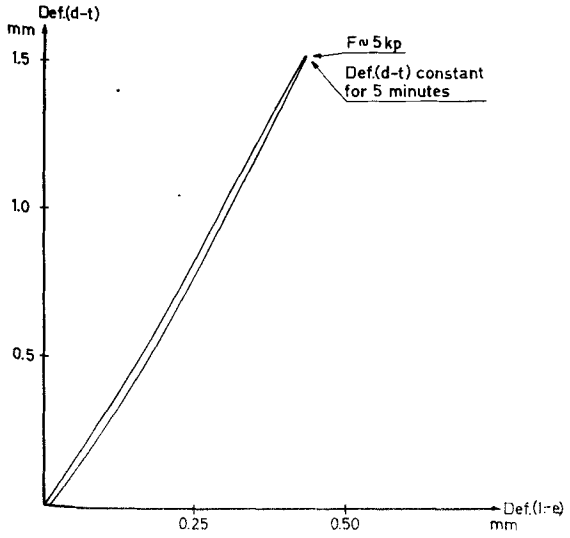

Fig 5. Deformation measured with the differential-transformer, Def. (d-t) versus deformation measured by the Instron extensometer, Def. (I-e). Test of intact specimen. F = applied force. Def. (d-t) = distance between clamps. When it is kept constant Def. (I-e) is also constant, proving the absence of slipping of specimen in the clamps.

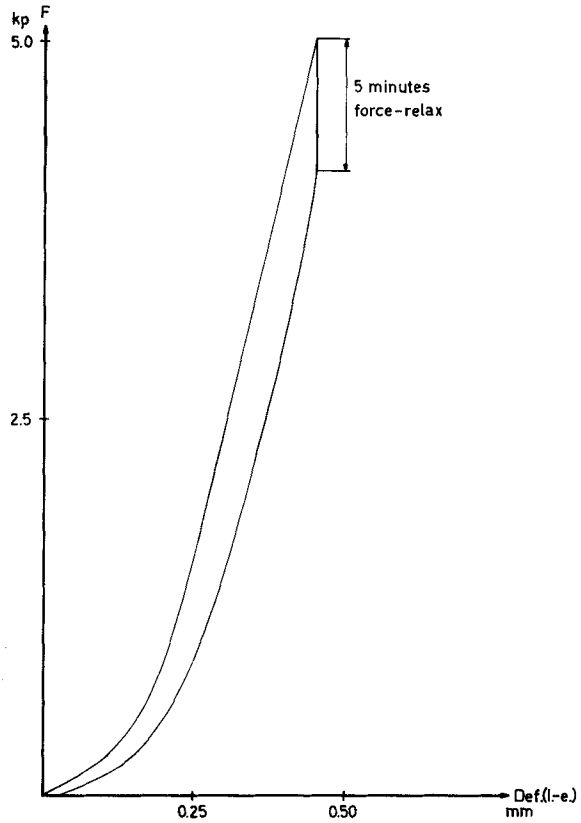

Fig 6. Force-deformation diagram for an intact tendon. F = force. Def. (l-e) = deformation measured with Instron extensometer mounted on specimen. Interclamp distance contant during 5 min. In the absence of slipping of the specimen in the clamps a pure force-relaxation, i.e. a vertical drop of the curve could be expected. There is a slight deviation to the left during relaxation, corresponding to a shortening of .01 mm.

(relaxation test). In the absence of slipping only a reduction in force should be recorded. In the graphs there were usually a maximum shortening of .01 mm (fig 6). This was not regarded as a true slipping. It was considered a reflection of the changes imposed on the tendon material in the vicinity of the borderline between the clamped part of the tendon and the free part.

Environmental control during testing

Soft collagenous tissues change their tensile properties substantially with alterations in water content (Rollhäuser 1950, Stucke 1950, Galante 1967). If they are stored in dry air, water loss is rapid. If, on the other hand, they are put in isotone solutions such as Ringer's solution or plasma, they swell (Galante 1967, Tkaczuk 1968). Of all solutions tried, plasma produces least swelling (Tkaczuk 1968).

In this investigation a continuous plasma drip was used during testing to maintain the water content of the specimens. The drops were delivered between the steel plates of the upper clamp, providing a thin film of plasma coating the tendons.

The plasma was obtained by drawing and centrifugating 100 ml of blood from the same rabbit that delivered the test specimen.

As a further guarantee against exsiccation all tests were performed in a transparent chamber with 100 % humidity (fig 3 page 24).

Temperature was kept constant at 25°C with the aid of a thermostat. It was not possible to raise the temperature further and still keep 100 % humidity due to condensation of water vapour on the walls of the transparent chamber.

Testing was rather time-consuming, up till two hours per specimen depending on actual breaking strength.

Water content changes during testing

Seven specimens were tested for alterations in water content during testing. Rabbits not previously operated were anaesthetised and a short peroneus brevis tendon removed. The tendon was immediately weighed. Thereafter it was fitted in the clamps and the plasma drip started. It was preloaded to .1 kp, unloaded and allowed a 5 minute rest (as was done in all tests). It was removed from the clamps and again weighed. The weight increased in 5 and decreased in 2 cases (table 3). The weight change is probably the resultant of water having been pressed out of the tissues gripped by the clamps and water uptake in the free part between the clamps.

The specimen was refitted into the clamps and run through the complete test program (see page 28), and finally removed and weighed once more. The difference between the second and the third weighing was taken as an indication of water content changes during testing. Two out of the seven specimens showed a small weight increase and those were the two who lost weight during preload. All specimens gained som weight compared to weight before preload (table 3).

A sign test (page 38) revealed that weight changes during testing proper were not statistically significant.

Table 3. Weight changes of specimens before test, after preload and after completed test.

Specimen nr.	Weight before test. Grms	Change after preload.		Further change after test	
		Grms	%	Grms	%
1	.18405	+.02450	13.00	−.00785	3.76
2	.17341	−.00351	2.02	+.00948	5.58
3	.13546	+.01152	8.50	−.01117	7.60
4	.16347	+.01055	6.45	−.00891	5.12
5	.16793	+.01554	9.25	−.01164	6.34
6	.11668	−.00389	3.33	+.01298	11.51
7	.12088	+.01268	10.49	−.00041	.31

Mechanical testing

The overall mechanical behaviour of any biological material is composed of three basic properties: elasticity, plasticity and viscosity.

It has been the aim to design a test model that will give separate measurements of these three properties.

The tensile tests were performed as follows:

The rabbit was anaesthetised with barbiturates as earlier described (page 18). The same incision as for suturing was employed and the short peroneal tendon from the musculo-tendineal junction to the insertion at the base of the fifth metarsal, was removed. Adhesions were removed from the specimen to the extent possible without disturbing the suture. Great care was taken to keep the specimen moistened. The tendon was immediately fitted in the clamps, with an interclamp distance of 20 mm, loaded to .1 kp, directly unloaed and allowed 5 min rest. The preload of .1kp strengthened the clamp grip on the tendon.

The specimen was then given a load of .25 kp, which was kept constant for 5 min. A force-deformation diagram (fig 7) and a graph of deformation versus time (creep test, fig 8 page 29), were recorded. After the 5 min load period the specimen was unloaded and allowed 5 min rest.

The specimen was again loaded to the same level. The deformation was now kept constant for 5 min. A force-deformation diagram and a force versus time graph, force-relaxation test (fig 9 page 29), were recorded. The specimen was unloaded and allowed 5 min rest.

The entire procedure (except for the preload) was repeated at load levels .50 kp, 1.00 kp, 2.50 kp and 5.00 kp. If the specimen withstood 5.00 kp it was run to the breaking point (fig 10 page 29).

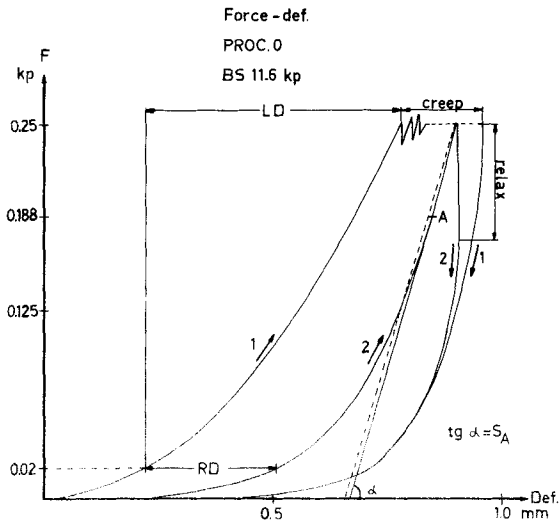

Fig 7. Force-deformation diagram for an intact peroneus brevis tendon. Deformation (Def.) on the abscissa, force (F) on the ordinate. During the first load cycle (1) F is kept constant for 5 min – creep test. During the second load cycle (2) Def. is kept constant for 5 min when .25 kp has been reached – force-relaxation test. Load deformation (LD) and residual deformation (RD) are calculated by dividing the distances indicated by the original length, that is the length under a load of .02 kp when loading to .25 kp for the 1st time. Stiffness (S) is defined as the slope of the line drawn through .25 kp and .125 kp on the ascending part of the 2nd load cycle = tan α. The line is considered a tangent to the curve in point A = 3/4 x .25 = .19 kp.

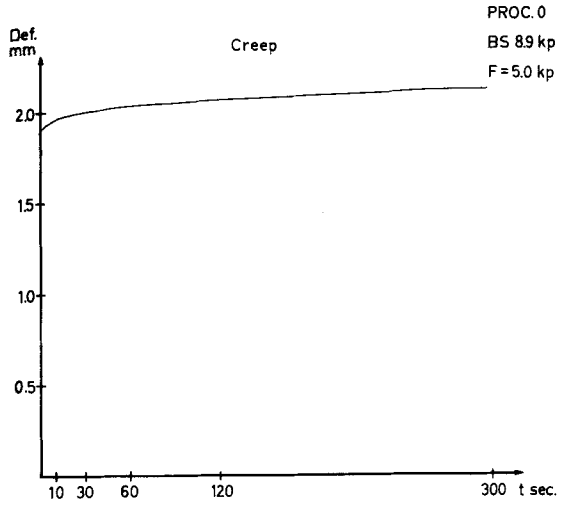

Fig 8. Creep diagram for an intact peroneus brevis tendon (procedure nr 0). t = time. Def. = deformation. F = applied force. BS = breaking strength.

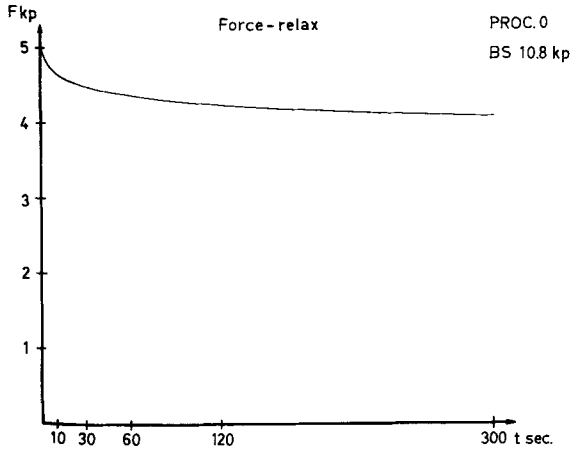

Fig 9. Force-relaxation diagram for an intact peroneus brevis tendon (procedure nr 0). t = time. F = force. BS breaking strength.

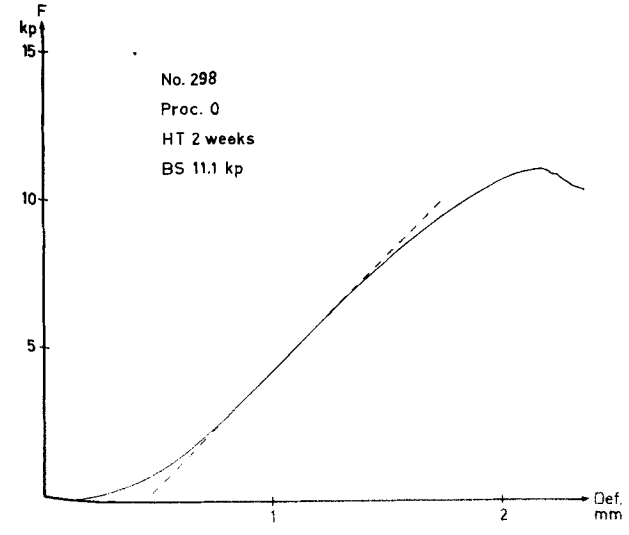

Fig 10. Force-deformation diagram for an intact specimen (procedure nr 0) tested for breaking strength (BS). BS is defined as the highest registered load. F = force. Def. = deformation. HT = healing time and refers to the surgical procedure performed on the contralateral leg.
Part of the curve around 5 kp is approximately linear.

In all tests strain rate was constant 25 %/min = 5 mm/min.

Rupture of intact tendons occurred in the free part between the clamps, but for a few specimens (< 2 %) which were rejected (table 5 page 31).

Sutured tendons, divided or undivided, always separated in the suture line or over the distance covered by the suture. Rupture of suture material or knot insufficiency was never observed.

Measured variables

1. *Breaking strength (BS) – the highest registered load* (fig 10 page 29).
2. *Stiffness (S) – slope of force-deformation curve* (for a defined force). Measurements taken from the force-deformation charts. A line is drawn from a point on the second curve at a given load level and through another point on the same curve at half that level (fig 7 page 28). The line is transferred to the right until it becomes a tangent to the curve. The constructed line intersects the abscissa and tan for the angle between them (α) is taken as stiffness for 3/4 of the higher load used for constructing the tangent.
3. *Load deformation (LD) – relative change in length with load.* Deformation measured in the force-deformation chart at the beginning of the creep test, as the length increase in % of original length (fig 7 page 28). Original length is defined as the length of the specimen under load of .02 kp.
4. *Creep – relative length increase with time for constant load.* Measured from the deformation-time charts as the increase in length in % of original length at 10 sec, 30 sec, 60 sec, 120 sec and 300 sec after intended load level was reached (fig 8 page 29). Deformation at 0 sec = LD. Total deformation can be calculated by adding LD and creep (fig 7 page 28).
5. *Residual deformation (RD) – irrecoverable relative length change* after loading, unloading and 5 min rest. Measured in the force-deformation chart as the length increase between load cycles 1 and 2 in % of original length under a load of .02 kp (fig 7 page 28)
6. *Force-relaxation – relative decrease of force with time for constant length.* Measured from the force-time chart. Defined as load decrease in % of originally applied load. Measured at 10 sec, 30 sec, 60 sec, 120 sec, and 300 sec after intended load level was reached (fig 9 page 29).

Experimental groups

The rabbits used were divided into the following test groups according to the surgical procedures performed:

Procedure nr 0 – no surgery on peroneal muscle or tendon.
Procedure nr 1 – release of 2/3 of origin of peroneal muscle. No surgery on peroneal tendon.
Procedure nr 2 – release of 2/3 of origin of peroneal muscle. No division of peroneal tendon. 4 interrupted 8/0 silk sutures on undivided tendon.

Procedure nr 3 – release of 2/3 of origin of peroneal muscle. No division of peroneal tendon. Criss-cross suture a.m. Bunnell on undivided tendon using 5/0 stainless steel wire.

Procedure nr 4 – release of 2/3 of origin of peroneal muscle. Division of peroneal tendon. Tendon suture with 4 interrupted sutures using 8/0 silk.

Procedure nr 5 – release of 2/3 of origin of peroneal muscle. Division of peroneal tendon. Tendon suture with criss-cross technique a.m. Bunnel using 5/0 stainless steel wire.

Procedures nr 0 and 1 were always performed on alternat legs of the same rabbits. The same applies for procedures nr 4 and 5. Procedures nr 2 and 3 had procedure nr 0 on the opposite side. The reason for grouping the procedures together in this fashion was that differences of tensile properties between the two procedures used on the same rabbit were anticipated to be small. By grouping them together and comparing the two sides, biological variations could be partly eliminated, promoting statistical discrimination.

Table 4. Distribution of material. Number of specimens.

Procedure nr.	Healing time, weeks						Total
	0	1	2	4	8	24	
0	10	19	21	21	18	14	103
1	–	8	11	11	10	11	51
2	5	5	5	5	5	–	25
3	5	5	5	11	5	3	34
4	10	11	10	10	9	6	56
5	11	16	14	11	11	6	69
						Total	344

Table 5. Complications leading to rejection of specimens.

Procedure nr.	Complications					
	Died	Postop. infect.	Suture insuff.	Techn. failure at test	Misc.	Total
0	22	–	–	5	2	29
1	13	–	–	4	2	19
2	3	–	–	–	–	3
3	9	–	–	–	–	9
4	17	11	38	1	4	71
5	17	9	9	2	8	45
Total	81	20	47	12	16	176

For procedures nr 0, 3, 4 and 5 tensile tests were conducted 0, 1, 2, 4, 8 and 24 weeks postoperatively. In connection with procedure nr 0 healing time (HT = weeks postoperatively) refers to the surgical procedure performed on the contralateral side. For procedure nr 1 there were no tests at healing time 0 since this is equal to performing no surgery at all and testing immediately, i.e. procedure nr 0 healing time 0. For procedure nr 2 healing time 24 weeks was not tested. Creep values for healing time 24 weeks are not given for procedures nr 4 and 5.

The distribution of the material is evident from table 4 (page 31). The table only shows specimens accepted for tensile tests, i.e. no postoperative complications developed. The number and type of postoperative complications leading to rejection of a particular specimen are given in table 5 (page 31).

Sources of errors

Systematic errors could be introduced in several ways when determining the tensile characteristics of the tendon specimens.

Preparation of test specimens

The entire tendon from the musculo-tendineal junction to the bony insertion was always removed for testing. Difficulties were encountered when adhesions had formed, which was invariably the case with sutured tendons. In most instances the tendon proper was easily freed from adhesions. Only in the region of the suture line was the borderline between tendon and adhesions difficult to see. The specimens were cut out with "macroscopically" uniform dimensions over the suture line. Variations should be randomly distributed between groups.

Length of specimens

Values of tensile parameters vary with length of specimens tested (Welsh et al, 1971). The longer the specimen the weaker it will be.

The distance between the clamps when fitting the specimens in the material tester was always 20 mm. It was, however, impossible to adjust the tendons so that 0 force coincided exactly with this length. The distance denoted as original length was determined after preloading and defined as the length of the specimen under a load of .02 kp, when it was being loaded to .25 kp for the first time (fig 7 page 28). It was impossible to separate curves at 0 kp, which is the reason for using .02 kp.

The original length of the specimens is thus 20 mm plus a few tenths of a mm. The exact length determined for each specimen was always used in calculations.

Cross-section area of specimens

It was decided not to attempt stress instead of force measurements, the reason being the difficulty of obtaining correct cross-section areas even of resting tendons. Ellis, 1969, compared 7 different methods of measuring tendon cross-section areas. He

concluded that methods applicable to fresh moist specimens had poor repeatability and numerical values could differ with a factor of 3 between methods.

Since the rabbits were randomly chosen for surgery it is assumed that cross-section area was also randomly distributed in the experimental groups, meaning that mean values of cross-section area in any group should not be statistically different from that in any other group. Consequently, omitting measurements of cross-section area does not invalidate comparison of tensile properties between groups.

Influence of body weight is discussed on page 62.

Post-mortem decomposition of specimens

Post-mortem decomposition of soft collagenous tissues is slight within the first 4 hours after death (Gratz 1931, Rigby et al 1959, Viidik et al. 1965, Galante 1967, Matthews & Ellis 1968). Specimens were taken out for testing while the animals were still alive and immediately tested. In view of the low metabolic turnover in tendons (Neuberger et al. 1951, Peacock 1957, White et al. 1964), and the precaution taken to coat the tendons with plasma, post-mortal decomposition of specimens was in all probability slight during the 2 hour test.

Environmental control during testing

1. *Temperature.* All specimens were tested fresh, none were deepfrozen and thawed. All tests were conducted at 25°C.
2. *Humidity.* Changes in water content are readily produced when tendons are removed from the body. When kept in dry air, tendon specimens rapidly decrease their water content (Galante 1967). If immersed in isotone solutions tendon specimens swell. Minimal swelling has been found with plasma (Tkaczuk 1968). Drying or swelling significantly alters tensile properties (Rollhäuser 1950, Stucke 1950, Partington & Wood 1963, Galante 1967, Tkaczuk 1968). After swelling stiffness is reduced and deformations increased.

   If tendon specimens are loaded in tension, water is expelled from them (Rollhäuser 1950, Elden 1964, Kenedi et al. 1964).

   In order to obtain an indication of alteration in water content during testing, 7 specimens were weighed immediately after removal from the rabbit, again after preload and finally after completion of the entire test programme (page 27). All of them had then gained some weight as compared to the time of removal. During the test proper (that is after preload), two out of seven increased in weight and those were the two who had lost weight after preload as compared to time of removal (table 3 page 27). The weight changes during testing are not statistically significant (sign test, page 38).

   It can be concluded that coating tendons subjected to loading-unloading cycles with a thin film of plasma does not significantly alter the water content during a two hour test.

Mode of testing

The earlier history of the tested material with respect to loads and deformations is relevant to the tensile characteristics found at tests *in vitro* (Stucke 1950, LaBan 1962, Rigby 1964, Viidik 1968, Gross & Arnold 1973).

The strain rate influences the mechanical behaviour of collagenous tissues (Rigby et al. 1959, Morgan 1960, McElhaney 1965, van Brocklin & Ellis 1965, Abrahams 1967, Viidik 1968, Welsh et al. 1971, Gross & Arnold 1973). Stiffness for instance increases with strain rate.

The loading-unloading sequence, applied forces, duration of creep and force-relaxation tests and recovery time as well as strain rate remained the same for all specimens tested, subject only to unavoidable differences due to variations in breaking strength.

Slipping in the clamps

Accuracy of clamps used for holding specimens was checked (page 24). With simultaneous use of one extensometer fastened directly on the tendon and one differential-transformer measuring interclamp distance, a maximum slip of .01 mm was found. Assuming original length of specimens was 20 mm (page 24), the introduced error in deformation measurements is + .05 %.

Accuracy of testing and recording equipment

Total accuracy of load measurements ±1.25 %.

Total accuracy of deformation measurements ±.75 %.

All units used were recalibrated before each individual test.

Accuracy of measurements taken from recorded graphs

The recorded graphs were read to the nearest half mm. In force-deformation graphs maximum load error will be ±.4 % and maximum deformation error ±.0.05 %.
In creep graphs maximum deformation error will be ±1 %.
In force-relaxation graphs maximum load error will be ±1 %.
Maximum time error ±1.5 %.

The force-deformation diagram is not perfectly linear for forces less than 5 kp (fig 10, page 29). In an attempt to avoid "optical illusions" when drawing the tangent to the curve for stiffness calculations, the construction described on page 30 was adopted. It introduces an error: the line will not be a tangent to the curve midway between the two points used to draw the line, i.e. 3/4 of applied force (fig 7 page 28). The exact magnitude of the introduced error cannot be calculated, but it is considered negligible.

Residual deformation was measured with an applied force of .02 kp due to the difficulty of separating curves at 0 kp. If this force (.02 kp) could have been diminished, residual deformation would have decreased (fig 7 page 28). The amount of reduction cannot be assessed in the present graphs.

When the specimens tore during the 5-minute period of creep- or force-relaxation test, breaking strength was noted as the actual load level. It would have been somewhat higher had the specimen been tested directly for breaking strength.

The errors emanating from biological factors are not systematic. They are assumed to be randomly distributed in all experimental groups, and not considered to have any decesive influence on statistical results.

The errors due to inaccuracy of testing and recording equipment are not of significant magnitude.

Symbols and their definitions

n = number of observations

$\bar{x}, \bar{y}$ = arithmetic mean for x and y. $\bar{x} = \frac{\Sigma x}{n}, \bar{y} = \frac{\Sigma y}{n}$

s_x^2, s_y^2 = variance for x and y.

$$s_x^2 = \frac{1}{n-1}\left[\Sigma^2 - \frac{(\Sigma x)^2}{n}\right], s_y^2 = \frac{1}{n-1}\left[\Sigma_y{}^2 - \frac{(\Sigma y)^2}{n}\right]$$

s_x, s_y = standard deviation for x and y.

r = coefficient of correlation between x and y.

$$r = \frac{n\Sigma xy - \Sigma x \Sigma y}{\sqrt{[n\Sigma x^2 - (\Sigma x)^2][n\Sigma y^2 - (\Sigma y)^2]}}$$

$d = r^2$ = coefficient of determination for linear regression.
The equation for the straight line is written as
$y = bx + a$, where a is the intercept and b the coefficient of regression.
a and b are determined according to the method of least squares.

$$b = \frac{n\Sigma xy - \Sigma x \Sigma y}{n\Sigma x^2 - (\Sigma x)^2} \quad ; a = \bar{y} - b\bar{x}$$

s_{yx} = residual deviation for y on x.

$$s_{yx} = s_y \sqrt{\frac{n-1}{n-2}(1 - r^2)}$$

s_{yx}^2 = residual variance

Comparison of two mean values μ_1 and μ_2

Null hypothesis: μ_1 equals μ_2.
Normal distribution of population assumed.
Population variance is not known and therefore estimated from the samples, i.e. $s_{x_1}^2$ and $s_{x_2}^2$ are calculated. The quotient between the larger and the smaller variances is

denoted F and compared with the critical value from the so-called F-distribution for the combined degrees of freedom $n_1 - 1$ and $n_2 - 1$. If no significant difference between estimated variances is detected, a mean variance is calculated according to the formula.

$$s^2 = \frac{(n_1 - 1)\, s_1^2 + (n_2 - 1)\, s_2^2}{n_1 + n_2 - 2}$$

As test variable for the null hypothesis ($\mu_1 = \mu_2$) the quotient

$$t = \frac{\bar{x}_1 - \bar{x}_2}{s\sqrt{\frac{1}{n_1} + \frac{1}{n_2}}}$$ is used.

Critical value is taken from the student's t-distribution for $n_1 + n_2 - 2$ degrees of freedom. Two-sided alternative hypothesis is used.

If absolute value for the quotient $t \leq$ critical value, the null hypothesis is not rejected, otherwise it is rejected.

Comparison of two linear regressions

Normal distribution of population assumed.
The test is executed in two steps.

1. Null hypothesis: the two coefficients of regression are equal.

The quotient $t = \frac{b_1 - b_2}{\sqrt{s^2 \left[\frac{1}{s_{x_1}^2 (n_1 - 1)} + \frac{1}{s_{x_2}^2 (n_2 - 1)}\right]}}$ is calculated

where $s^2 = \frac{(n_1 - 2)\, s_{y_1 x_1} + (n_2 - 2)\, s_{y_2 x_2}^2}{n_1 + n_2 - 4}$

If absolute value of $t \leq$ critical value taken from t-distribution for $n_1 + n_2 - 4$ degrees of freedom with two-sided alternative hypthesis, null hypothesis is not rejected, i.e. the lines have equal coefficients of regression – are parallel. If absolute value of $t >$ critical value null hypothesis is rejected.

2. If null hypothesis under 1 is not rejected, a new null hypothesis that the parallel lines are identical is tested.
   Mean coefficient of regression is first calculated according to the formula

$$b = \frac{b_1 s_{x_1}^2 (n_1 - 1) + b_2 s_{x_2}^2 (n_2 - 1)}{s_{x_1}^2 (n_1 - 1) + s_{x_2}^2 (n_2 - 1)}$$

The numerator is denoted h and the denominator g.

The quotient $t = \dfrac{\bar{y}_1 - \bar{y}_2 - b(\bar{x}_1 - \bar{x}_2)}{\sqrt{s^2 \left[\dfrac{1}{n_1} + \dfrac{1}{n_2} + \dfrac{\bar{x}_1 - \bar{x}_2}{g}\right]}}$ is calculated

where $s^2 = \dfrac{1}{n_1 + n_2 - 3} \left[s^2_{y_1} (n_1 - 1) + s^2_{y_2} (n_2 - 1) - \dfrac{h^2}{g}\right]$

The absolute value of t is compared to the critical value from the t-distribution for $n_1 + n_2 - 3$ degrees of freedom. If less than or equal to critical value with two-sided alternative hypthesis the null hypothesis is not rejected, i.e. the two lines are not significantly separated, otherwise it is rejected.

Sign test

Two separate observations on each individual. If the last observation shows an increase over the first one it is denoted +, if there is a decrease it is denoted –. No difference between observations is excluded.

Null hypothesis: the probability that the first observation exceeds the last is .5.

Probability for actual number of + and – or a more extreme outcome is calculated from the binomial distribution.

If the calculated probability is greater than .01 the null hypothesis is not rejected, otherwise it is rejected.

Significance levels

Only statistical significance on the 1 % level or better ($p \leq .01$) is accepted.

RESULTS

Presentation of data

It will be shown below that each of the measured variables for any single specimen, with the exception of breaking strength, can be represented by a regression line if the independent variable, that is time or force, is on a logarithmic scale.

It is also possible to calculate a mean regression line for any number of specimens.

The six experimental groups (surgical procedures nr 0–5) were divided into 5 or 6 subgroups according to healing time. Mean regression lines for these subgroups were calculated and used for statistical comparision with subgroups of the same and other surgical procedures.

For statistical nomenclature, definitions and details of calculations the reader is referred to page 36.

Regression lines for single specimens

Stiffness (S)

From the force-deformation chart an infinite number of stiffness measurements can be obtained. For practical reasons, however, measurements were only taken for loads corresponding to 3/4 of predetermined, arbitrarily chosen load levels earlier described (page 28). A maximum number of 5 stiffness measurements per specimen is thus possible (depending on the breaking strength for the particular specimen) and corresponding to loads of .19 kp, .38 kp, .75 kp, 1.18 kp and 3.75 kp.

A diagram of stiffness values versus logarithm of load for single specimens in any experimental group showed correlation to be linear within the tested load interval. Examples are given for all surgical procedures in figs 11–16 (page 41–46).

Load deformation (LD)

An infinite number of LD measurements can be obtained from the force-deformation chart. Again a maximum of 5 measurements, one for each predetermined load level, were taken. In figs 11–16 (page 41–46) graphs of LD versus log load are shown for single specimens from different experimental groups. The linear relationship within the tested load range is well established.

Residual deformation (RD)

A maximum of 5 measurements of RD (depending upon breaking strength of the specimen tested) can be obtained from the force-deformation chart. In figs 11–16 (page 41–46) RD versus log load is shown. The relationship is linear within the tested interval.

Creep

An infinite number of creep measurements can be taken from the deformation-time chart. 5 were taken at arbitrarily chosen time intervals, viz 10, 30, 60, 120 and 300 sec. The deformation at 0 sec equals LD. Creep can be added to LD to yield total deformation.

In figs 11–16 (page 41–46) graphs of creep versus log time are given. Within the studied time interval the relationship is linear.

Force-relaxation

From the force-time chart the percentage decrease of force from applied (predetermined) force was calculated. The same arbitrarily chosen time intervals as for creep measurements, described above, were used.

In figs 11–16 (page 41–46) the relationship between force decrease and log time is illustrated. The relationship is linear within the studied time range.

The linear regressions described above are proved valid only within the tested load or time interval. As is indicated in the graphs (figs 11–16 page 41–46), the stiffness curve is somewhat sigmoid in shape and the curve for residual deformation convex towards the abscissa. This might well be accentuated outside the test range.

Regression lines for experimental groups

Since it was found that each of the measured parameters (except breaking strength) for any single specimen showed a linear regression with either logarithm of load or logarithm of time, the same correlation between variables could be expected for groups of specimens having had the same surgery and healing time, provided the biological differences between specimens were not too large. With large differences between individual specimens the coefficient of correlation for a mean regression line would decrease too much. Trials showed that this was not the case.

Data presentation with the aid of mean regression lines was therefore adopted.

As is described on page 37 concerning statistics, it is possible to compare two regression lines statistically. They can have different coefficients of regression, i.e. the slopes differ. If the two lines have the same coefficient of regression they can be parallelly displaced, meaning that they have the same rate of change but absolute values of the dependent variables may differ between the populations.

Graphic presentation of tensile characteristics for experimental groups

Breaking strength (BS), figs 23–40 page 82–91

Presented in a diagram of BS in kp versus healing time (HT) in weeks. The results are given as mean values ±1 SD. With each mean value is noted the number of observations on which it is based.

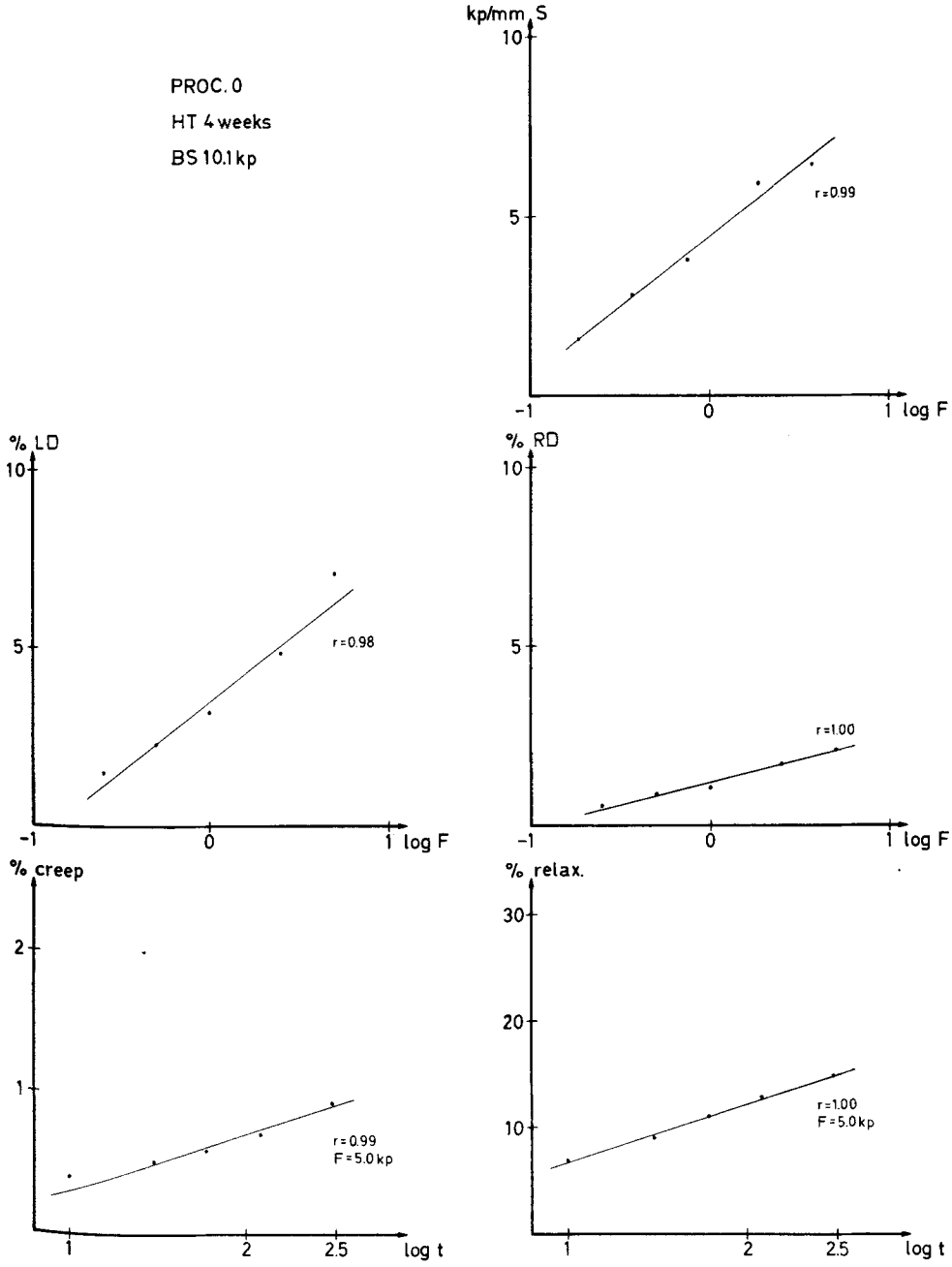

Fig 11. Regression lines for one intact specimen (procedure nr 0). HT = healing time, referring to the surgical procedure performed on the contralateral leg. BS = breaking strength. F = force in kp. t = = time in sec. S = stiffness (upper right diagram). LD = load deformation (middle left diagram). RD = = residual deformation (middle right diagram), relax = force-relaxation (lower right diagram), r = = coefficient of correlation.

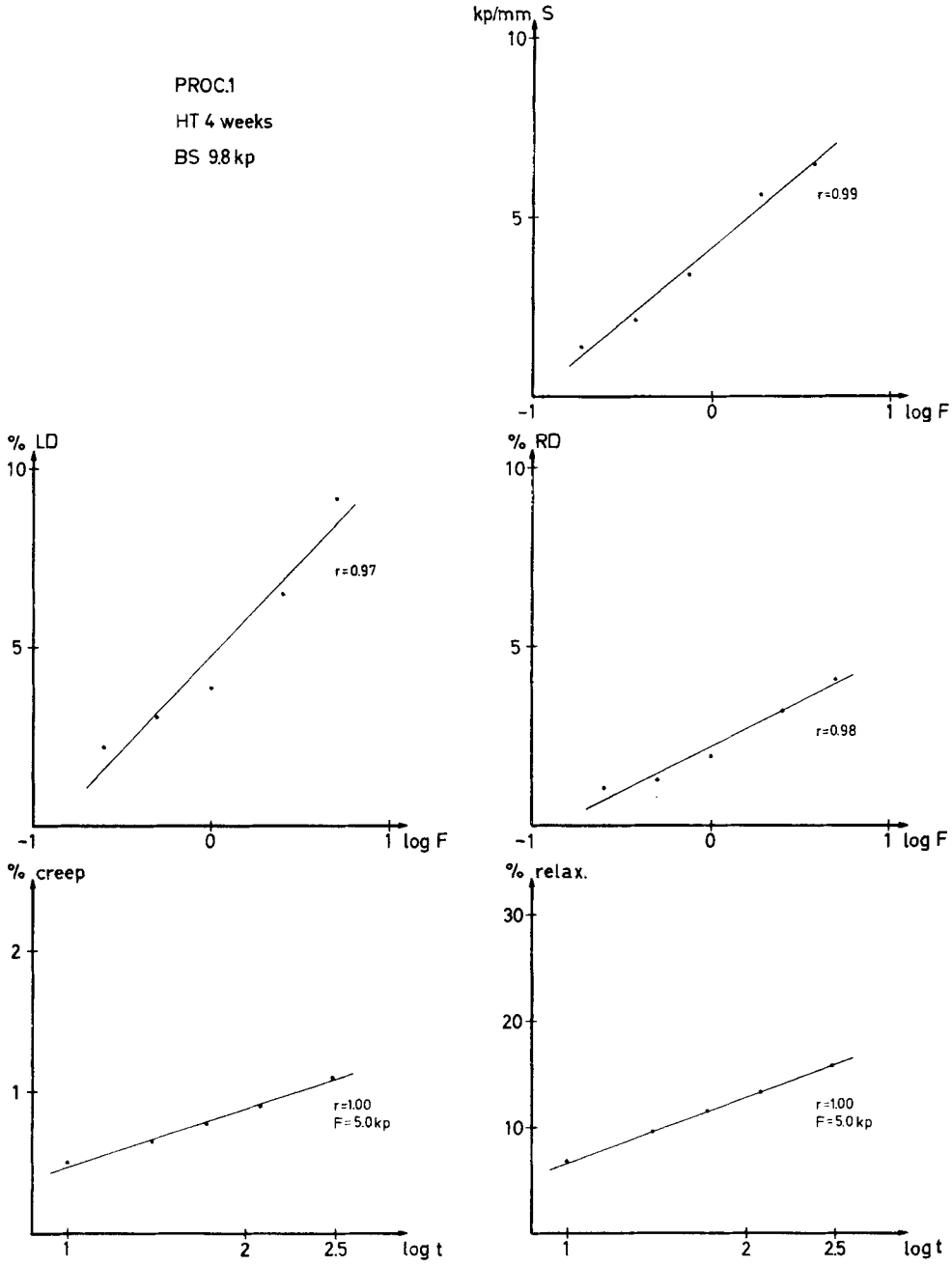

Fig 12. Regression lines for one intact specimen 4 weeks after muscle release operation (procedure nr 1). HT = healing time, BS =breaking strength, F = force in kp, t = time in sec. S = stiffness, LD = = load deformation, RD = residual deformation, relax = force-relaxation, r = coefficient of correlation.

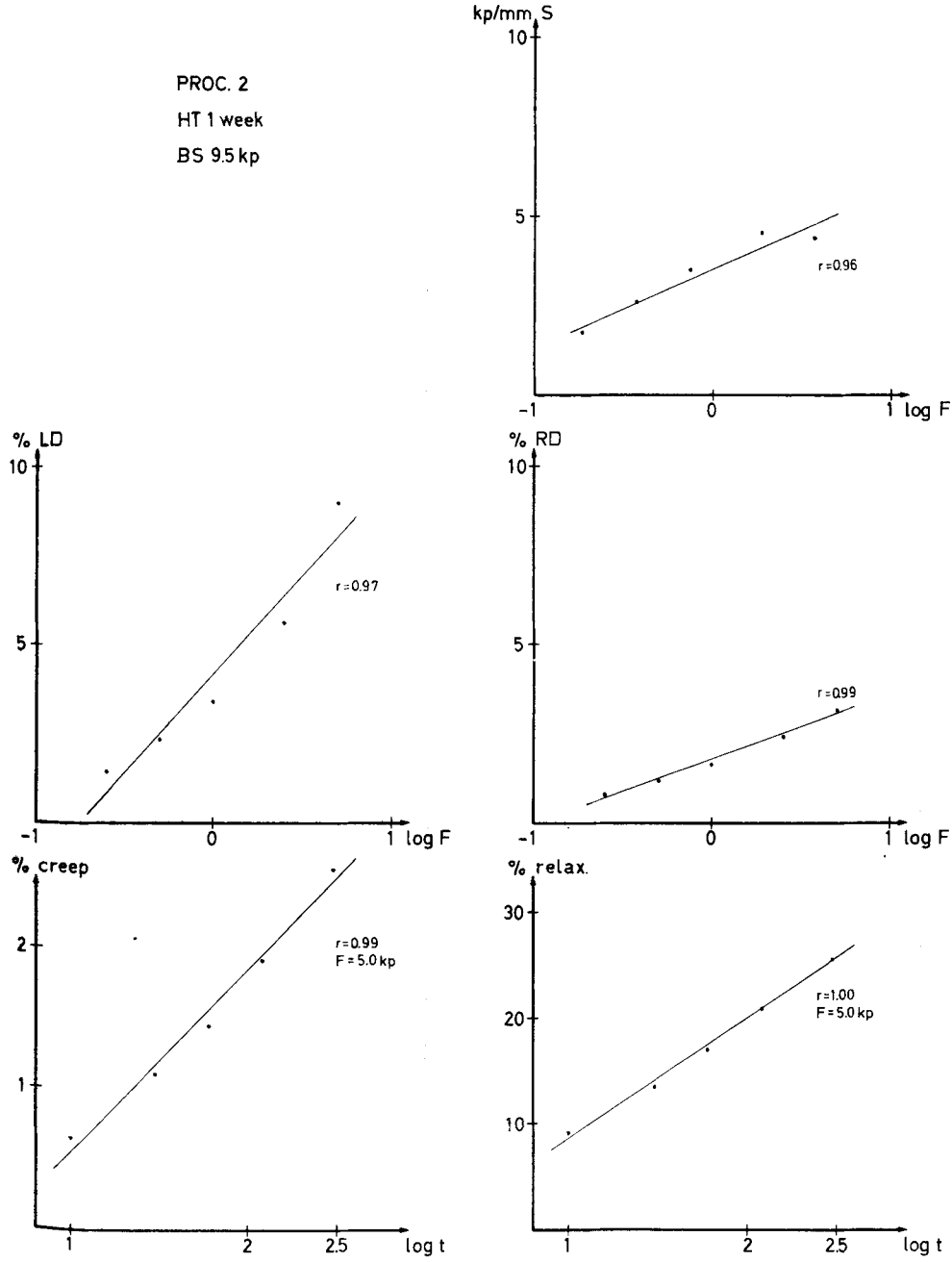

Fig 13. Regression lines for one specimen 1 week after muscle release and interrupted sutures on undivided tendon (procedure nr 2), HT = healing time, BS = breaking strength, F = force in kp, t = = time in sec, S = stiffness, LD = load deformation, RD = residual deformation, relax = force-relaxation, r = coefficient of correlation.

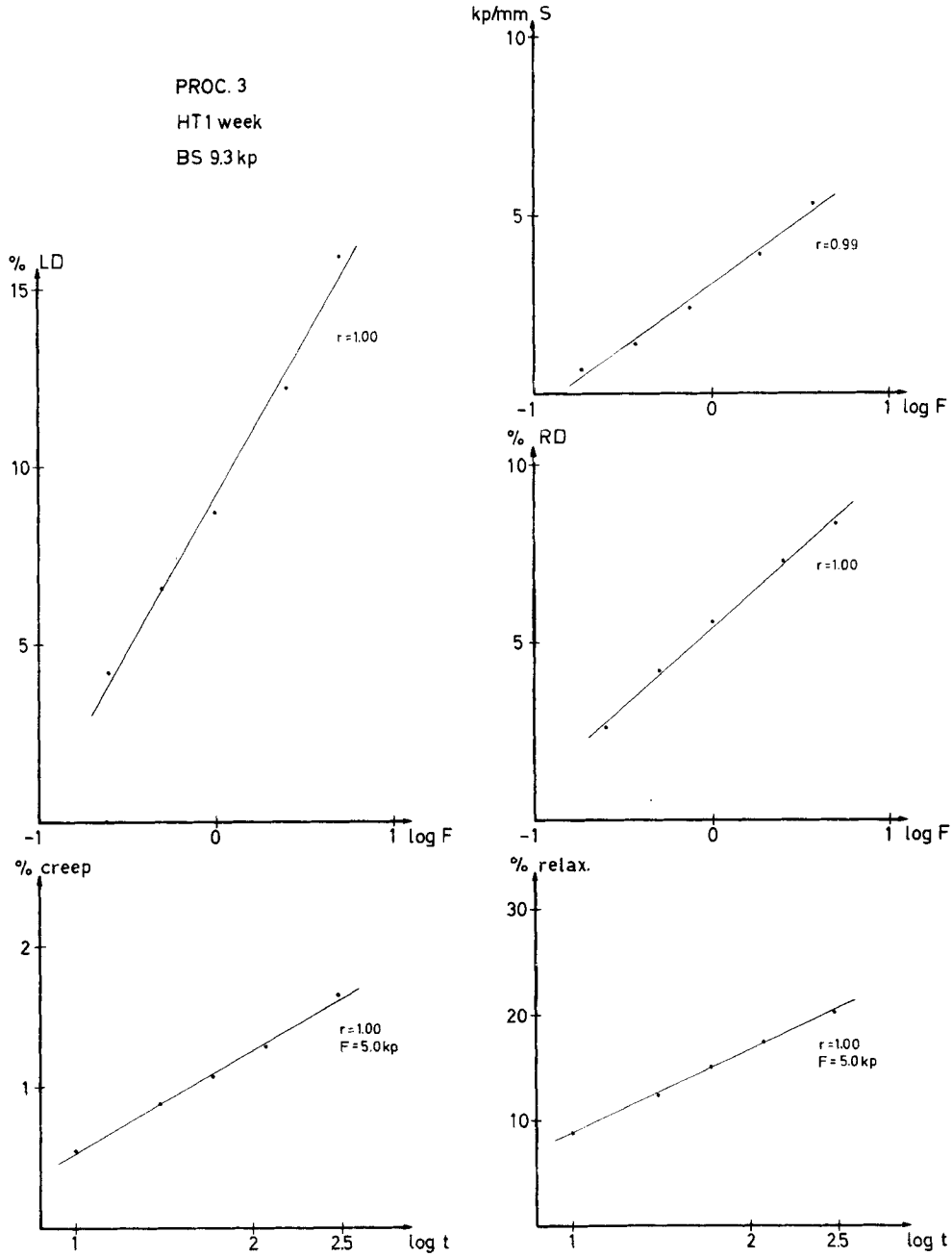

Fig 14. Regression lines for one specimen 1 week after muscle release and criss-cross suture on undivided tendon (procedure nr 3). HT = healing time, BS = breaking strength, F = force in kp, t = = time in sec, S = stiffness, LD = load deformation, RD = residual deformation, relax = force-relaxation, r = coefficient of correlation.

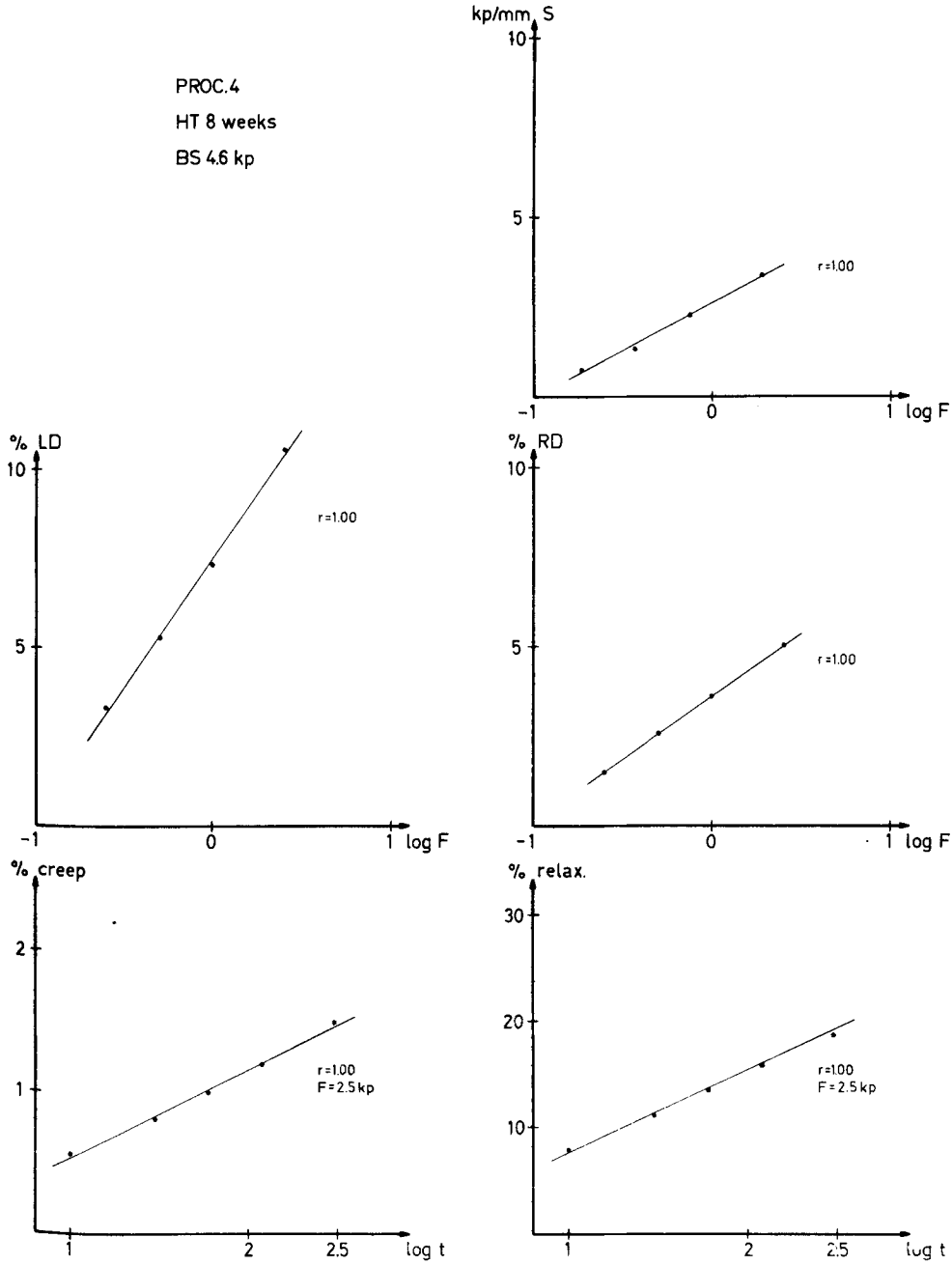

Fig 15. Regression lines for one specimen 8 weeks after muscle release and interrupted sutures on divided tendon (procedure nr 4). HT = healing time, BS = breaking strength, F = force in kp, t = = time in sec, S = stiffness, LD = load deformation, RD = residual deformation, relax = force-relaxation, r = coefficient of correlation.

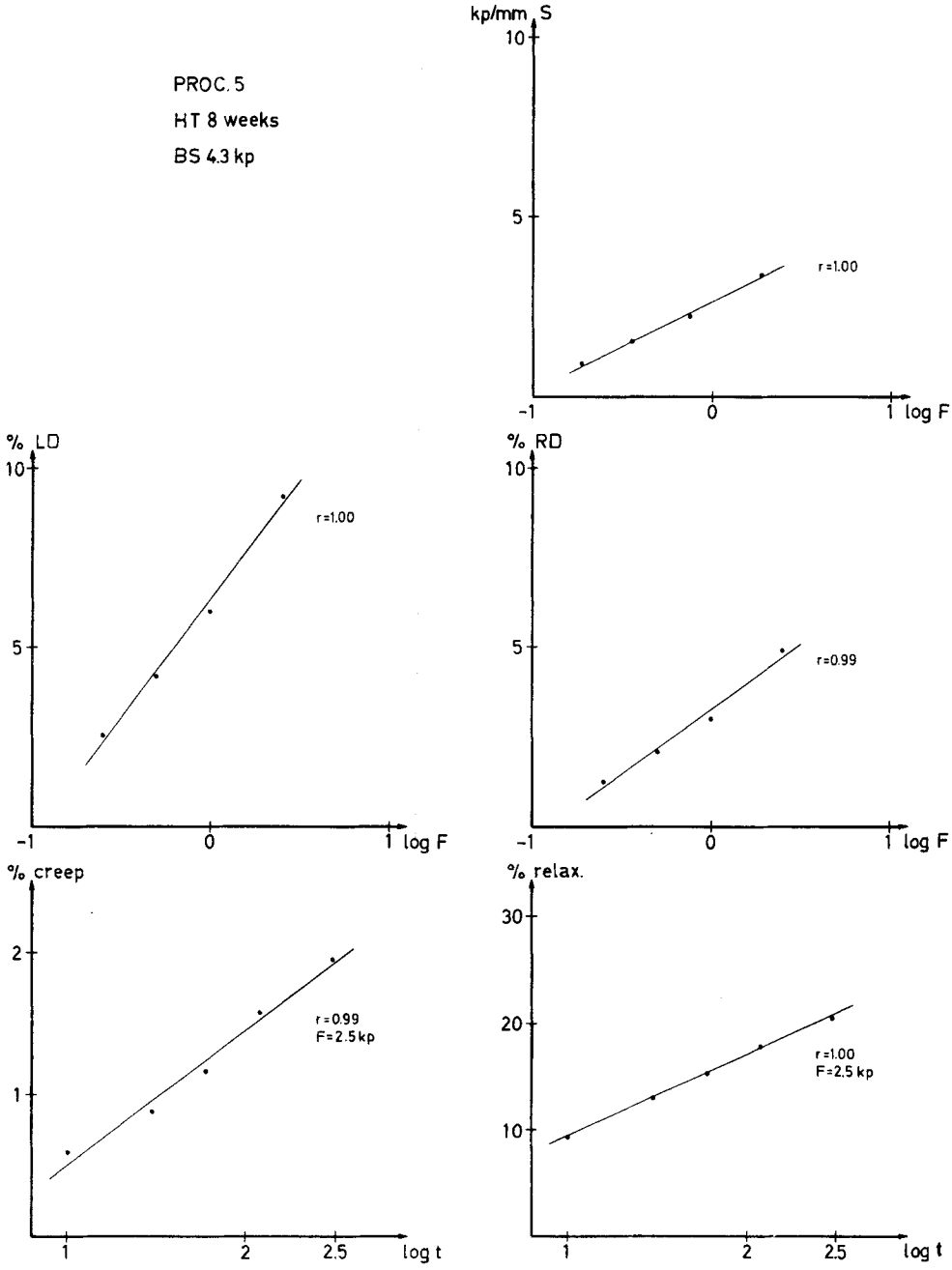

Fig 16. Regression lines for one specimen 8 weeks after muscle release and criss-cross suture on divided tendon (procedure nr 5). HT = healing time, BS = breaking strength, F = force in kp. t = = time in sec. S = stiffness, LD = load deformation, RD = residual deformation, relax = = force-relaxation, r = coefficient of correlation.

Together with the diagrams are given the statistical significance of trends observed. They are read as scoreboard tables. The scoreboards relate to trends observed with healing time for the *same surgical procedure.*

On the opposite page the same data for *another surgical procedure* are given. In between is a vertical column showing the results of statistical comparison week by week between the two procedures.

The signs used in the scoreboards and the vertical columns are:

– = statistical evaluation not possible
0 = statistical significance less than 5 % ($p>.05$)
\+ = statistical significance on the 5 % level ($p\leq.05$)
++ = statistical significance on the 1 % level ($p\leq.01$)
+++ = statistical significance on the .1 % level ($p\leq.001$)

Stiffness (S), residual deformation (RD) and load deformation (LD), figs 41–58 page 92–109

These three parameters are always illustrated on the same page in three different graphs with S at the bottom and LD at the top.

They are always plotted on the ordinate, while log load is plotted on the abscissa. In each graph the abscissa is repeated six times corresponding to six different healing times as indicated by the vertical broken lines. The healing time (HT) in weeks is given at the top in bold figures.

The mean regression line calculated for a group of specimens having had the same surgery and healing time is drawn in the appropriate diagram. The surgical procedure is indicated by the procedure number at the very top of the page.

Together with each regression line a fraction is noted, the numerator denoting the coefficient of correlation and the denominator denoting the number of observations constituting the line. (Not number of specimens; there are up till 5 observations on each specimen.)

As a visual aid the end points of the regression lines have been joined horizontally with broken lines.

Results of statistical evaluation of regression line differences with altered HT for the *same surgical procedure* are given in the scoreboard tables immediately to the right.

On the opposite side the same data for *another surgical procedure* are shown. In between is a vertical column showing results of statistical comparison week by week between the two procedures.

Each square in the scoreboard tables and the vertical columns is here diagonally divided into two triangles. In the upper left we find statistical evaluation of coefficients of regression. If the significance was not on the 1 % level or better, calculations were carried on for test of intercept (= mean value of dependent variable = $\bar{y}$), the result of which appears in the lower right triangle. The signs in the triangles are the same as listed above for breaking strength.

Creeps, figs 59–76 page 110–127

The change in creep with healing time for one surgical procedure was studied for each of the tested load levels. The results are illustrated on one page. The creep is always on the ordinate, while log time (t) is on the abscissa. The ordinate is repeated 5 times corresponding to the load levels. The load level is noted at the extreme right just above the abscissa.

The abscissa is repeated six times as shown by the vertical broken lines and corresponding to different healing time (HT) in weeks noted at the top in bold figures.

The mean regression line for specimens having had the same surgery and HT is drawn in the appropriate diagram. In a few instances the entire line could not be contained within the diagram. In those cases the end point value of the ordinate is given within brackets.

Together with the line a fraction is noted, the numerator denoting the coefficient of correlation and the denominator denoting the number of observations constituting the line. (Not number of specimens; there are usually 5 observations for each specimen.)

At the top we find one scoreboard table for each healing time, giving the results of statistical evaluation for trends observed comparing regression lines *with increasing load levels for the same HT.*

Immediately to the right are the scoreboard tables giving results of statistical evaluation comparing regression lines *at the same load level with increasing healing time.*

The same data for *another surgical procedure* are given on the opposite side. In between is the vertical column giving results of statistical evaluation at each load level week by week comparing the two procedures.

The type of surgery performed is shown by the procedure number at the very top of the page.

Force-relaxation, figs 77–94 page 128–145

The force-relaxation diagrams are constructed in the same way as the creep diagrams, the only difference being a change of parameter on the ordinate. Scoreboards and vertical columns are not altered.

In the scoreboards statistical evaluations comparing extremes of HT or load levels are given if the trend is only rising or falling. If the trend shows an inflexion point, statistical evaluation is carried out also comparing extremes and that inflexion point. It is not necessary to perform calculations between all possible values of HT or load level to secure statistical significance of a trend.

For reasons that will be discussed later statistical comparison between different surgical procedures was only done at equal HT.

Since each surgical procedure had to be compared with several others, graphic presentation of results for each procedure appears several times in different combinations.

Tensile properties during healing

The object of this investigation was to study alterations of tensile properties along the healing time axis as a result of surgery. Only statistically significant differences are commented upon in the following unless otherwise stated.

No surgery (procedure nr 0)

60 specimens. Healing time distribution is given in fig 23 page 82.

In connexion with the tendons not operated upon, the term healing time refers to the surgical procedure performed on the contralateral leg.

The breaking strength (BS) increased significantly (fig 23 page 82).

The stiffness (S) for low loads was unaltered. Its rate of change with load was quickened with increased HT, leading to higher values of S for bigger loads after HT 24 weeks as compared to HT 0 weeks. Maximum change approximately 1.5 kp/mm (fig 41 page 92).

Load deformation (LD) increased around 1 % the first week and then remained almost constant. The rate of change with load was unaltered. The same was true for residual deformation (RD) (fig 41 page 92).

The amount of creep was dependent upon load level. The lowest value vas encountered with a load of .50 kp. Increased loads added a maximum of 2 % to the creep. Also the rate of change quickened (fig 59 page 110).

The pattern was repeated in all experimental groups, the differences being gradually more pronounced from procedure nr 2 to procedure nr 5 (fig 62, 64, 66 and 68 in the appendix).

For *constant loads* there was a creep increase of less than .5 % during the first weeks of healing. After 24 weeks it had returned to original values, or in the case of high loads, below original values (fig 59 page 110).

The force-relaxation was also dependent upon load level. With increasing load it diminished, the difference between .25 and 5.00 kp being 6–10 % (fig 77 page 128).

For *constant loads* it was increased during the first week or weeks and then returned to or below original values. For high loads it was decreased up till 10 % after 24 weeks (fig 77 page 128).

In summary: Time and/or surgery on the contralateral side altered tensile properties of intact tendons. Breaking strength and stiffness increased in the long run. Load- and residual deformation temporarily increased but eventually diminished. The same was true for creep and force-relaxation.

Muscle release (procedure nr 1)

50 specimens. Healing time distribution is given in fig 24 page 83.

The same trends as described above for intact tendons (procedure nr 0) were found in this experimental group.

Comparison of procedures nr 0 and 1

For all parameters studied changes occured with increasing healing time even for tendons not surgically treated. Therefore they should be compared with the muscle release group after equal healing time. To reduce the effect of inevitable biological differences, the animals who had muscle release on one side and intact tendons on the other side were selected for the comparison. This is designated as the groups being matched.

The vertical columns in figs 23–24, 41–42, 59–60, 77–78 in the appendix give the statistical differences between the two groups. There were no differences for breaking strength and stiffness. Up till 2 weeks postoperatively there was a small reduction in load deformation and residual deformation in the released group. Also there was a reduction in creep after short healing times, but a small increase after 24 weeks. The force-relaxation showed no changes.

In summary: Muscle release on intact tendons led to the same changes as described for intact tendons without release.

Control specimens (procedure nr 0+1)

154 specimens. Healing time distribution is given in fig 25 page 84.

The influence of release of 2/3 of the origin of the peroneus brevis muscle on the tensile properties of the pernoeus brevis tendon here studied was considered negligible. The two groups were therefore combined into one. The new group was called procedure nr 0+1 and consisted of 51 released and 103 not released otherwise intact tendon specimens. The group included not only the specimens accounted for on page 49 but also specimens where the tendon on the opposite leg was rejected or where surgical procedures other than muscle release were performed. This explains why the number of specimens in the new group is not the sum of specimens in groups 0 and 1.

The new group is hereafter used as a control against other surgical procedures. Comparisons are always made at *equal healing time.*

Muscle release and interrupted sutures on undivided tendons (procedure nr 2)

25 specimens. Healing time distribution is given in fig 26 page 85.

Breaking strength (BS) changed considerably with HT, but the differences were not statistically significant (fig 26 page 85).

Stiffness (S) initially decreased both in absolute value (approximately 1 kp/mm) and in rate of change with load. After the second week it was constant (fig 44 page 95).

Load deformation (LD) and residual deformation (RD) decreased about 2 % (fig 44 page 95).

With the exception of the .25 kp load level, creep increased during the first two weeks of healing. For loads up till 1.00 kp it then returned to original values or below. For higher loads it remained elevated. The changes never exceeded 1 %, except for 5.00 kp where it reached 2 % (fig 62 page 113).

The force-relaxation showed a decrease (less than 5 %) with increasing loads for constant HT (as observed for procedures nr 0 and 1). For constant loads it increased during the first weeks of healing. Eventually it did return to original values or in some cases remained higher (fig 80 page 131).

Comparison of procedures nr 0+1 and 2

Breaking strength was not significantly altered (fig 25–26 page 85–86).

The stiffness showed no differences at HT 0. Later on the controls had higher stiffness values (1 kp/mm after 8 weeks) and also the rate of change with load was quicker among the controls (fig 43–44 page 94–95).

Load deformation and residual deformation were increased 2–3 % in the sutured group after 0 weeks. The difference disappeared after 8 weeks (fig 43–44 page 94–95).

The controls had less creep. Differences for low loads were best seen after short HT, while differences for high loads persisted after 8 weeks, being numerically largest, 1.5 %, after 4 weeks with 5.00 kp (fig 61–62 page 112–113).

Force-relaxation was 1–6 % lower among the controls. Differences were not significant after short periods of healing and high load levels (fig 79–80 page 130–131).

In summary: Placing interrupted silk sutures in an undivided tendon caused no significant change in its breaking strength as compared with intact tendons. Its stiffness was diminished, its load deformation and residual deformation temporarily increased. Creep and force-relaxation were permanently elevated.

Muscle release and criss-cross suture on undivided tendons (procedure nr 3)

34 specimens. Healing time distribution is given in fig 28 page 85.

Breaking strength diminished from the 2nd to the 8th week. After 24 weeks there was no statistically distinguishable difference from 0 weeks (fig 28 page 85).

Stiffness steadily increased for low loads. Its rate of change with load was markedly decreased from 2 till 8 weeks and returned to original values after 24 weeks (fig 46 page 97).

Load deformation showed a gradual decrease, as did its rate of change with load. Residual deformation behaved in the same way. The overall reduction from 0 to 24 weeks was around 3 % (fig 46 page 97).

The creep pattern was somewhat irregular. For small loads there was a continuous fall amounting to 1 %. For loads in the vicinity of breaking strength there was a marked increase (up till 3 % or more) between 2 and 8 weeks and a return to original values after 24 weeks (fig 64 page 115).

Force-relaxation very substantially decreased with increasing loads, from 40 % to just over 20 %. For small constant loads it fell from 0 to 24 weeks with a maximum for .25 kp. For loads close to breaking strength there was a rise of 5–10 % between the 2nd and the 8th week and a return to original values after 24 weeks (fig 82 page 113).

Comparison of procedures nr 0+1 and 3

There was a significant reduction in breaking strength for sutured tendons from the 2nd week. It was still reduced after 24 weeks (fig 27–28 page 84–85).

Stiffness showed a significant reduction for fresh specimens with sutures and the rate of change with load was different from the 2nd week (fig 45–46 page 96–97).

Load and residual deformation were accentuated for sutured tendons up till 8 weeks postoperatively. Maximum difference, 10 %, at HT 0. The rate of change with load was altered during the same period of time (fig 45–46 page 96–97).

The creep was doubled or tripled for sutured tendons, except after 24 weeks and for small loads, when it had returned to original values. It also had a faster rate of change with time (fig 63–64 page 114–115).

Force-relaxation was larger in the sutured group and with a faster rate of change. The rate of change was back to original values after 24 weeks, but the total amount of force-relaxation was still above that of controls. Differences were largest for small loads and short HT and high loads and long HT (fig 81–82 page 132–133).

Comparison of procedures nr 2 and 3

Breaking strength was reduced for procedure nr 3 for all HT except for 1 week (fig 33–34 page 88–89).

Stiffness was lower for procedure nr 3, especially for fresh specimens and after 8 weeks (fig 51–52 page 102–103).

Load and residual deformation were more pronounced for procedure nr 3, 5–7 % difference at HT 0, declining to 1 % after 8 weeks (fig 51–52 page 102–103).

Creep was doubled for procedure nr 3 and the rate of change with time quickened (fig 69–70 page 120–121).

Force-relaxation was larger for procedure nr 3 up till 4 weeks postoperatively (fig 87–88 page 138–139).

In summary: The changes of tensile properties imposed upon undivided tendons with criss-cross sutures are the same as described for undivided tendons with interrupted sutures – only more pronounced and prolonged.

Muscle release and interrupted sutures on divided tendons (procedure nr 4)

56 specimens. Healing time distribution is given in fig 30 page 87.

The breaking strength was extremely low for fresh specimens, but from the 2nd week there was a rapid increase (fig 30 page 87).

On account of the low breaking strength immediately postoperatively, meaningful calculations of the other parameters were impossible and thus omitted in the diagrams for HT 0 and 1 week.

From the 2nd week stiffness steadily increased, as did its rate of change with load (fig 48 page 99).

The amount of deformation, both under load and residual, was approximately halved from HT 2 to HT 24 weeks. Its rate of change with load was the same after 2 and 24 weeks, but decreased after 4 and 8 weeks (fig 48 page 99).

For constant loads creep diminshed with increased HT both in amount and in rate of change with time. The total amount was halved after 24 weeks (fig 66 page 117).

After HT 2 weeks force-relaxation was not diminished at higher load levels, as was described for procedures nr 0–3. From the 4th week the usual pattern was reestablished (fig 84 page 135).

Along the healing time axis there was a decrease of 10–15 % (fig 84 page 135).

Comparison of procedures nr 0+1 and 4

Breaking strength was significantly reduced in procedure nr 4 for all HT (fig 29–30 page 86–87).

Stiffness was lower in procedure nr 4 and with altered rate of change with load (fig 47–48 page 98–99).

Deformations both under load and residual were increased in procedure nr 4 and also in most instances with altered rate of change with load (fig 47–48 page 98–99).

The sutured tendons revealed a more pronounced and faster creep than the controls (fig 65–66 page 116–117).

The force-relaxation was increased and faster for HT less than 8 weeks, but later on returned to the same values as for controls (fig 83–84 page 134–135).

Comparison of procedures nr 2 and 4

Breaking strength was lower for all HT in the group of divided tendons (fig 35–36 page 88–89).

Stiffness was significantly lower for procedure nr 4 (fig 53–54 page 104–105).

Both load deformation and residual deformation were substantially higher for divided tendons (fig 53–54 page 104–105).

The creep was initially doubled in procedure nr 4, but with a tendency towards equalization after HT 8 weeks and for bigger loads (fig 71–72 page 122–123).

Force-relaxation was constantly smaller in the divided group at the lowest load level. At higher load levels it was larger after HT 2 weeks, equalized after 4 weeks and smaller after 8 weeks (fig 89–90 page 140–141).

In summary: Dividing and suturing a tendon with interrupted sutures led to a profound and persistent reduction in breaking strength and stiffness and a marked increase of load- and residual deformation. Creep was elevated. Force-relaxation was temporarily elevated.

Muscle release and criss-cross suture on divided tendons (procedure nr 5)

69 specimens. Healing time distribution is given in fig 32 page 87.

The breaking strength showed a significant and steady rise (fig 32 page 87).

Other parameters were not calculated for HT 0 and 1 week owing to the low breaking strength.

The stiffness gradually increased both in numerical values and in rate of change with load (fig 50 page 101).

Load and residual deformation decreased 3–4 % with HT. Their rate of change with load was slowed down (fig 50 page 101).

Velocity and amount of creep were reduced after longer HT, .5 % for low loads, 1.5 % for high ones (fig 68 page 119).

Force-relaxation decreased with increasing loads for constant HT. For constant loads there was a continuous fall (up to 20 %) with increasing HT. For lower loads the velocity was slowed down after successively longer periods of healing (fig 86 page 131).

Comparison of procedures nr 0+1 and 5

Procedure nr 5 had lower breaking strength (fig 31–32 page 86–87).

Stiffness was markedly diminished in the sutured group, and so was its rate of change with load (fig 49–50 page 100–101).

Both load- and residual deformation were increased (5 % for high loads) in the sutured group together with the rate of change with load (fig 49–50 page 100–101).

Creep was 3–4 times that of controls after HT 2 weeks and doubled after 8 weeks (fig 67–68 page 118–119).

Force-relaxation was larger after short HT but had returned to normal after 24 weeks at load levels .50 and 1.00 kp, was below normal for .25 kp and still above normal for 2.50 kp (fig 85–86 page 136–137).

Comparison of procedures nr 3 and 5

Lowered breaking strength for divided tendons up till 4 weeks postoperatively but from there on no significant difference (fig 37–38 page 90–91).

Stiffness decreased among the divided tendons, but had the same rate of change with load as the undivided specimens (fig 55–56 page 106–107).

Deformation both under load and residual was larger and with a higher rate of change with load for divided tendons after HT 2 and 4 weeks (fig 55–56 page 106–107).

Creep was more marked in the divided group, at load levels .25–1.00 kp roughly doubled (fig 73–74 page 124–125).

Similiar to the findings when comparing procedures nr 2 and 4 (page 53), force-relaxation was diminished in the divided group for all HT except 2 weeks and loads of .50 or 1.00 kp (fig 91–92 page 142–143).

Comparison of procedures nr 4 and 5

In general the same trends were exhibited in both groups.

For statistical evaluation matched groups were used, i.e. only animals with procedure nr 4 on one side and nr 5 on the contralateral side were selected.

Breaking strength was reduced for procedure nr 4 up till HT 2 weeks. From 4 weeks and onwards there was no statistical difference (fig 39–40 page 90–91).

The only difference in stiffness appeared after 8 weeks when criss-cross sutured tendons had lower values (fig 57–58 page 108–109).

For load deformation also a difference appeared only after 8 weeks, interrupted sutures having less deformation (fig 57–58 page 108–109).

Residual deformation showed no difference (fig 57–58 page 108–109).

Creep was larger in the criss-cross group after 8 weeks (fig 75–76 page 126–127).

Force-relaxation was larger in the criss-cross group after HT 2 and 4 weeks (fig 93–94 page 144–145).

In summary: Criss-cross sutures on divided tendons produced in general the same changes in tensile properties as interrupted sutures on divided tendons.

MAXIMUM ISOMETRIC TENSION IN THE SHORT PERONEAL MUSCLE OF THE RABBIT

It is of considerable interest with regard to tensile properties of tendons to have at least an estimation of the maximum force that any particular muscle can transfer to its tendon. It was therefore attempted to find the maximum isometric tension of the peroneus brevis muscle in the rabbit.

Material

Four rabbits were used in these tests. Big rabbits were purposely chosen – body weight 3.4, 3.9, 4.7 and 3.3 kg respectively. The reason was that big rabbits could be expected to have stronger muscles than small rabbits and the measured maximum muscle force would then be as high as could be expected for any other rabbit in the experimental series (Barfred 1971).

On one side the rabbit were subjected to a release of the peroneus brevis muscle as described on page 19, on the other side no surgery was performed. Healing time was 4 weeks in all 4 cases.

Methods

The rabbits to be tested were anaesthetised with barbiturates as described for surgery on page 18. Through a lateral incision in the thigh the peróneal nerve was isolated. Another incision was made from the lateral malleolus and down to the base of the 5th metatarsal, where the peroneus brevis tendon inserts.The tendon was here divided. The part of the tendon distal to the lateral malleolus was fitted in the same clamps as used for mechanical testing. The load cell was removed from the Alwetron and placed on the operating table with the clamp connected to it. The clamp and the load cell were secured to the table. Angulation of the tendon round the lateral malleolus was avoided by adjusting the position of the rabbit. The rabbit's leg was secured to the table with the aid of two small Rissler pins (figs 2 and 17 page 23 and 57).

During the whole period of fitting the tendon into the clamp, adjustment of the rabbit's position, and the actual testing, great care was taken to keep both the peroneal nerve and the peroneal tendon moistened with Ringer's solution.

The peroneal nerve was stimulated with square DC pulses. The anode was always proximal on the nerve. Several tests were performed to find the optimal frequency, duration and voltage of the pulses. In these pilot tests maximum force was registered with a pulse frequency of 100 Hz, pulse duration of .3 millisec and a pulse voltage of 2 volts.

(The apparatus used for producing square DC pulses was manufactured by the Grass Instrument Company, model S4C.)

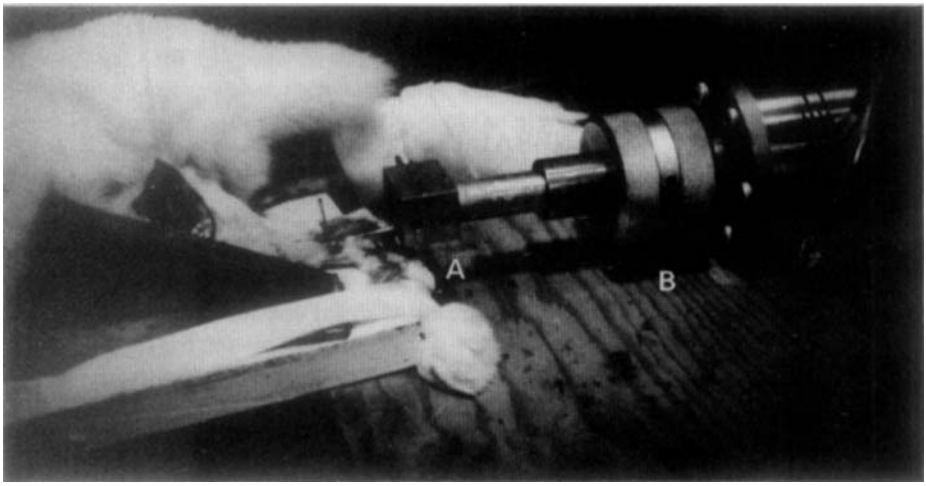

Fig 17. Measurement of maximum istometric tension in the short peroneal muscle. The peroneal nerve is isolated and stimulated in the proximal incision. The short peroneal tendon is divided at its insertion and connected to the clamp (A) and the load cell (B). The leg is fixed to the table with Rissler pins.

It was found necessary to apply a preload of .1 kp to the tendon and muscle to get maximum force response on stimulation.

Results

Maximum force registered for the untreated side was 3.0 kp, 3.0 kp, 2.6 kp and 1.8 kp respectively.

On the released side corresponding values were 1.9 kp, 1.9 kp, 1.6 kp and 1.3 kp.

The reduction in maximum isometric tension after muscle release was approximately 30 % after 4 weeks of healing as compared to the untreated muscle.

The mean breaking strength of unharmed tendons (fig 23 page 82) is roughly 3 times the available muscle force.

The maximum load (5.00 kp) used for testing tensile properties of peroneus brevis tendons was probably above physiological levels.

Discussion

The type of stimulation used agrees in principle with those used in other studies of maximum muscle power (Elliott 1967, Barfred 1971). Elliott 1967 measured muscle power of unipennate muscles in the rabbit such as peroneus brevis and arrived at 3 kp. In several studies it has been concluded that the safety margin to tendon rupture is 3–4 times the available muscle force (Stucke 1950, Rigby et al. 1959, Harkness 1961, LaBan 1962, Walker 1964, Abrahams 1967, Elliott 1967).

GENERAL DISCUSSION

Experimental model

Several authors have described tensile properties of both intact and sutured tendons. The tendons used, test methods employed and measurements taken have varied widely. Consequently numerical values presented differ considerably and are in most instances not comparable.

Evaluation of tensile properties of sutured tendons necessitates a directly comparable control group, viz. intact tendons (procedure nr 0). When it was discovered that tendon sutures on the peroneus brevis tendon in the rabbit needed relaxation by muscle release, the influence of such an operation on tensile properties had to be assessed (procedure nr 1).

It was impossible to remove the sutures from the tendons before testing without disturbing the scar between the stumps, especially after short healing time. Furthermore in clinical praxis they are often left in place. The influence of the direct surgical trauma on the tendon, including the effect of leaving sutures in an otherwise intact tendon, was considered of interest. Therefore specimens with muscle release and sutures on undivided tendons (procedures nr 2 and 3) were included in the investigation. Large differences from controls were not expected, which is why the contralateral side of those animals was left intact, instead of matching procedures nr 2 and 3 against each other. The assumption turned out to be erroneous, at least for criss-cross sutures on undivided tendons (procedure nr 3) (page 52).

Methodological considerations

Suture techniques

The choice of suture technique was dictated by the author's wish to use those which in the unhealed state were mechanically most and least sufficient. The investigations of tensile strength of fresh tendon sutures reported in the literature agree that a plaited suture gives a higher tensile strength than a nonplaited one (Malewitsch 1908, Kimura 1912, Flückiger 1952, Cowan & Courtemanche 1959, Schink & Gersbach 1961, Shaw 1968). In two investigations where the criss-cross suture was compared to other suture techniques it was one of the two with the highest tensile strength (Cowan & Courtemanche 1959, Schink & Gersbach 1961). Schink & Gersbach 1961 also found interrupted sutures to be by far the weakest.

Mechanical testing

The load levels employed were arbitrarily chosen, because there was no way of anticipating the breaking strength of a particular specimen. Tests of maximum

isometric tetanic contraction power of the peroneus brevis muscle in the rabbit showed that 5.00 kp probably was beyond physiological limits (page 57).

The first load cycle at each load level, including the creep test, was performed to obtain a measurement of the greater part of the plastic, i.e. irrecoverable, deformation. The second load cycle could then be used for estimating the viscoelastic properties, since most of the plastic deformation had already been "taken out" of the specimen (fig 7 page 28).

The duration of creep and force-relaxation tests was limited to 5 min for obvious practical reasons. In theory one has to observe a specimen for an infinite period of time to arrive at the correct value for these parameters (the curve is exponential, figs 8 and 9 page 29). Tests revealed that the creep and force-relaxation taking place after 5 minutes had passed, was almost too small to be measurable with the available recording setup.

Strain rate influences mechanical behaviour of soft collagenous tissues (page 11). A constant rate was employed in all tests, 25 %/min = 5.0 mm/min. It was chosen merely for practical reasons. The X-Y-recorders have rather high moments of inertia. When too high strain rates are applied defects in the registrations will appear.

The strain rate chosen is low compared to most physiological situations, but may be comparable to, for instance, walking.

Measured variables

The function of a tendon is to convey muscle forces to an advantageous point of action. The muscle can produce both isometric and isotonic contractions. It has a limited range of contraction. It contracts several hundred times a day.

These aspects of striated muscle function puts special demands on the tensile properties of tendons:

- breaking strength must exceed maximum muscle force
- deformation under load must not be too large or it cannot be compensated for by further muscular contraction, leading to loss of power or range of movement, i.e. the tendon must not exhibit too marked creep or force-relaxation phenomena.
- plastic deformation must be small or the tendon will elongate following repeated loading.

The measured variables (breaking strength, load and residual deformation, creep and force-relaxation) were considered of interest with regard to the abovementioned functional demands put upon tendons.

Cross-section area of tendon specimens was not measured due to methodological difficulties, discussed on page 32. Consequently force measurements had to be substitued for stress measurements. Breaking strength was measured in kp instead of kp/mm^2. Modulus of elasticity was replaced by stiffness. (It could furthermore be argued that modulus of elasticity is not defined for non-linear elastic materials such as tendons.)

Measuring force instead of stress and stiffness instead of modulus of elasticity does not invalidate statements as to the qualitative behaviour of *single* tendon specimens.

Cross-section areas of tendons tested were assumed to be randomly distributed in the experimental groups. Mean values of tensile parameters for experimental groups are considered to be relative and only used for statistical comparison of the effect of surgical procedures performed.

Factors affecting tensile properties in *in vitro* tests

- post-mortem decomposition of specimens
- test environment (temperature, humidity)
- preparation of test samples
- mode of testing
- accuracy of testing and recording equipment and of measurements taken from recordings
- stress-strain history of specimens prior to test
- collagen content
- geometrical arrangement of collagen fibers
- composition of ground substance

The influence of the five first listed factors is discussed on page 32.

For intact tendons interest is focused in this discussion upon qualitative rather than quantitative behaviour. For sutured tendons numerical values should be considered relative and used only for comparison of sutured and intact tendons.

With this in mind the influence of the remaining four factors listed above will be discussed in relation to the tensile properties found after different types of surgery.

Tensile properties of intact tendons

The tested load range, with the exception of 5.00 kp, is considered to fall within physiological limits (page 57). The normal working range of a tendon is believed to be within 3 % strain (Rigby et al. 1959, Elliott 1965, Abrahams 1967). For rabbit peroneus brevis tendons it means a load of approximately 1 kp. However, maximum muscle force was found to be around 3 kp (page 57) giving a load deformation (=strain) of roughly 6 % (fig 41 page 92).

For the peroneus brevis tendon in the rabbit complete relaxation does not seem to be physiological. This is demonstrated by the fact that irrespective of ankle or knee joint position sufficient relaxation during anaesthesia for performing interrupted sutures could not be obtained. The lowest possible value is not known.

Within the physiological load interval force-deformation, creep and force-relaxation curves are all exponential for single specimens. This follows from the linear regressions described on page 39 (fig 11 page 41).

The general form of the force-deformation curve for intact tendons is well known (Rollhäuser 1950, Rigby et al. 1959, Morgan 1960, Partington & Wood 1963, Rigby 1964, Abrahams 1967, Elliott 1967, Viidik 1968, Stromberg & Wiederhielm 1969, Welsh et al. 1971, Minns et al. 1973). The intermediate portion of the force-deformation curve is usually described as almost linear.

However, the complete curve is sigmoid. Some part of the curve must therefore appear approximately linear. The linearity can be accounted for if one assumes that

some fibres have started slipping while some are being increasingly stressed. There must be a region where the two mechanisms are "balanced", yielding a linear force-deformation curve.

Slipping of individual fibres is probably due to overload. Consequently, where force-deformation curves are linear, loads are above physiological limits.

This agrees with the observations in this study: The force-deformation curve is not linear for loads less than 5 kp, which is above maximum muscle force (page 57).

In graphs recorded when breaking strength was tested, part of the curve around 5 kp could be regarded as almost linear (fig 10 page 29).

An analysis of curves for loads less than 5 kp shows that stiffness, load- and residual deformation correlate very well with logarithm of applied load. Morgan 1960, and Stromberg & Wiederhielm 1969, arrived at similar results for isolated collagen fibres. Fung 1967, demonstrated a correlation between stiffness and load (not log load) for rabbit gut mesentery.

The rabbit peroneus brevis tendon is not perfectly elastic (when tested *in vitro*) even for such a small strain as 2 %, in contrast to properties described for other tendons (Rigby et al. 1959, Partington & Wood 1963, Rigby 1964, Abrahams 1967, Diamant et al. 1972, Minns et al. 1973). There is always a residual deformation, as also reported by Rollhäuser 1950, Stucke 1950 and Viidik 1968.

The safety margin for the peroneus brevis tendon before it is torn is large. Breaking strength is approximately 3 times available muscle force (page 57). It agrees with the established clinical experience, that with the exception of tendo achillis (where degenerative changes are common) true tendon ruptures of long tendons due to tensile forces are rare.

Effects of surgery on tensile properties

As is shown in figs 11–16, page 41–46 force-deformation, creep and force-relaxation curves are all exponential. This is true for both intact and sutured tendons. Surgery brings about quantitative rather than qualitative changes of tensile properties. Different types of surgery will exert a variable degree of influence depending on the adverse effects a particular procedure may have on tendon constituents, namely collagen content and its geometrical orientation, ground substance and water content. Equally important is intact blood supply.

No surgery (procedure nr 0)

Surgery on one leg brings about changes in tensile properties of tendons on the contralateral side, as demonstrated for intact tendons when muscle release or sutures on undivided tendons were perfomed on the opposite side (page 49).

Both anaesthesia and trauma are known to cause overall tissue salt and water retention. Water retention in soft collagenous tissues alters their tensile characteristics, deformations are increased and stiffness diminished (Rollhäuser 1950, Stucke 1950, Galante 1967). Exactly the same changes are found here for intact tendons 1–2 weeks postoperatively.

The changes seen a few weeks postoperatively completely disappear with time (page 49). Instead there is generally an improvement of tensile properties after 24 weeks. The mechanism responsible for the improvement cannot be definitely outlined, but changes in physical fitness, body weight and age will be considered.

Influence of physical fitness

Considerable training of rabbits or rats has been shown to lead to a decrease of stiffness and an increase of breaking strength and deformation for tendons or ligaments (Tipton et al. 1967, Viidik 1968, Barfred 1971).

It is obvious that confining an operated rabbit to a narrow cage reduces its fitness, especially so if it is fed ad libitum, thereby gaining weight.

The result, according to Viidik 1968, would be increased stiffness and decreased breaking strength and deformation. Only stiffness changed in the anticipated direction. It is thus impossible to deduce that alterations in physical fitness are responsible for the observed changes of tensile properties for intact tendons without muscle release.

Influence of body weight

Some positive correlation could be expected between body weight of an animal and cross-section area of a particular tendon from the same animal. Enlargement of cross-section area leads to increased breaking strength, higher stiffness and smaller deformations.

With the exception of the immediate postoperative period, body weights generally increased with healing time for the rabbits used. Since only adult animals were accepted in this study the reason for their weight gain was their postoperative confinement to cages and feeding them ad libitum while physical excercise was minimal.

Fig 18 (page 63) gives the regression between body weight increase and HT for rabbits with intact tendons on one side. The coefficient of correlation is .68. A linear regression of body weight at surgery versus HT for the same rabbits gives a coefficient of correlation of .08, showing that there was no selection of heavy animals for long HT (fig 19 page 63). Fig 20 (page 64) shows a graph of body weight at time of surgery for the same animals versus breaking strength for the intact tendons of the animal. Coefficient of correlation = .50.

25 % of the variations in breaking strength observed can be explained on the basis of body weight (r^2 = d = coefficient of determination).

It seems unlikely that a gain in body weight, in all likelihood due to excessive caloric intake, could lead to a change in cross-section area of a tendon. Consequently increased cross-section area is probably not responsible for altered tensile properties postoperatively for intact tendons.

It is hard to visualize any other mechanism by which increased body weight due to fat accumulation could influence tensile characteristics in the direction observed.

The same pattern of weight gain was found in the other experimental groups (table 6 page 64). Equally, changes with HT observed within these groups probably cannot be explained on the basis of body weight increase.

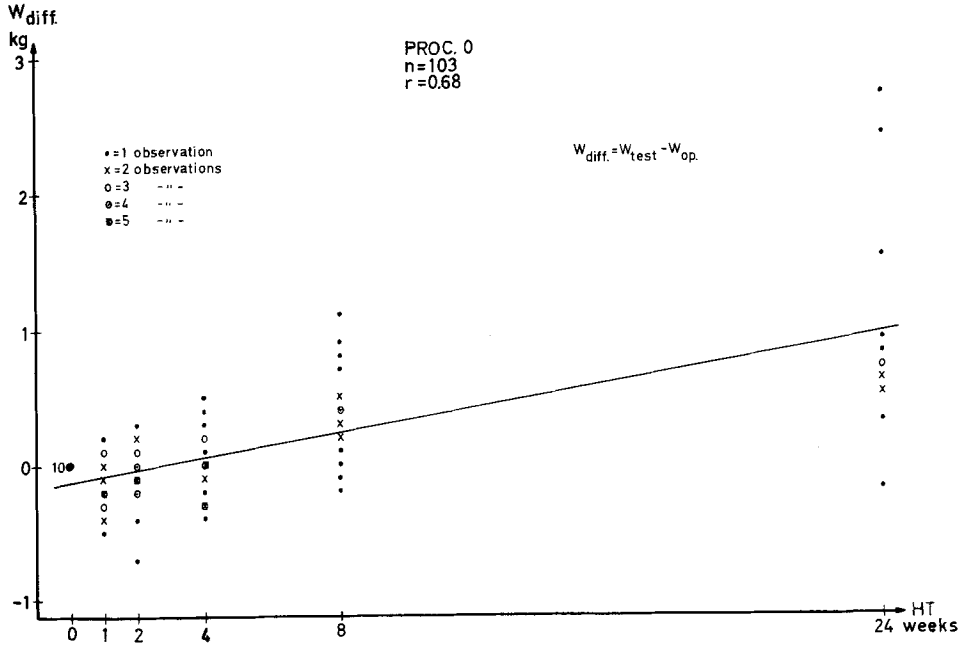

Fig 18. Body weight increase ($W_{diff}=W_{test}-W_{op}$) for rabbits with intact tendons (procedure nr 0) on one side versus healing time (HT) for tendon surgery performed on the contralateral side.
Number of specimens = n = 103
Coefficient of correlation = r = .68

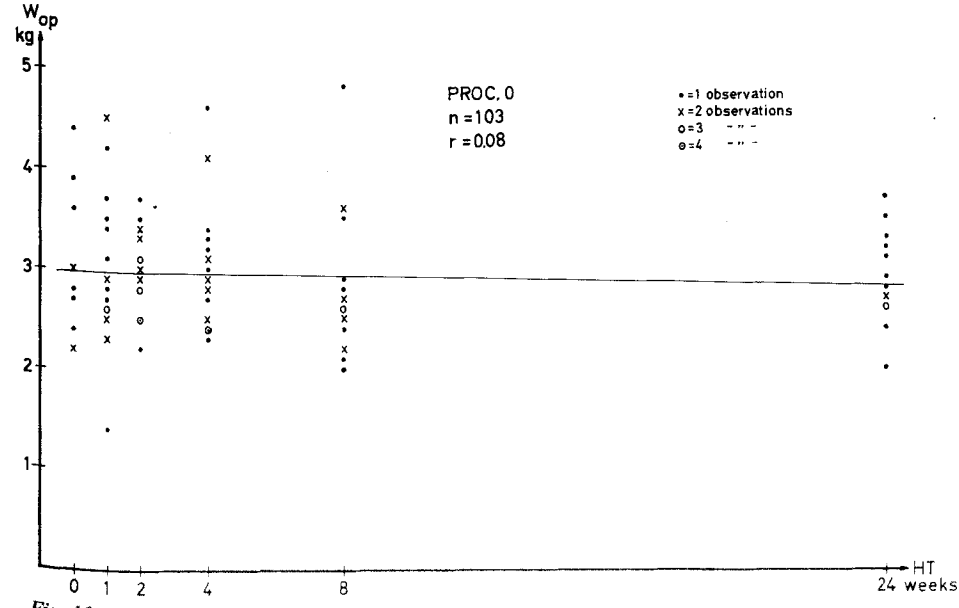

Fig. 19. Body weight (W_{op}) of rabbits with intact tendons (procedure nr 0) on one leg at time of surgery on the contralateral leg versus healing time (HT).
Number of specimens = n = 103.
Coefficient of correlation = r = .08.

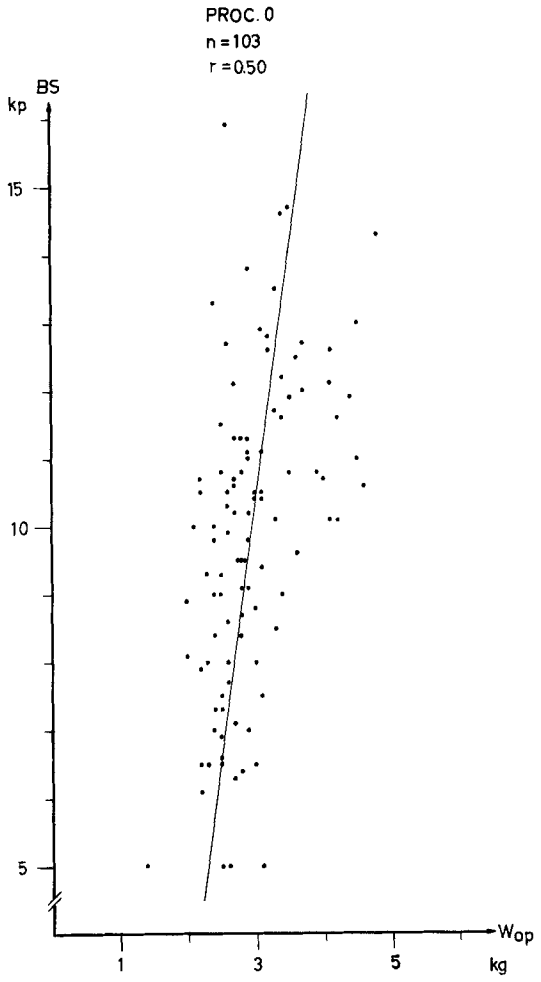

Fig 20. Breaking strength (BS) of intact tendons (procedure nr 0) versus body weight of rabbits (W_{op}) at time of surgery on the contralateral side.
Number of specimens = n = 103.
Coefficient of correlation = r = .50.

Table 6. Coefficients of correlation for linear regression of body weight increase from time of surgery to time of testing versus healing time for different procedures.

Procedure nr	Coefficient of correlation	n
0	.68	103
1	.72	51
2	.67	25
3	.59	34
4	.66	56
5	.65	69

Comparison between groups is always made at equal HT. Influence of body weight is here to a large extent eliminated since there are no statistical weight differences between groups.

Influence of age

As an animal grows older soft collagenous tissues decrease their water content and the tropocollagen particles develop more crosslinks (Ingelmark 1948, Rollhäuser 1950, Gross 1958). Waviness of fibrils observed in resting tendons is not so marked in older individuals (Diamant et al. 1972). Higher breaking strength and stiffness and diminished deformation could be expected and has been verified (Rollhäuser 1950, Stucke 1950, Anders et al. 1971, Diamant et al. 1972). Creep and force-relaxation will probably also be reduced.

Apart from load- and residual deformation, which does not decrease in the present investigation, the ageing pattern is reproduced for intact tendons (fig 23, 41, 59 and 74 in the appendix).

Only adult animals were accepted for surgery and six months may seem a short time, but it is a respectabel amount in the life of a rabbit and can therefore not be disregarded. It is possible that part of the long-time changes in tensile properties observed for intact tendons are due to ageing of the experimental animal.

The exact age of the animals at time of surgery was not known. It is assumed that the age distribution is the same in all experimental groups. Intergroup differences (always studied at equal HT) are therefore not attributable to age differences.

As has been pointed out several times, all comparisons between surgical procedures are conducted at equal healing time. This is necessary in order to eliminate influence from changes in all tendons with increasing postoperative time.

Muscle release (procedure nr 1)

Muscle release was necessary in order to obtain satisfactory tendon sutures. By and large muscle release exerted no influence on tensile properties of tendons, i.e. almost no relevant differences were found between intact tendons with and without muscle release (page 50).

The earlier history of loads and deformations is relevant for the tensile characteristics found at test (page 34). In this study the largest differences in earlier load history are probably found between intact tendons without muscle release and all other tendons, which had been subjected to muscle release. Since no differences were found between intact tendons with and without muscle release, intravital earlier load history seemingly exerts no relevant influence on tensile properties in the *in vitro* tests.

Muscle release and interrupted sutures on undivided tendons (procedure nr 2)

Proper tendon surgery can be expected to cause a local traumatic oedema. Furthermore foreign body inclusions in the tendon will cause an inflammatory reaction. The foregin bodies as well as the trauma disturb the strict geometrical arrangement of collagen fibers.

Disconnexion of the mesotenial vascular supply will lead to hypoxia and may cause some necrosis among the tenocytes.

The importance of the mesotenon for the survival of the tendon has been emphasized by several authors. According to Peacock 1959, the longitudinal vessels of the tendon can maintain the circulation for a maximum distance of 1/3 of the length of the tendon, without contribution from the mesotenial vessels in that third. Schatzker & Brånemark 1969, state that division of the vessel coming from the mesotenon completely abolishes circulation in the disconnected segment. On the other hand it has also been shown that after interruption of the mesotenial vascular supply, new vascular connexions are established within 3 days (Bergljung 1968). Even if a tendon is excised, partly wrapped up in silastic and moved to a new location in the body, it survives (Colville et al. 1969). In a cut and sutured tendon capillaries growing towards the suture line are apparent from the 3rd day (Bergljung 1968).

The local traumatic oedema and inflammatory reaction, the disturbance of the geometry of collagenous fibres and the temporary obstruction of blood flow are the probable causes of the deterioration of tensile properties observed for the undivided tendons with interrupted sutures. The deterioration is slight, compared to undivided tendons with criss-cross sutures or divided and sutured tendons. The recovery is better and faster compared to the other groups. This is probably a result of the prompt reestablishment of vascular supply in a tendon where anatomical derangements are small due to the construction of the suture.

The force-deformation characteristics of the suture material *per se* are not evident to any great extent in the tests, but rather those of the "bond" between the suture material and the tendon tissue. The breaking strength of the "bonds" is lower than that of the suture material. The total breaking strength of four 8/0 silk sutures would be at least .72 kp (page 20). Several single sutures were tested alone in the Alwetron material tester. The breaking strength always exceeded the minimum strength promised by the manufacturer. The strain for each suture carrying a load of .05 kp (4 sutures in a freshly sutured tendon with a breaking strength of .2 kp) was found to be considerably larger (fig 44 page 95). It can therefore be assumed that contributions from the suture material to the force-deformation characteristics are small compared to the contributions from the entire construction (tendon, suture and in most cases the "scar").

The discrepancy between tensile properties of stainless steel wire and tendons is obviously even more marked than between silk and tendons.

Muscle release and criss-cross sutures on undivided tendons (procedure nr 3)

The deterioration of tensile characteristics is more pronounced for undivided tendons with criss-cross sutures as compared to those with interrupted sutures (page 52). Differences are most marked for fresh specimens with the exception of breaking strength and stiffness. The latter two show maximum discrepancy 8 weeks postoperatively, whereas the other 4 parameters are approaching the values found for procedure nr 2 as time passes.

Applying and tightening a criss-cross suture crumples the tendon (fig 21 page 68). When the tendon is stressed the crumpling gradually disappears because the "bond" between the suture material and tendon tissue gives way. Two mechanisms are involved:

- a rearrangement of the configuration of the suture loops
- suture wire cutting through some collagenous fibres making further rearrangement possible

The former mechanism does not require much force since it only means slipping of the suture wire between individual tendon fibres. This is the same mechanism responsible for deformations in the case of divided tendons with interrupted sutures (procedure nr 4). The breaking strength of fresh procedure nr 4-specimens is extremely low (fig 30 page 87).

Considerably more force is needed for the cutting-through process, as proved by the higher breaking strength for divided and criss-cross sutured tendons (procedure nr 5, fig 32 page 87).

The straightening of a crumpled tendon is thus to a large extent achieved already with loads beneath .25 kp. The increase of load deformation, residual deformation (the crumpling is irrecoverable), creep and force-relaxation, together with the decrease of stiffness observed for fresh procedure nr 3-specimens could be explained as the straightening of an initially crumpled tendon.

As healing proceeds, crumpling is reduced due to muscle pull, because the muscle release is healing and the available muscle force therefore increasing (fig 22 page 68). Consequently, during the later stages of healing large deformations for small loads are more or less absent diminishing the differences between procedures nr 2 and 3.

The reduction in breaking strength for fresh procedure nr 3-specimens is moderate, indicating that only a few tendon fibres are cut through by the wire when small loads are applied.

The further reduction in breaking strength observed up to 8 weeks postoperatively cannot be accounted for by the straightening of a crumpled tendon. Neither can it be accounted for by the cutting-through mechanism unless one assumes that the fibres are now offering less resistance against the cutting wire. The reduction in breaking strength indicates a change in the tendon tissue *per se* postoperatively. This assumption is corroborated by the fact that stiffness also shows minimum values 8 weeks postoperatively (stiffness is measured from the 2nd load cycle, fig 7 page 28, and therefore not influenced to the same degree by the disappearence of crumpling as are deformations). The assumption is also confirmed by the fact that the same pattern is not displayed for undivided tendons with interrupted sutures.

The changes in the tendon material could be due to the strangulating effect on internal vascular supply caused by the criss-cross suture, as shown by Bergljung 1968. On account of the low metabolic turnover in tendons (page 9) the effect of inadequate blood supply will be fully developed only after a substantial period of time.

Regeneration has to be mediated through fibroblasts outside the tendon (page 12). With small defects in the epitenon of an undivided tendon with sutures, the possibility for ingrowth of cells is small (page 15), leading to a slow recovery of tensile properties.

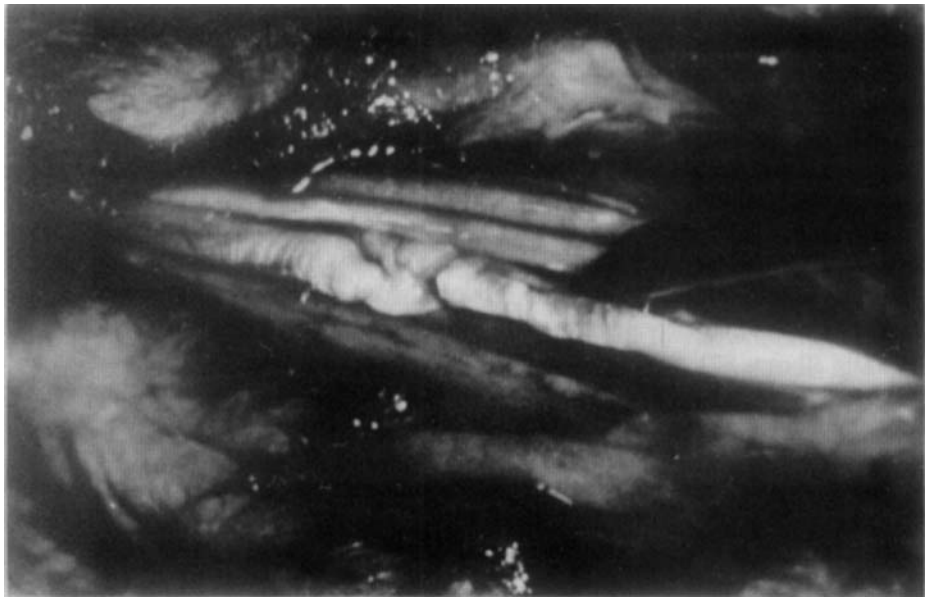

Fig 21. Divided tendon immediately after tightening of a criss-cross suture. Magnification 6x.

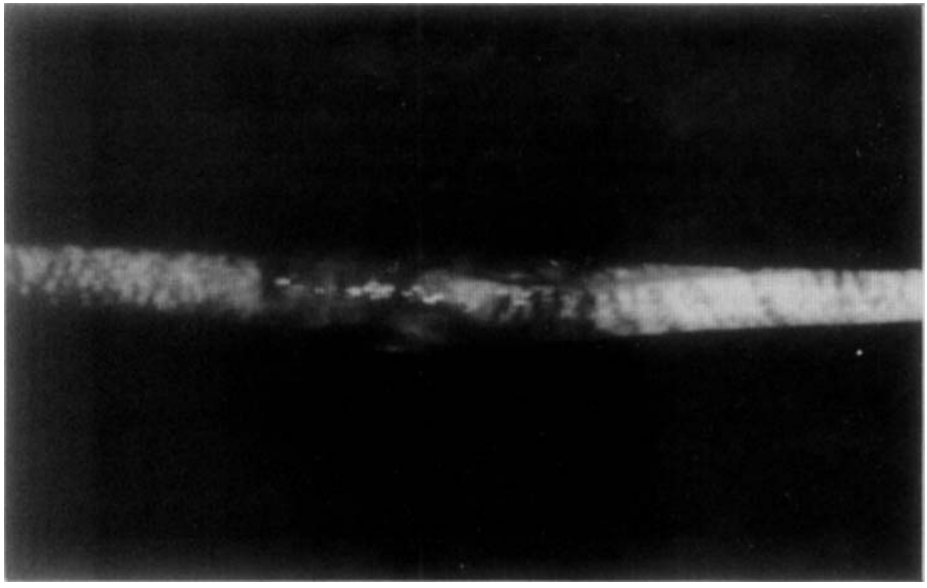

Fig 22. Divided and criss-cross sutured tendon 4 weeks postoperatively. Magnification 6x.

Muscle release and sutures on divided tendons (procedures nr 4 and 5)

When a tendon is divided and sutured the anatomical derangements have an overwhelming deteriorating impact on tensile properties. Large areas are not covered with protective epitenon making a fast and rich ingrowth of fibroblasts and capillaries from the surrounding tissues possible. The cell conglomerate has very low breaking strength and the stability of the suture line is almost entirely dependent upon the sutures. In this respect criss-cross sutures are superior as compared to interrupted sutures.

When breaking strength becomes substantially elevated as compared to plain suture strength at HT 0, which occurs earlier with interrupted sutures than with criss-cross sutures, it is due to collagen production. Production starts around the 4th day (Peacock 1962, Viljanto 1964), shows a peak somewhere between 3 and 4 weeks postoperatively and has a 3–4-fold increase over normal production even after 3 months (Peacock 1962, Birdsell et al. 1966). Tensile strength of granulation tissue is correlated to collagen content within the first 60 days of "healing" (Viljanto 1964, Bryant & Weeks 1967, Vogel 1970). Histologically the newly formed collagen fibres are often randomly oriented in the beginning. Fibre orientation in response to stress is a slow process, possibly not starting before the 3rd week (page 14). Normal structural arrangement may not be attained even after 1 year (Buck 1953, Lipscomb & Wakim 1961, Peach et al. 1961). In response to this slow process of orientation tensile properties gradually improve in spite of constant collagen content (Peacock 1962 and 1965), but are still far below normal tendon standards after 24 weeks of healing.

When comparing divided tendons with interrupted and criss-cross sutures considerable differences in breaking strength are found during the first 2 weeks of healing. From the 4th week breaking strength is equal (fig 39–40 page 90–91).

For criss-cross sutures deformations decrease. The effect of crumpling discussed earlier (page 67) is important only during early healing, later on it will largely disappear due to muscle pull (fig 22 page 68).

Blood supply is probably not seriously impaired since new capillaries growing into the cut ends are apparent from the 3rd day (Nichols et al. 1954, Bergljung, 1968).

The healing proceeds in much the same way in both groups and the tensile properties will be fairly equal once the strength of the scar between the stumps is above that of the strongest suture alone.

It is, possible however, that part of the differences between interrupted and criss-cross sutured tendons observed 8 weeks postoperatively for stiffness, load deformation and creep, could be explained on the basis of changes in the tendon tissue proper included within the criss-cross suture.

Influence of tensile forces on tendon healing

It is generally believed that a moderate amount of tensile forces favourably influences tendon healing. Breaking strength is believed to be elevated (page 14).

The amount of force transmitted over the suture line at various times postoperatively (before testing) is not known in this study. It can only be said that it is below

breaking strength (all suture insufficiences were rejected). It is also fair to assume that transmitted forces increased postoperatively due to healing of the muscle release.

The influence of stress has not been studied separately.

Clinical considerations

From a clinical standpoint interest is focused upon a return of adequate function to the sutured tendon. This means not only sufficient mechanical stability but also freedom of motion.

The tensile properties of sutured tendons, whether interrupted or criss-cross, are not on a level with intact tendons. The differences are sizable. Breaking strength is however after 8 weeks of healing higher than maximum available muscle force. At the same time deformations, both under load and residual, are larger although never increased more than 5 %. On a 10 cm tendon this would mean an extra elongation of .5 cm as compared to an intact tendon. In most instances further muscle contraction will be able to compensate for this. Nor would the extra creep displayed by the sutured tendons cause any significant functional impairment. After 8 weeks force-relaxation is usually back to values exhibited by intact tendons.

This investigation suggests that – in the long run – there are no advantages with suturing tendons according to the elaborate Bunnell technique (criss-cross) if mechanical stability is considered. Taking the short view, however, interrupted sutures cannot be successfully employed unless almost complete relaxation of the tendon can be guaranteed. Suture insufficiency was more frequent with interrupted sutures (table 5 page 31). It might be due to the muscle release healing too quickly for the suture. It might also be due to the rabbit's failure to comply with suitable postoperative behaviour.

Full power of active muscular contraction should probably be guarded against for at least 8 weeks. Up till that time the muscle may possess the power of pulling the tendon suture apart irrespective of type of suture employed.

For tensile properties other than breaking strength there seem to be no relevant differences between the two techniques.

Severe adhesions are more often found after criss-cross sutures than after interrupted ones (table 2 page 22). This could be interpreted as criss-cross sutures being more traumatic to the tendon.

All factors considered interrupted sutures would yield a better end result provided sufficient relaxation can be kept during the critical first 8 postoperative weeks.

Even with interrupted sutures serious deterioration of tensile properties and impairment of function from adhesions is often found. The question arises whether a non-surgical approach to tendon wounds could be justified.

In experimental studies on the tendo achillis of rats Lipscomb and Wakim 1961 showed very good regeneration even after resection of almost the entire tendon without suturing the ends.

There are reports of excellent clinical results after ruptures or cuts of the tendo achillis treated only with a walking cast for 8 weeks with the foot in equinus position (Gillies and Chalmers 1970, Lea and Smith 1972).

Lipscomb and Wakim 1961, reported however that resection of part of a deep flexor led to adhesions on the proximal end and atrophy of the distal one, indicating a different process of healing in long tendons.

If a non-suture approach in surgery of tendons other than the tendo achillis is going to be successful it seems that a correct and narrow apposition of cut ends is necessary, which in many instances is impossible without holding one or more joints in extreme positions.

In cases with partial cut of a long tendon but with good apposition of tendon edges, however, immobilisation in a plaster cast only may be the best therapy.

SUMMARY

Interrupted and criss-cross sutures (a.m. Bunnell) were performed on rabbit peroneus brevis tendons together with a release of the peroneus brevis muscle. The latter was necessary in order to obtain satisfactory sutures. Tensile properties of sutured tendons were determined up till 24 weeks postoperatively.

Tensile properties were compared with those of intact tendons with and without muscle release and with those of undivided tendons with sutures.

Results

All tendons

Stiffness (= slope of force-deformation curve), relative elongation, under load and residual, were proportional to logarithm of applied force, within the physiological load range. Force-relaxation and creep were proportional to logarithm of time in the physiological load interval.

Tendons were not perfectly elastic even for small strains.

Intact tendons (surgery performed on the contralateral side)

Immediately postoperatively there was a moderate deterioration of tensile properties, interpreted as an effect of anaesthesia and trauma in connexion with surgery on the contralateral leg. The deterioration was reversed 24 weeks postoperatively, possibly due to ageing of the experimental animal.

The breaking strength averaged 10 kp. Maximum muscle force indicating physiological load range was approximately 3 kp, giving a considerable margin of safety.

Muscle release

Releasing 2/3 of the origin of the short peroneal muscle without performing surgery on the tendon proper did not significantly alter tensile properties of the tendon.

Muscle release and interrupted sutures on undivided tendons

A moderate deterioration of tensile properties was found postoperatively. The recovery was good.

Muscle release and criss-cross suture on undivided tendons

More marked changes in tensile properties were encountered, probably due to interference with blood supply. Recovery was not complete and started late.

Criss-cross sutures were mechanically stronger during the first 2 weeks of healing. From the 4th week tensile properties were approximately the same for tendons with interrupted sutures and criss-cross sutures. There was a considerable improvement of tensile properties during the 24 postoperative weeks studied, but there remained a substantial difference as compared to intact tendons. Reduction in breaking strength was approximately 50 % 24 weeks postoperatively.

Breaking strength of divided and sutured tendons did not exceed maximum muscle power until 8 weeks postoperatively.

Criss-cross sutures produced more adhesions than interrupted sutures.

The use of interrupted sutures is advocated when sufficient relaxation of tendons can be achieved at surgery.

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APPENDIX

(figs 23–91).

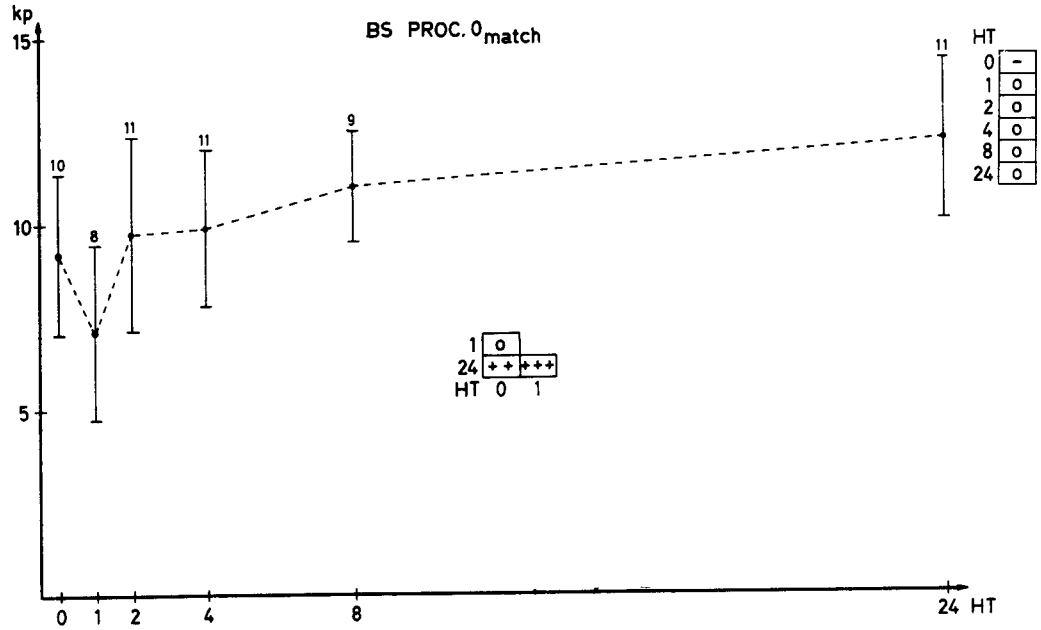
(Legends to figs 23–24, 41–42, 59–60 and 77–78 to be found on foldouts to the left of the figures).

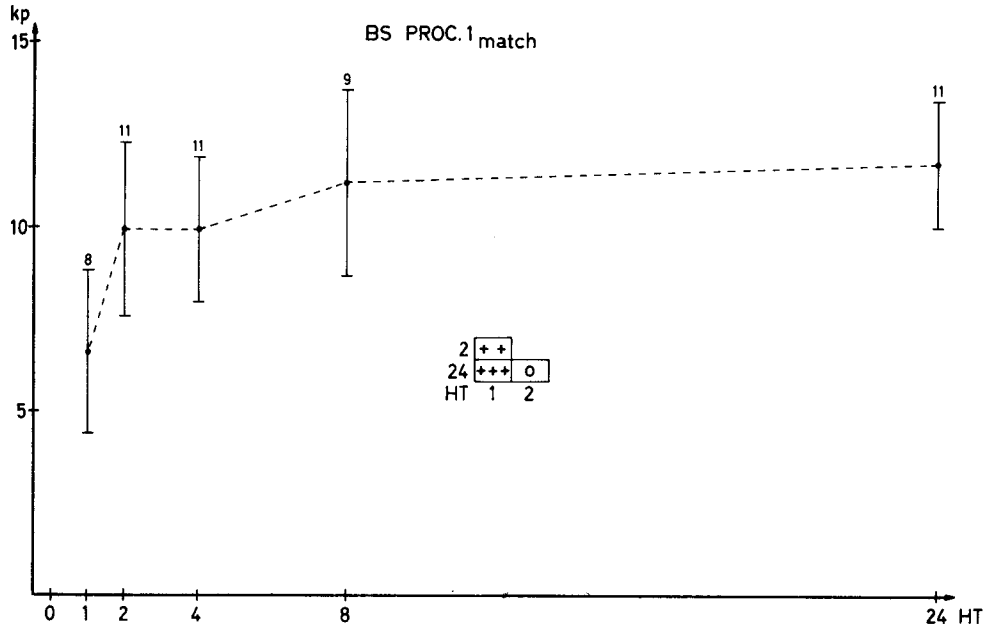
APPENDIX

(figs 23–91).

(Legends to figs 23–24, 41–42, 59–60 and 77–78 to be found on foldouts to the left of the figures).

Fig 23–24. Breaking strength (BS) in relation to healing time (HT) in weeks for intact tendons with and without muscle release (procedures nr 0 and 1). For procedure nr 0 HT relates to the surgical procedure performed on the contralateral leg. Match after procedure number = matched groups, see page 50.
BS is given as mean values ±1 SD. Together with each mean value number of specimens tested is given.
Statistical differences comparing mean values for the *same* procedure are given in the scoreboards. Signs in scoreboards: 0 = $p > .05$, +, ++, +++ = $p \leq .05$, .01, .001 respetively. (For procedure nr 0 for instance there is no difference between HT 0 and 1 but a significant one between HT 1 and 24.) Statistical differences *comparing* procedures 0 and 1 at *equal* HT are given in the vertical column in the middle.

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0 1 2 4 8 24 HT

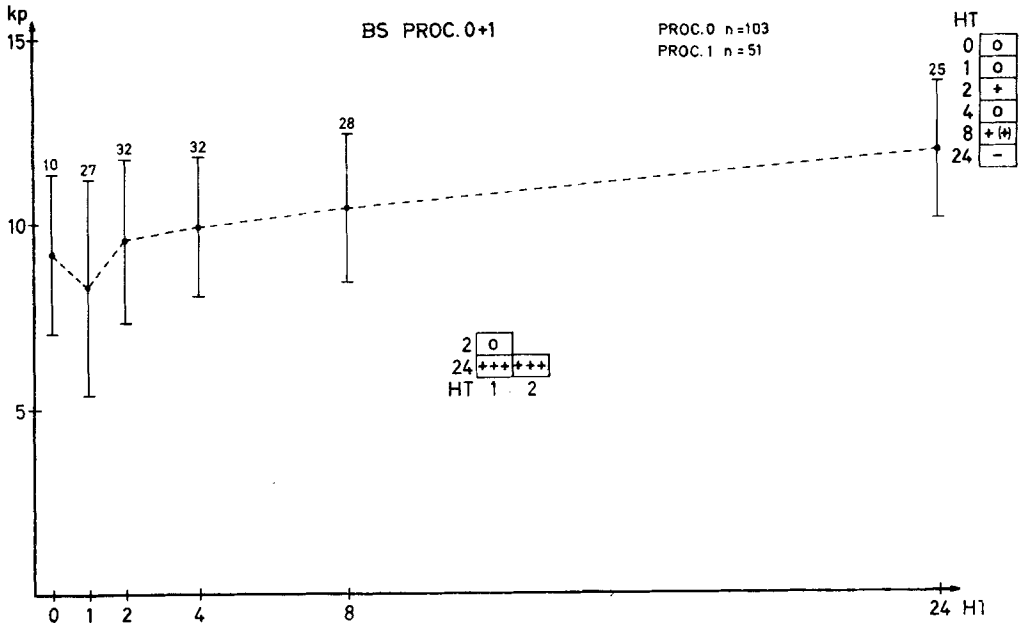


Fig 25–26. Breaking strength (BS) in relation to healing time (HT) in weeks for control specimens (procedure nr 0+1) and specimens with muscle release and interrupted sutures on undivided tendons (procedure nr 2, opposite page). For details see legend to fig 23–24.

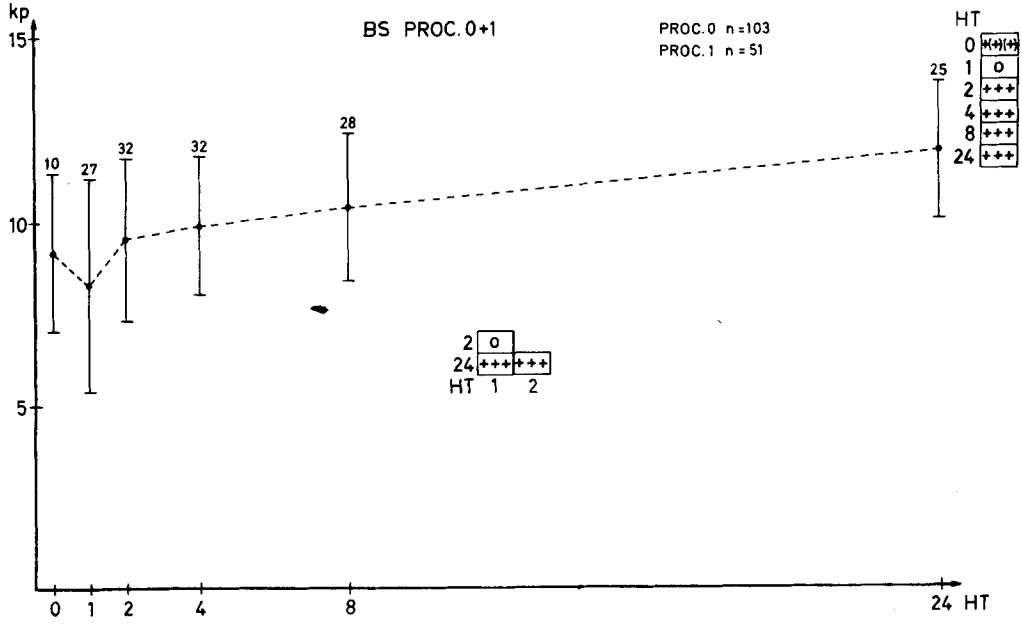
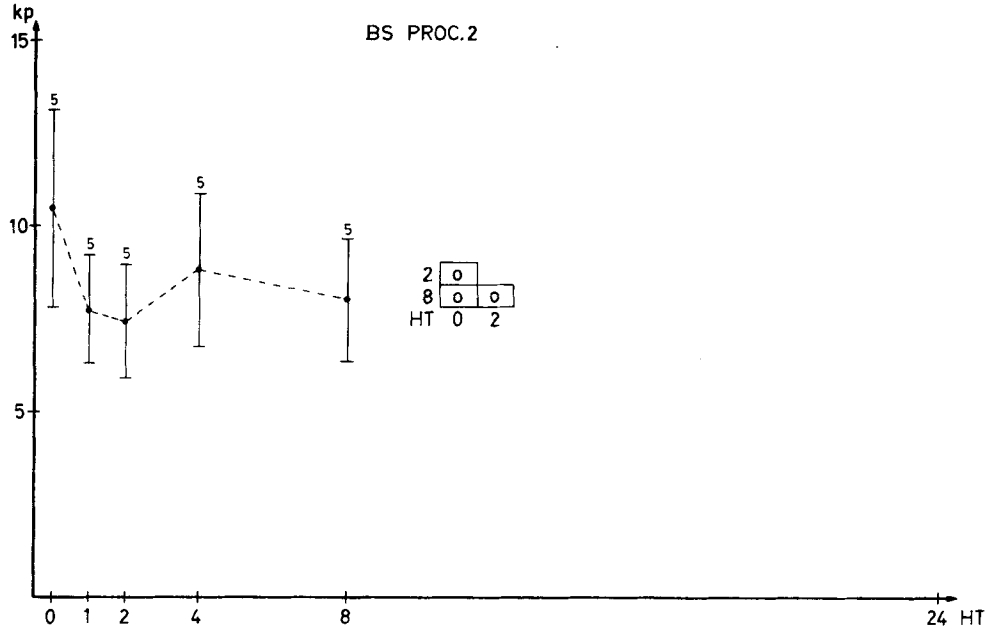
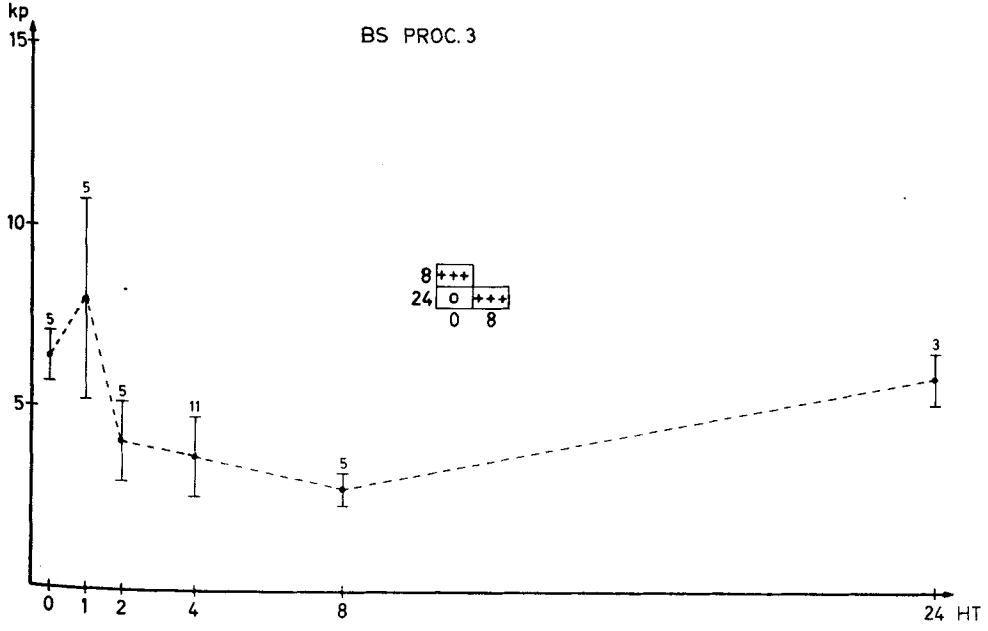


Fig 27–28. Breaking strength (BS) in relation to healing time (HT) in weeks for control specimens (procedure nr 0+1) and specimens with muscle release and criss-cross sutures on undivided tendons (procedure nr 3, opposite page). For details see legend to fig 23–24.


kp
BS PROC.2
15
10
5
5
5
5
5
2 o
8 o o
HT 0 2
0 1 2 4 8 24 HT


kp
BS PROC. 3
15
10
5
5
5
5
11
5
3
8 +++
24 o +++
0 8
0 1 2 4 8 24 HT

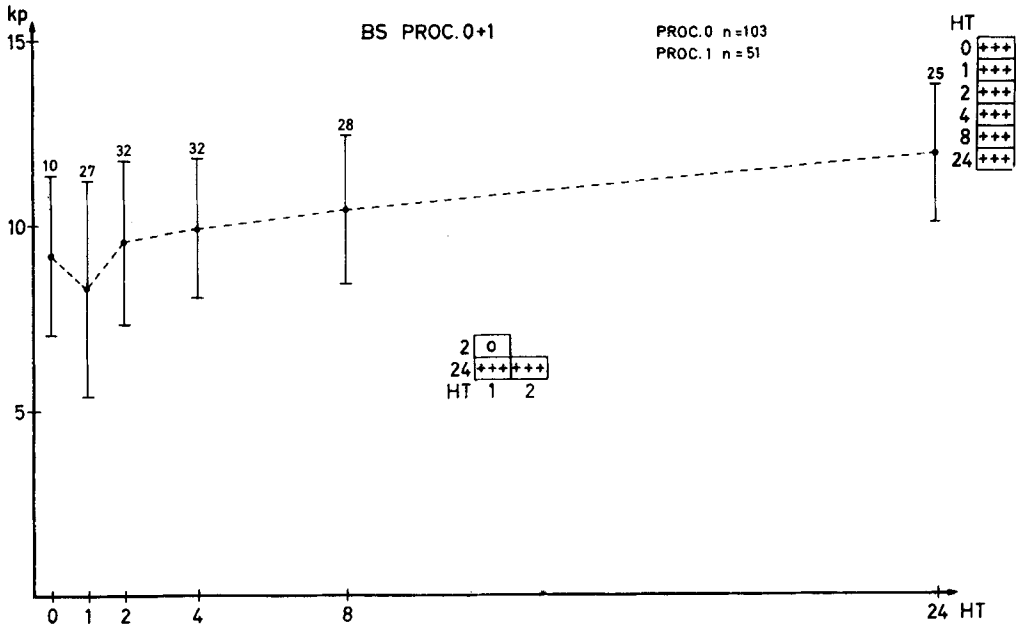


Fig 29–30. Breaking strength (BS) in relation to healing time (HT) in weeks for control specimens (procedure nr 0+1) and specimens with muscle release and interrupted sutures on divided tension (procedure nr 4, opposite page). For details see legend to fig 23–24.

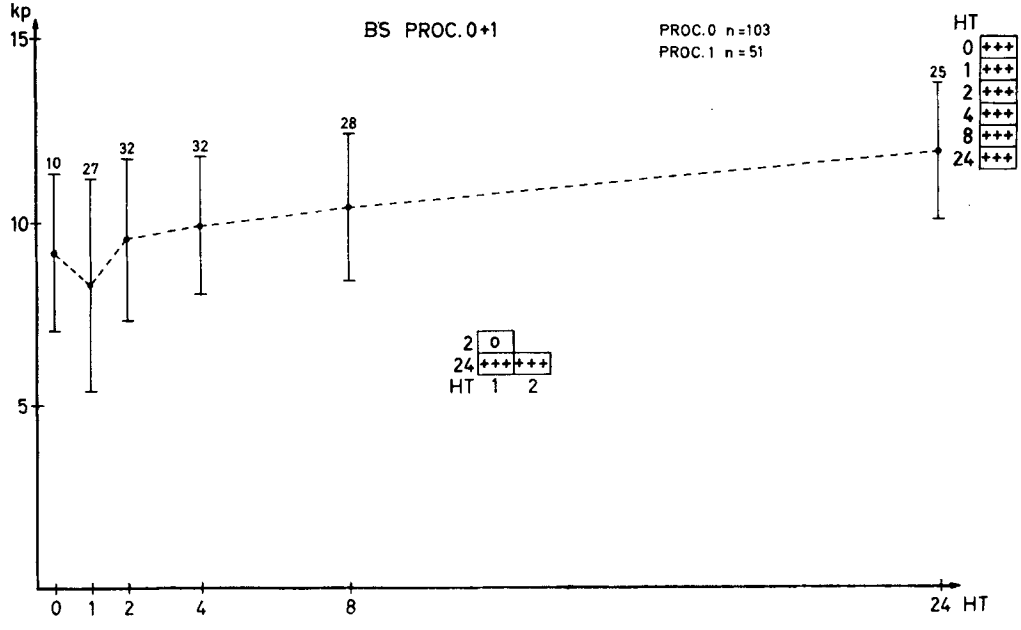
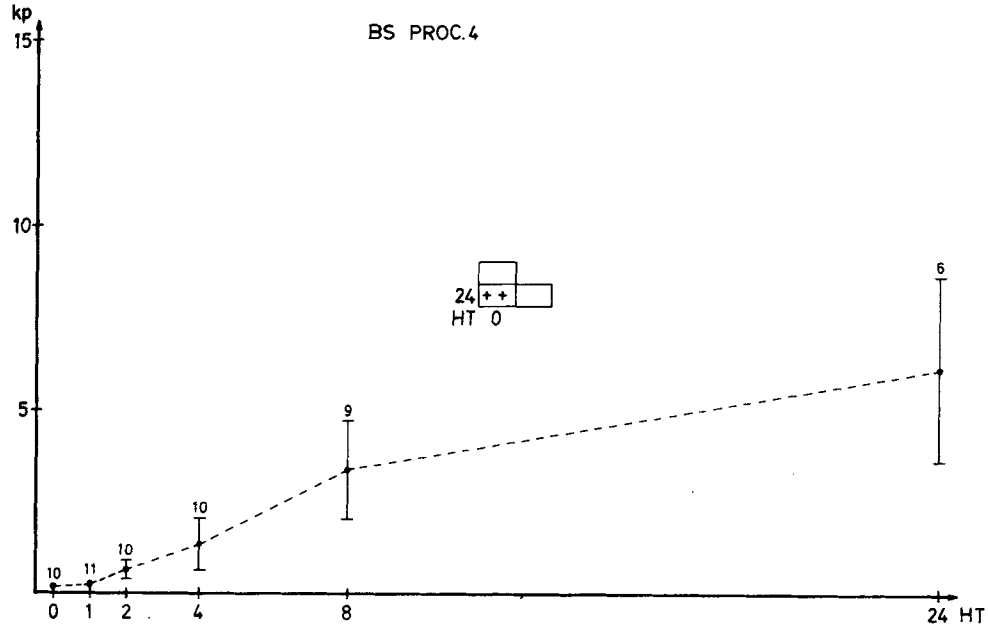
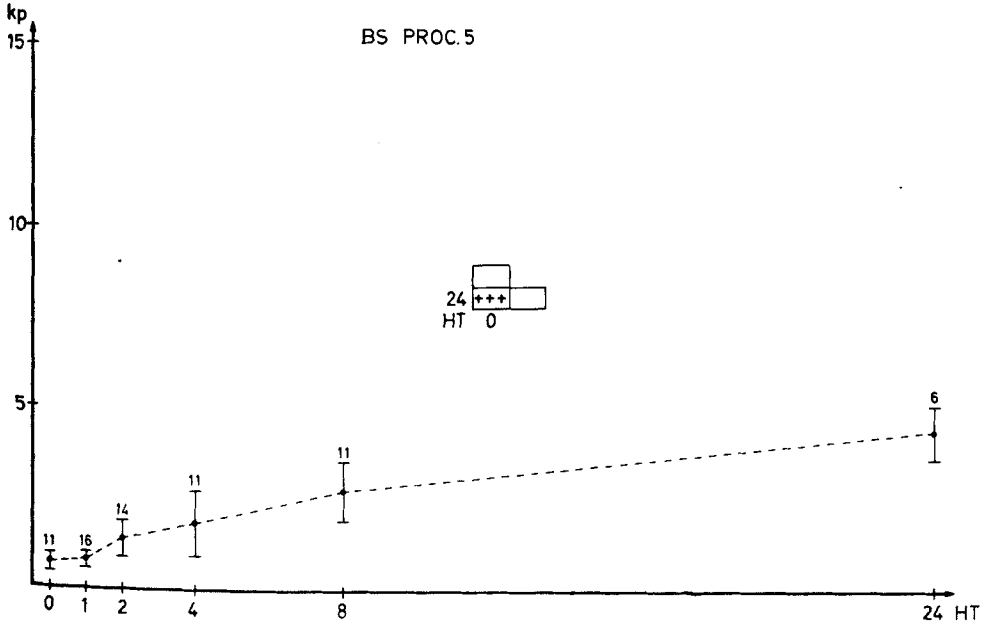


Fig 31–32. Breaking strength (BS) in relation to healing time (HT) in weeks for control specimens (procedure nr 0+1) and specimens with muscle release and criss-cross sutures on divided tendons (procedure nr 5, opposite page). For details see legend to fig 23–24.


kp
15
10
5
BS PROC.4
24
HT 0
10
11
10
10
9
6
0
1
2
4
8
24 HT


kp
15
10
5
BS PROC.5
24
HT 0
11
16
14
11
11
6
0
1
2
4
8
24 HT

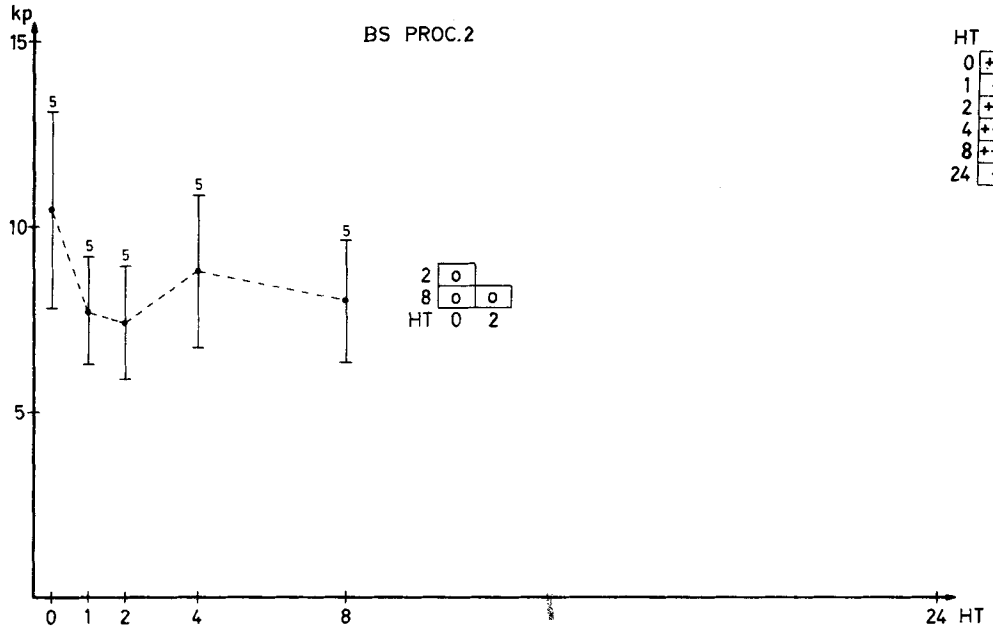


Fig 33–34. Breaking strength (BS) in relation to healing time (HT) in weeks for specimens with muscle release and interrupted sutures on undivided tendons (procedure nr 2) and specimens with

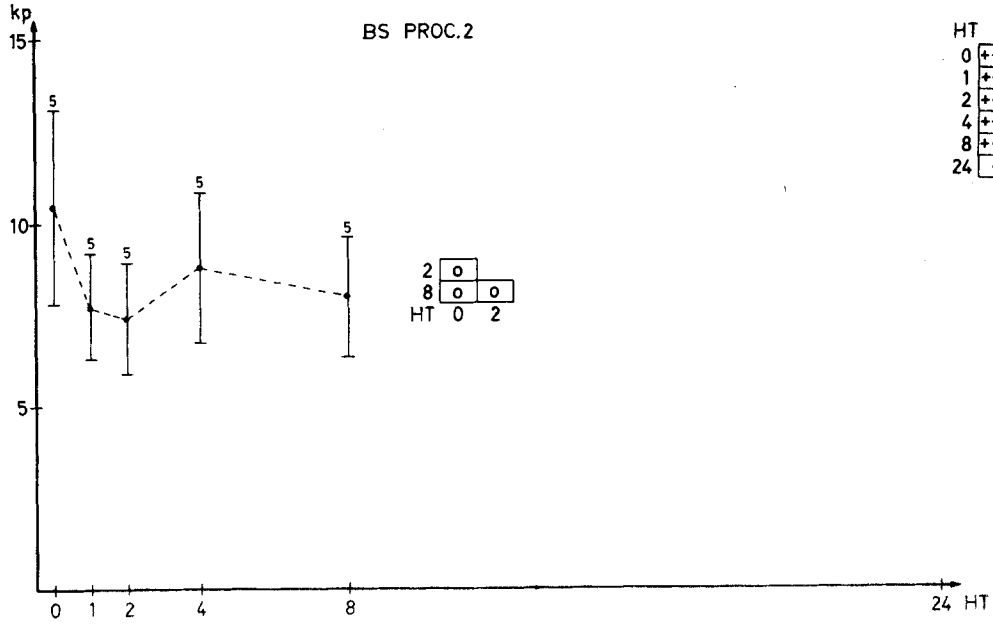
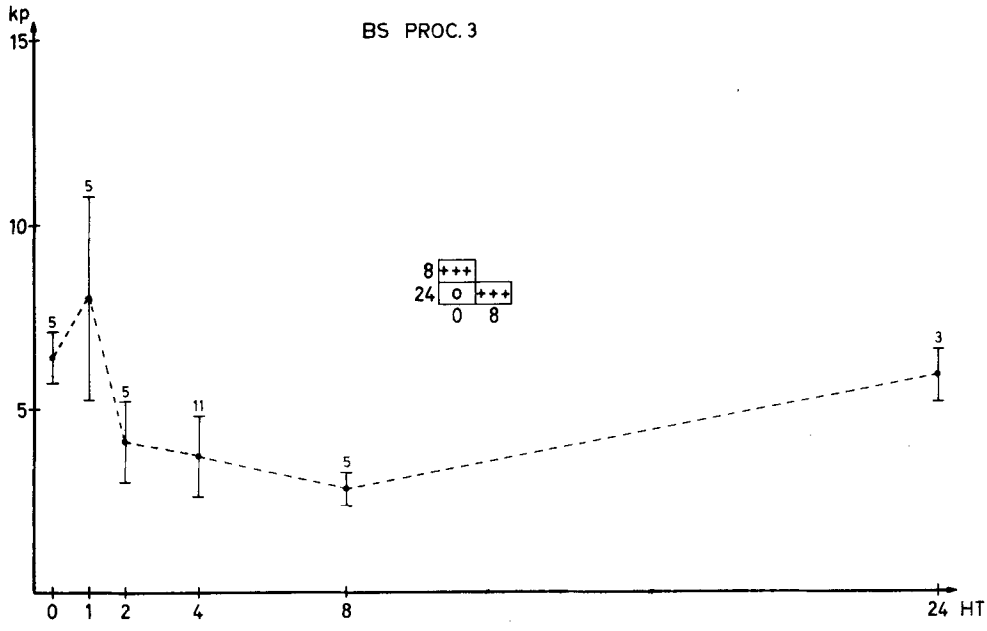
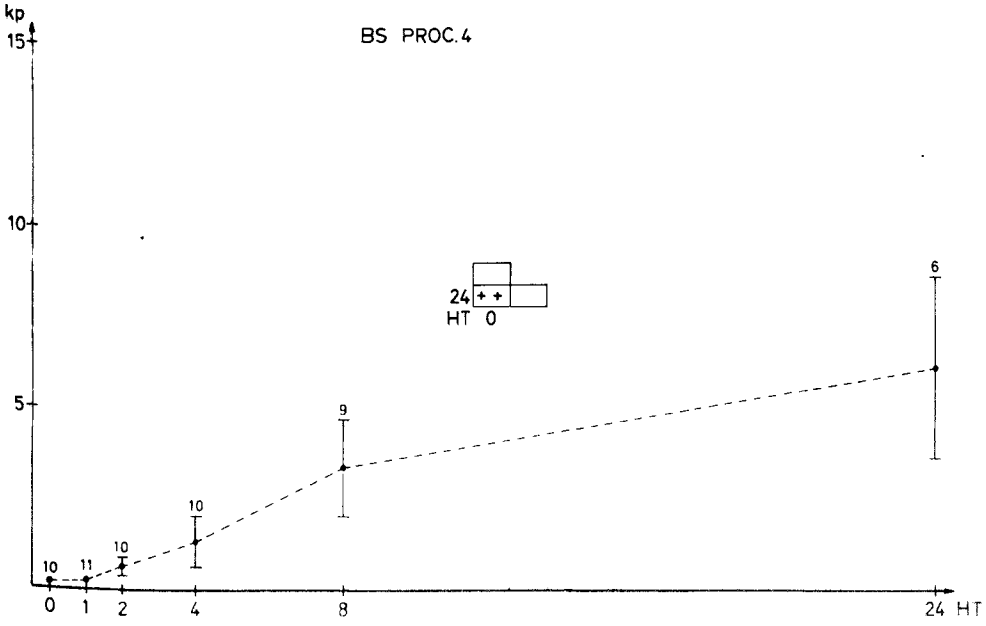


Fig 35–36. Breaking strength (BS) in relation to healing time (HT) in weeks for specimens with muscle release and interrupted sutures on undivided tendons (procedure nr 2) and specimens with



muscle release and criss-cross sutures on undivided tendons (procedure nr 3). For details see legend to fig. 23–24.



muscle release and interrupted sutures on divided tendons (procedure nr 4). For details see legend to fig 23–24.

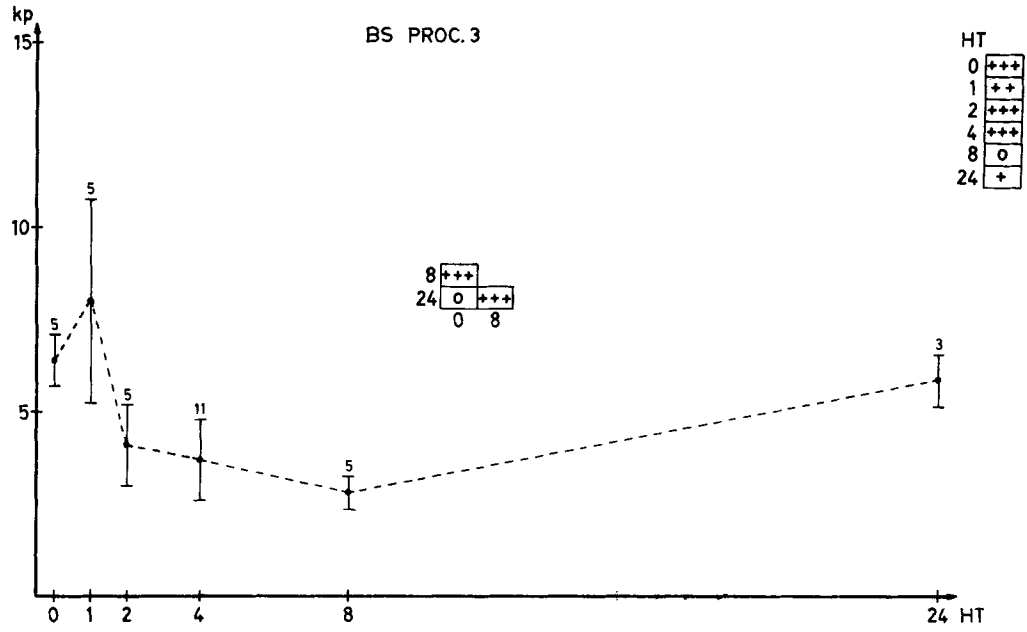


Fig 37–38. Breaking strength (BS) in relation to healing time (HT) in weeks for specimens with muscle release and criss-cross sutures on undivided tendons (procedure nr 3) and specimens with

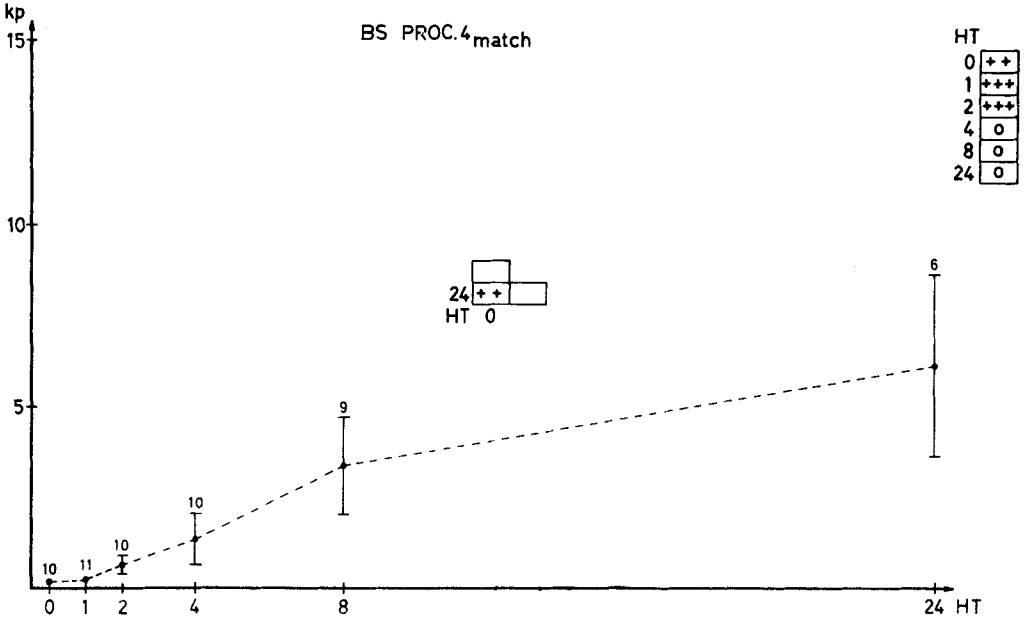
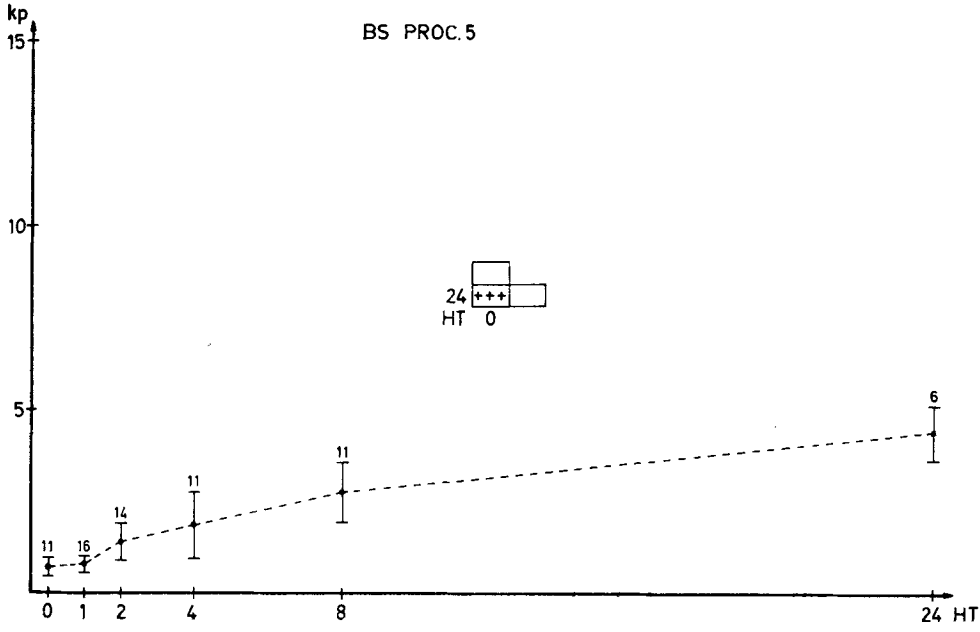
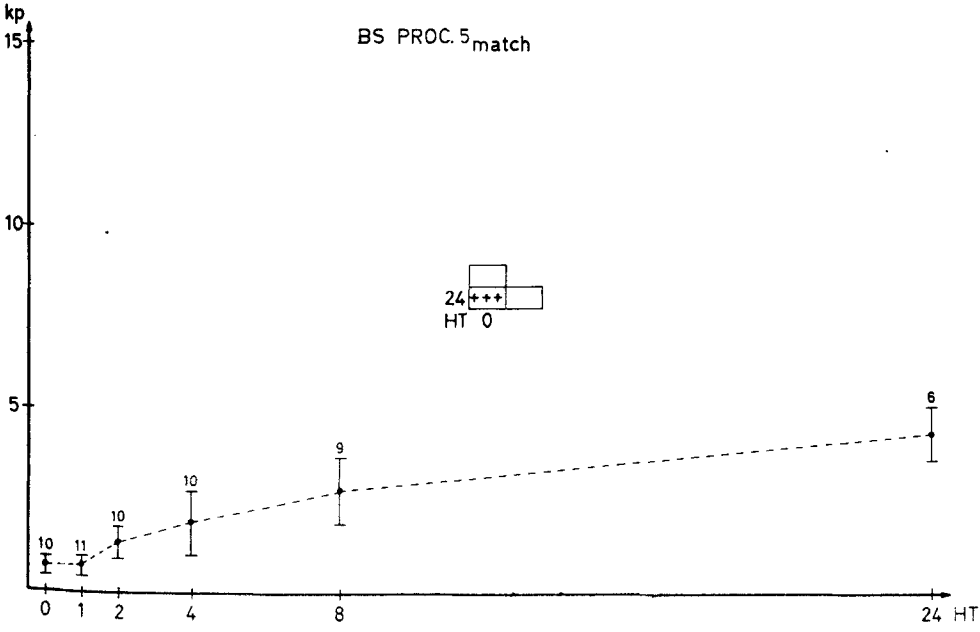


Fig 39–40. Breaking strength (BS) in relation to healing time (HT) in weeks for specimens with muscle release and interrupted sutures on divided tendons (procedure nr 4) and specimens with



muscle release and criss-cross sutures on divided tendons (procedure nr 5). For details see legend to fig 23–24.



muscle release and criss-cross suture on divided tendons (procedure nr 5). For details see legend to fig 23–24.

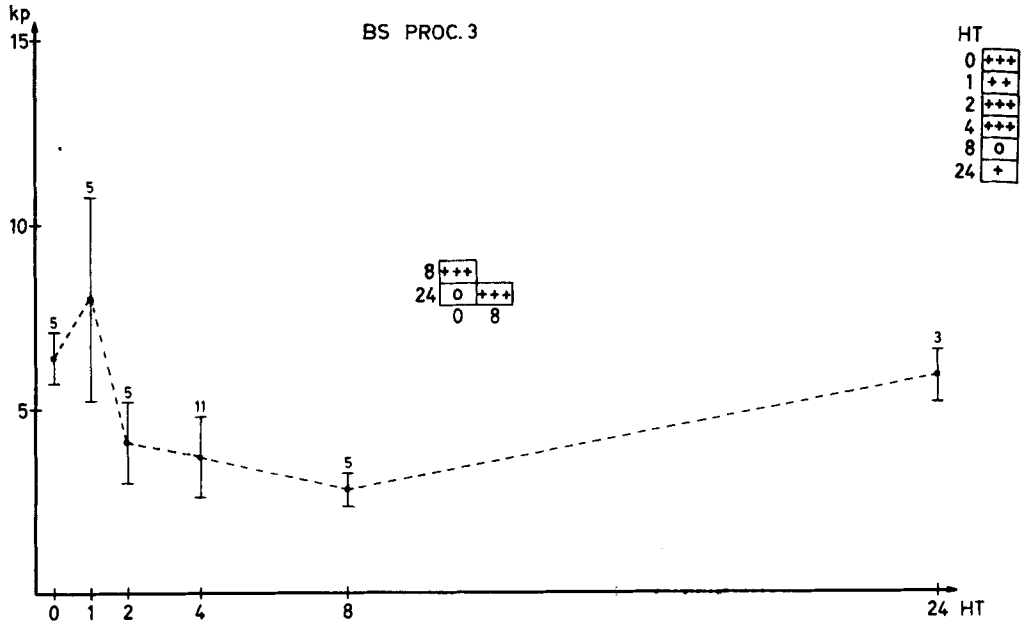


Fig 37–38. Breaking strength (BS) in relation to healing time (HT) in weeks for specimens with muscle release and criss-cross sutures on undivided tendons (procedure nr 3) and specimens with

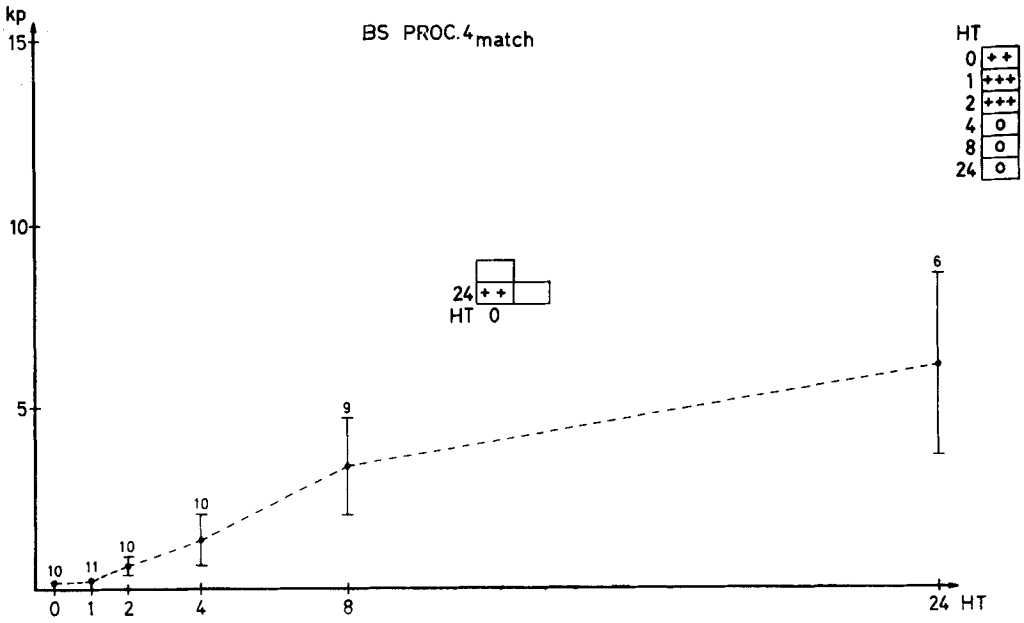
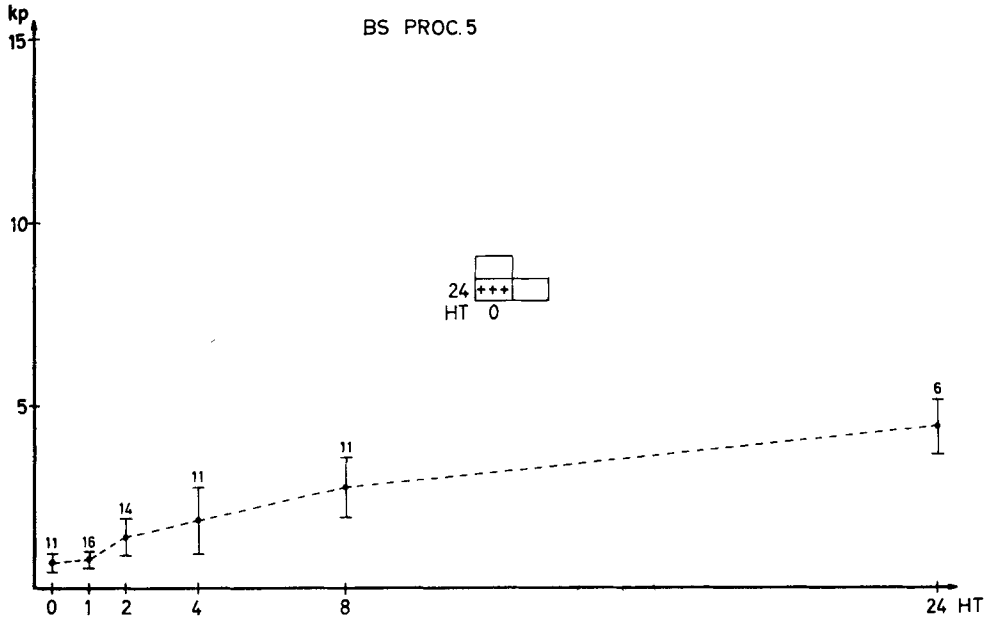
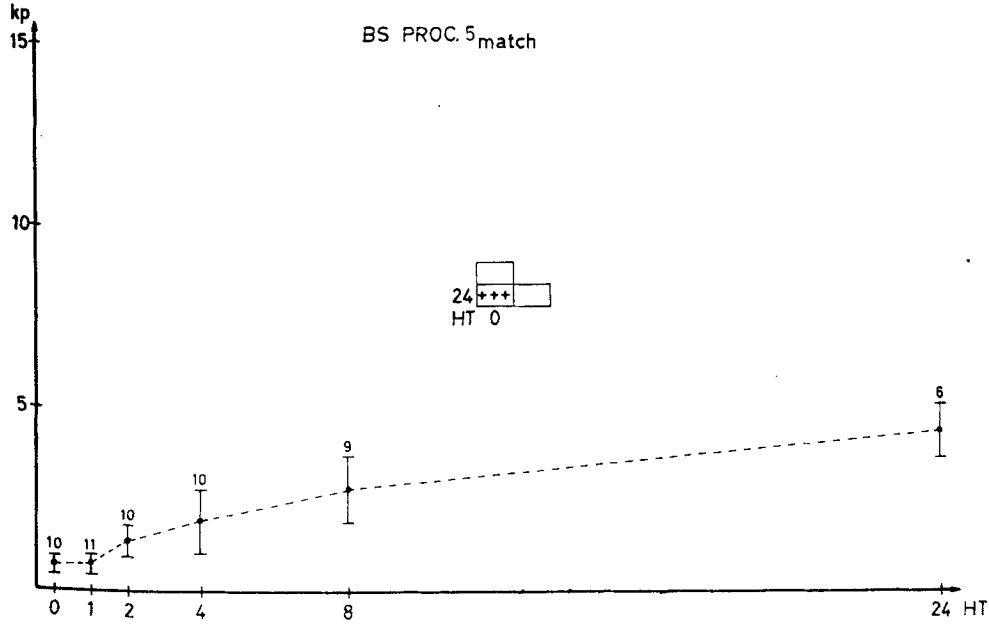


Fig 39–40. Breaking strength (BS) in relation to healing time (HT) in weeks for specimens with muscle release and interrupted sutures on divided tendons (procedure nr 4) and specimens with

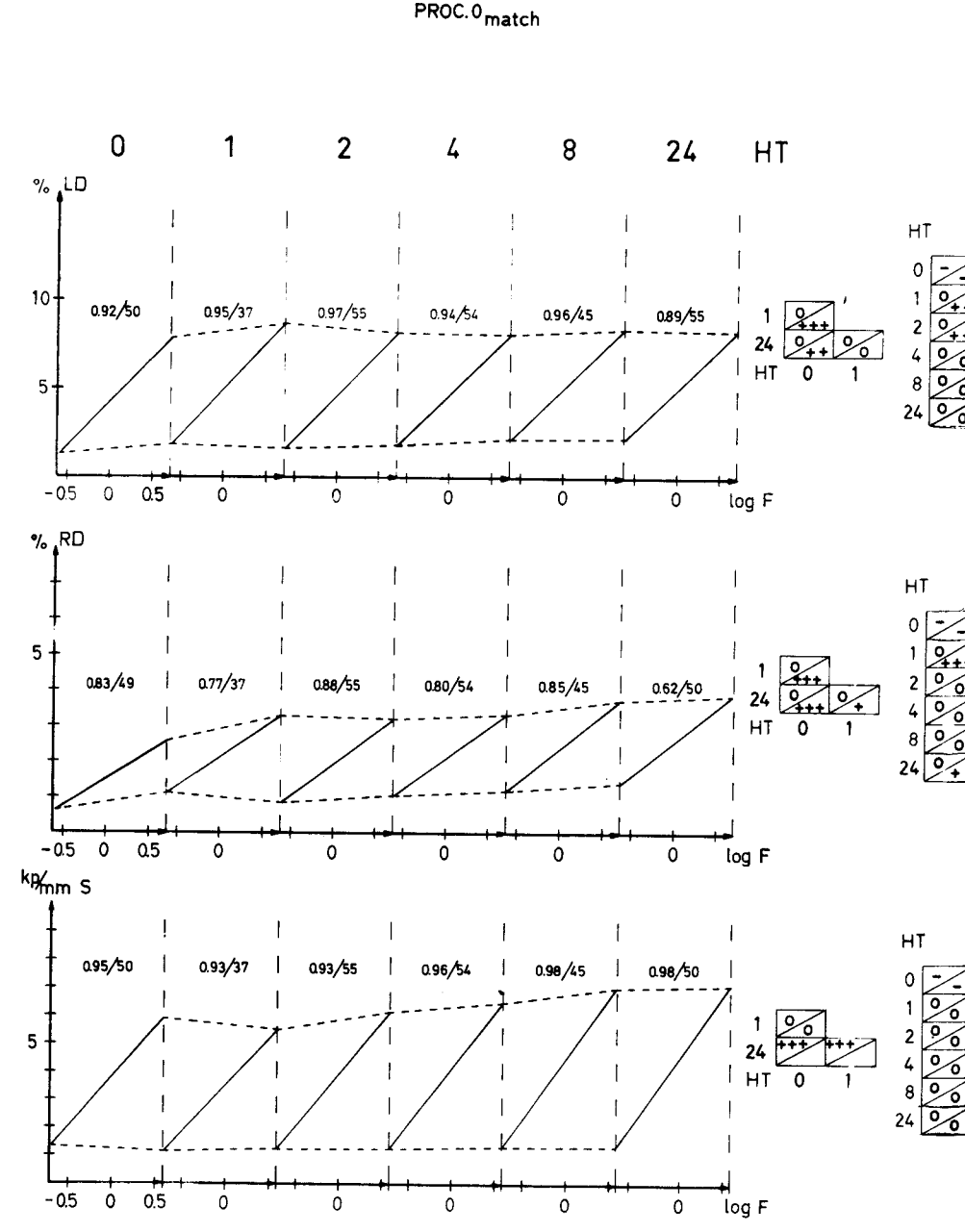


muscle release and criss-cross sutures on divided tendons (procedure nr 5). For details see legend to fig 23–24.

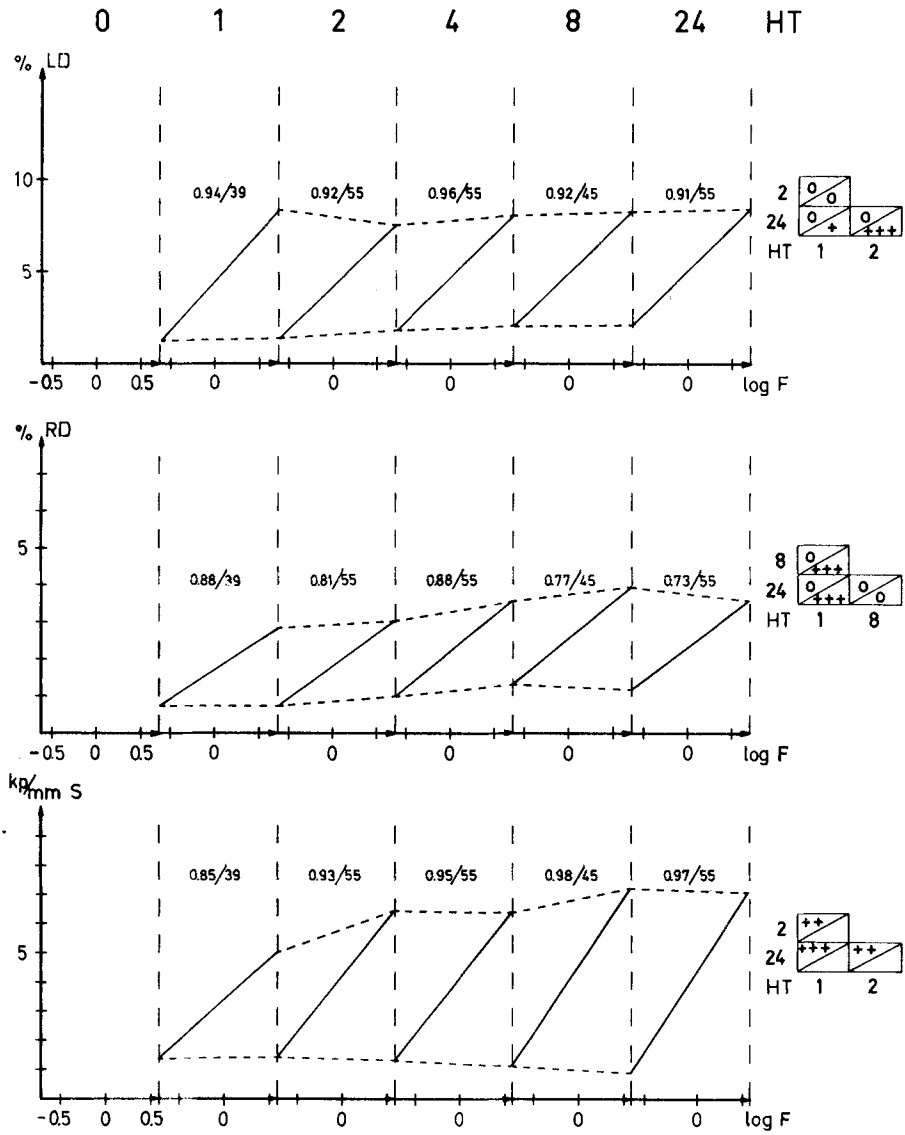


muscle release and criss-cross suture on divided tendons (procedure nr 5). For details see legend to fig 23–24.

Fig 41–42. Mean regression lines for load deformation (LD), residual deformation (RD) and stiffness (S) versus log F (force in kp) in relation to healing time (HT) in weeks. Left page intact specimens = procedure nr 0. Right page specimens with muscle release only = procedure nr 1. Match after procedure number (at the top) = matched groups see page 50. HT for intact tendons relates to the muscle release performed on the contralateral leg.
The abscissa (log F) is repeated 6 times as indicated by the vertical broken lines and corresponding to various HT noted at the top in bold figures.
With each regression line a fraction is given. The numerator = coefficient of correlation = r, the denominator = number of observations = n.
Results of statistical analysis for the *same* procedure are given in the scoreboards. Signs in the scoreboards: 0 = p > .05, +, ++, +++ = p ≤ .05, .01, .001 respectively. Statistical differences for coefficients of regression = b are given in the upper left triangle, and for mean values of the ordinate = intercept = a in the lower right triangle. (For procedure nr 0 for instance LD is the same if HT 1 and 24 are compared as indicated by 0 in both triangles, between HT 0 and 24 b is equal, 0 in the upper left triangle but a is higher for HT 24, ++ in the lower right triangle.)
Results of statistical analysis *comparing* procedures at *equal* HT are given in the vertical columns in the middle. (For instance comparing RD at HT 24 b is the same, 0 in the upper left triangle but a lower for proc nr 1, + in the lower right triangle.)



PROC. 1 match


0
1
2
4
8
24
HT
% LD
10
5
0.94/39
0.92/55
0.96/55
0.92/45
0.91/55
2
24
HT 1 2
-0.5 0 0.5 0 0 0 0 0 log F
% RD
5
0.88/39
0.81/55
0.88/55
0.77/45
0.73/55
8
24
HT 1 8
-0.5 0 0.5 0 0 0 0 0 log F
kp/mm S
5
0.85/39
0.93/55
0.95/55
0.98/45
0.97/55
2
24
HT 1 2
-0.5 0 0.5 0 0 0 0 0 log F

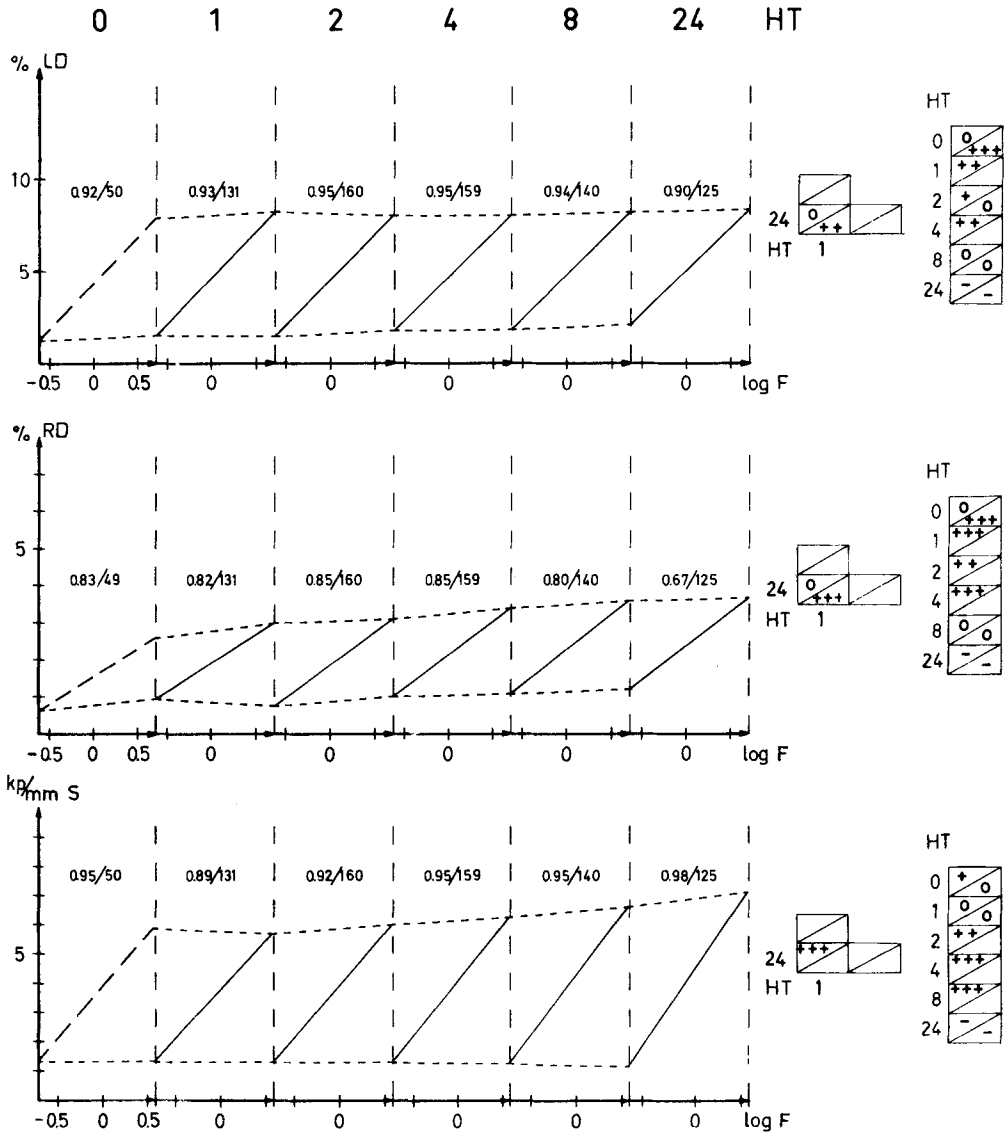
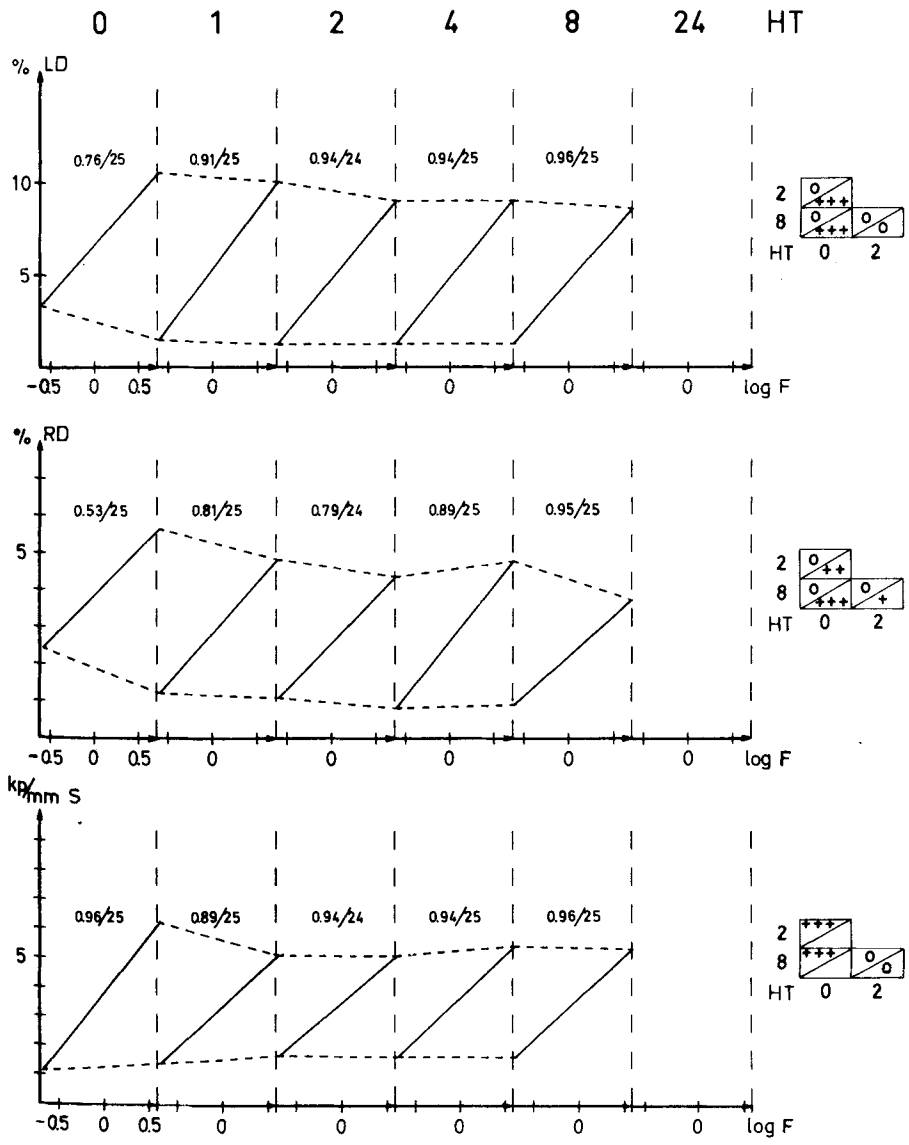


Fig 43–44. Mean regression lines for load deformation (LD), residual deformation (RD) and stiffness (S) versus log F (force in kp) in relation to healing time (HT) in weeks. Left page control



specimens (procedure nr 0+1). Right page specimens with muscle release and interrupted sutures on undivided tendons (procedure nr 2). For details see legend to fig 41–42.

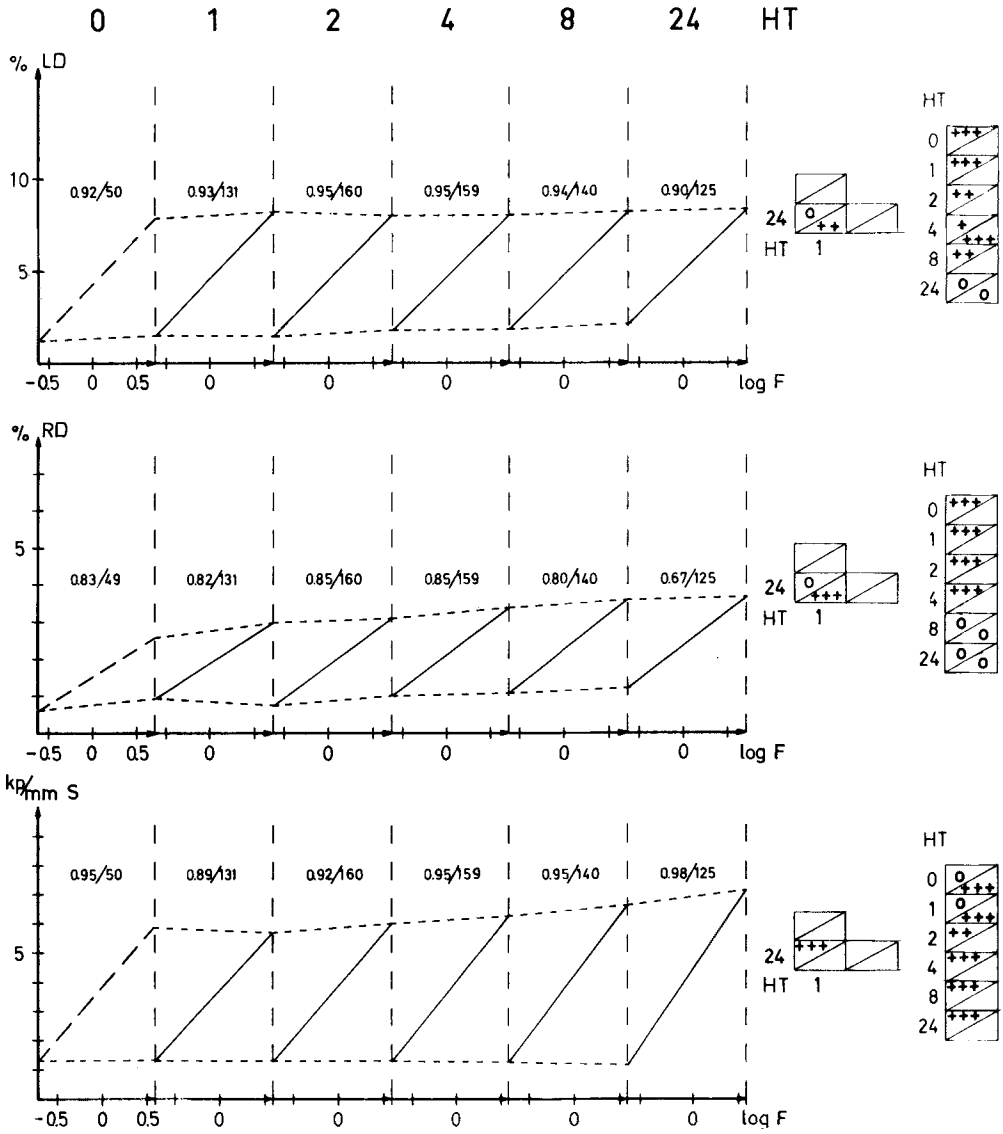
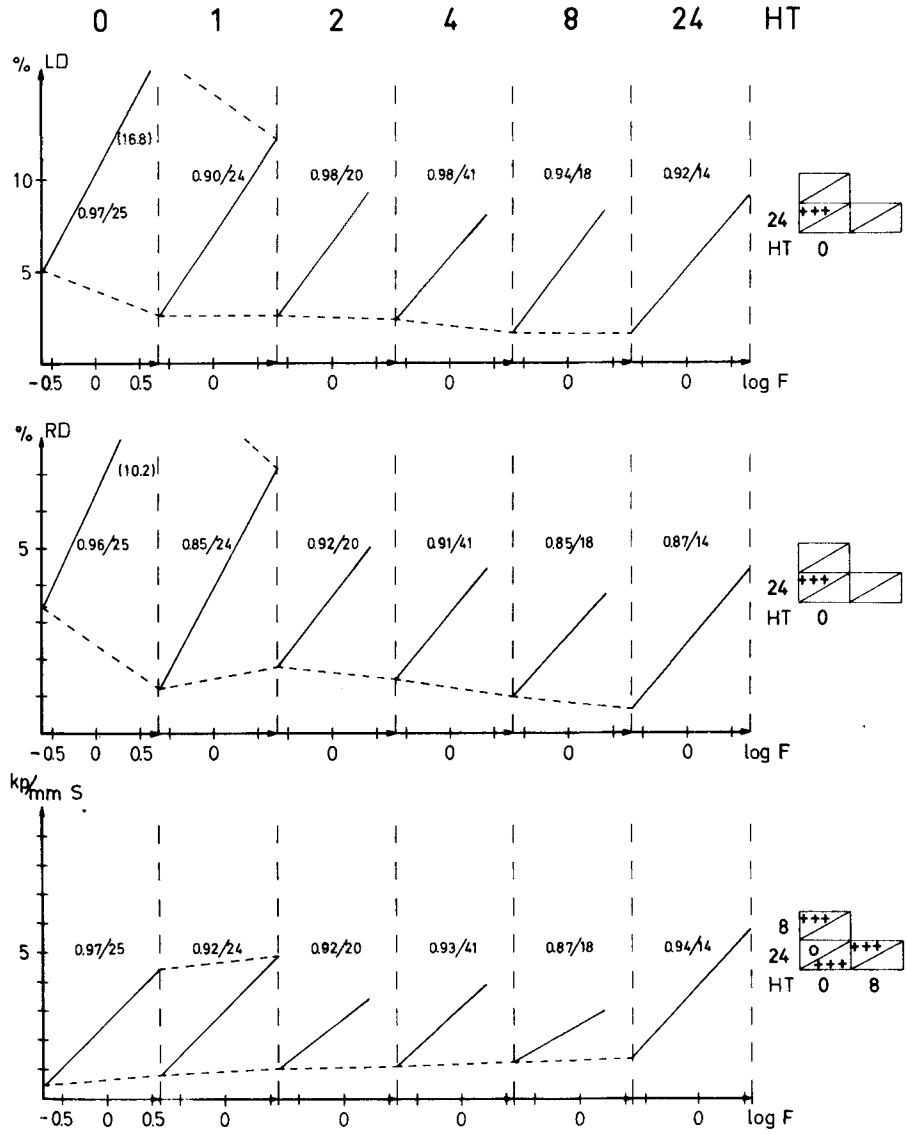


Fig 45–46. Mean regression lines for load deformation (LD), residual deformation (RD) and stiffness (S) versus log F (force in kp) in relation to healing time (HT) in weeks. Left page control



specimens (procedure nr 0+1). Right page specimens with muscle release and criss-cross sutures on undivided tendons (procedure nr 3). For details see legend to fig 41–42.

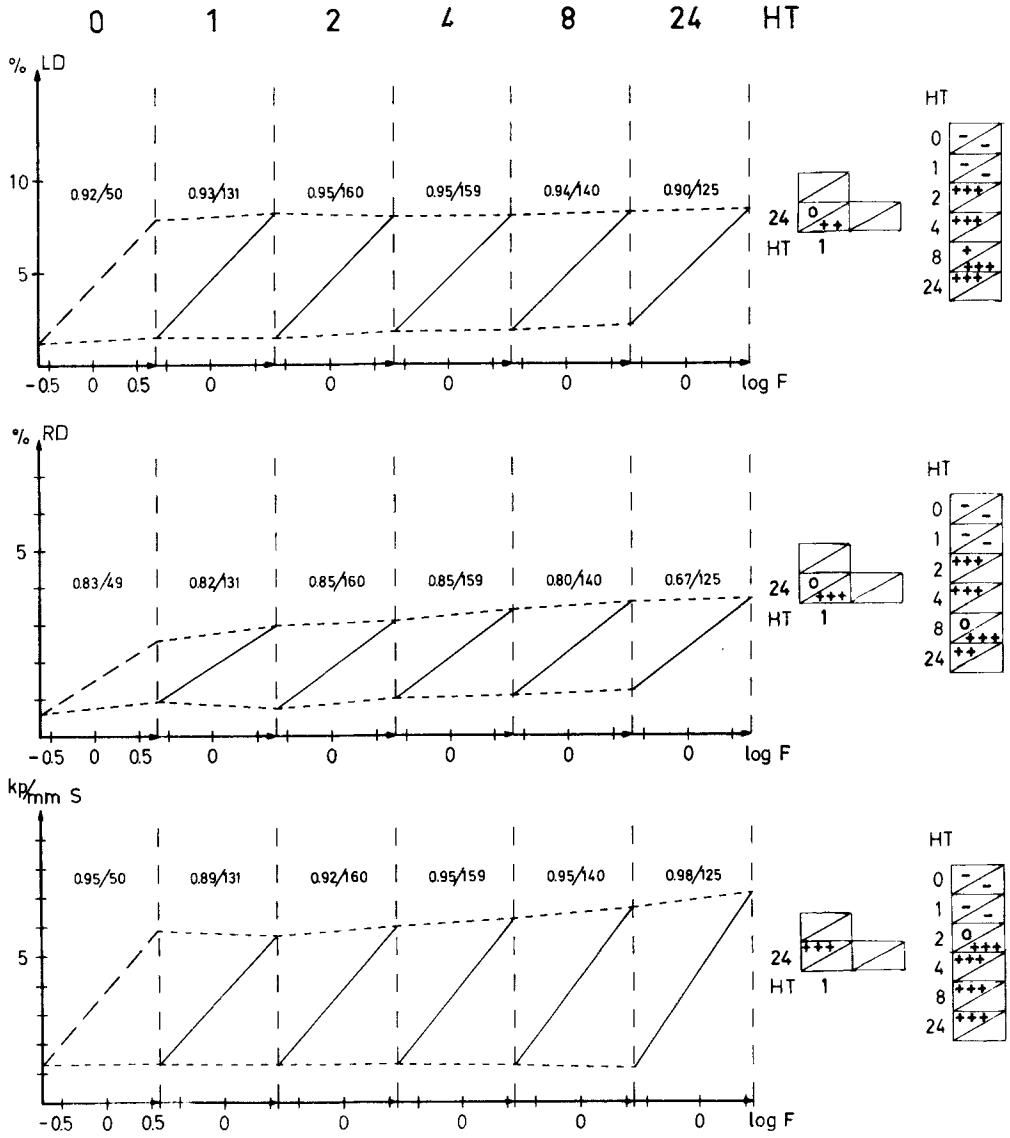
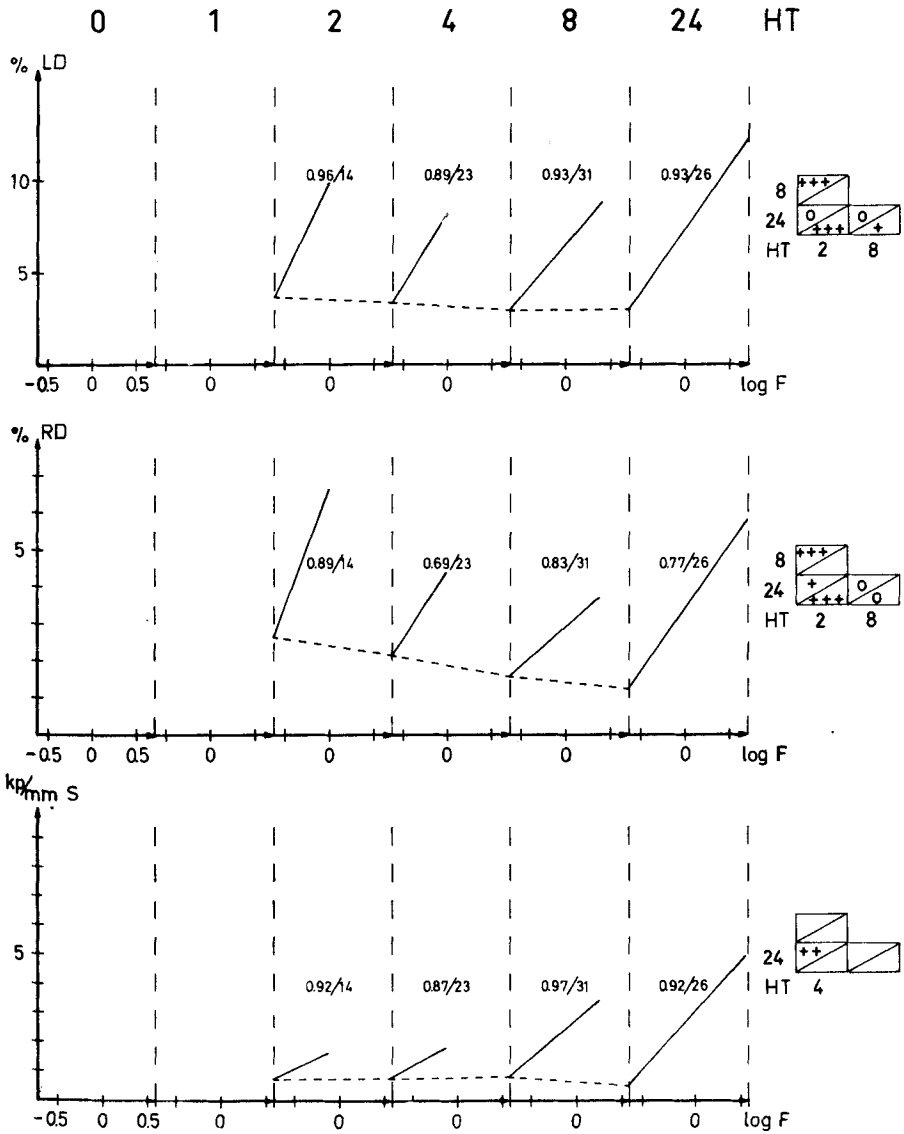


Fig 47–48. Mean regression lines for load deformation (LD), residual deformation (RD) and stiffness (S) versus log F (force in kp) in relation to healing time (HT) in weeks. Left page control



specimens (procedure nr 0+1). Right page specimens with muscle releade and interrupted sutures on divided tendons (procedure nr 4). For details see legend to fig 41 – 42.

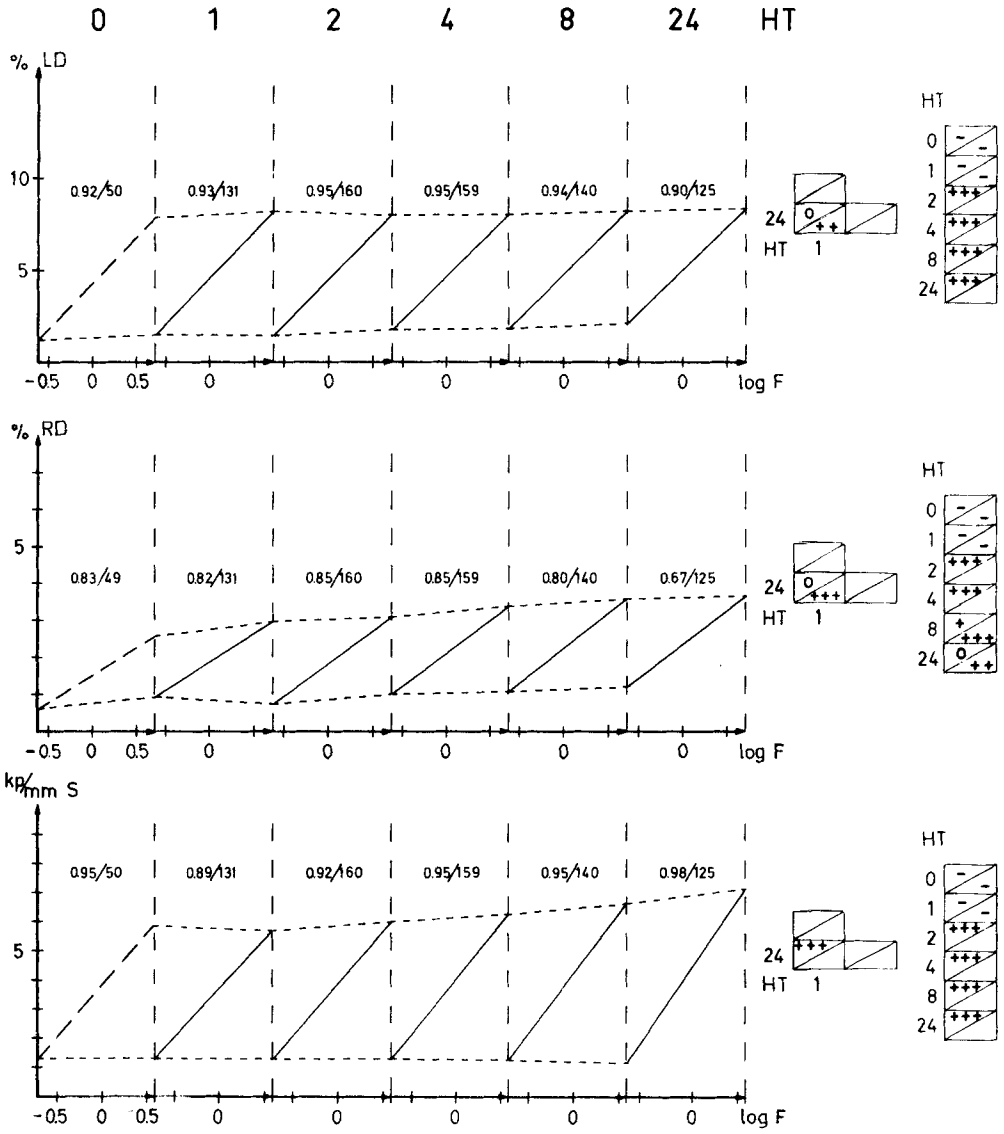
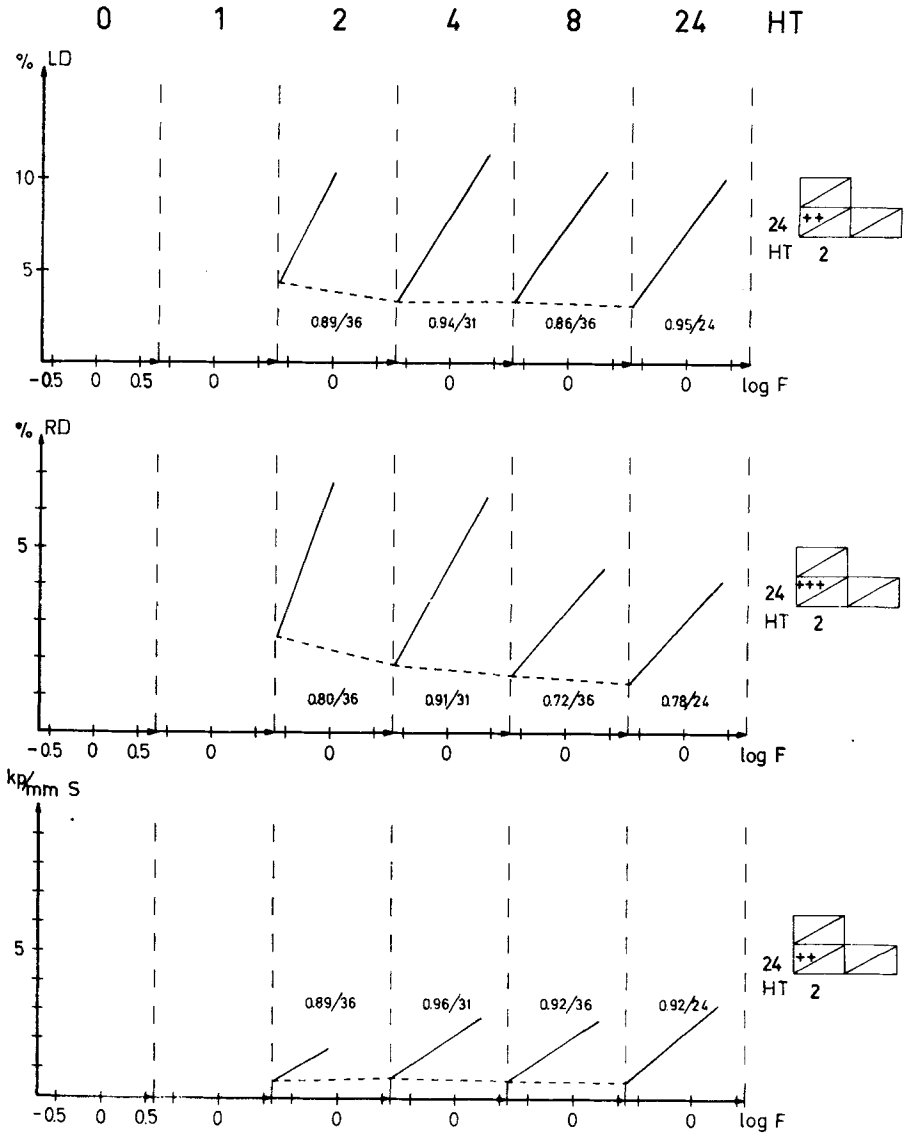


Fig 49–50. Mean regression lines for load deformation (LD), residual deformation (RD) and stiffness (S) versus log F (force in kp) in relation to healing time (HT) in weeks. Left page control



specimens (procedure nr 0+1). Right page specimens with muscle release and interrupted sutures on divided tendons (procedure nr 4). For details see legend to fig 41 - 42.

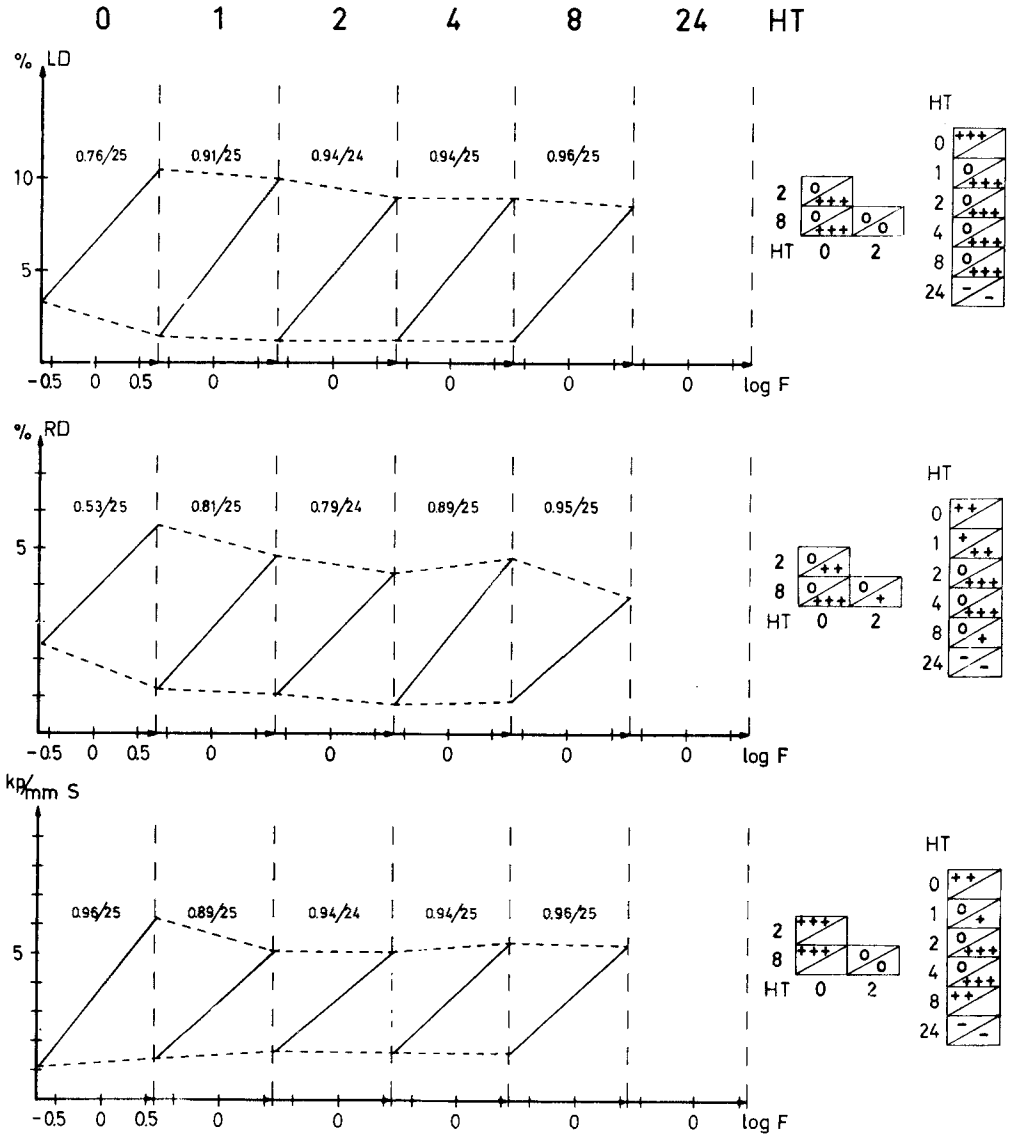
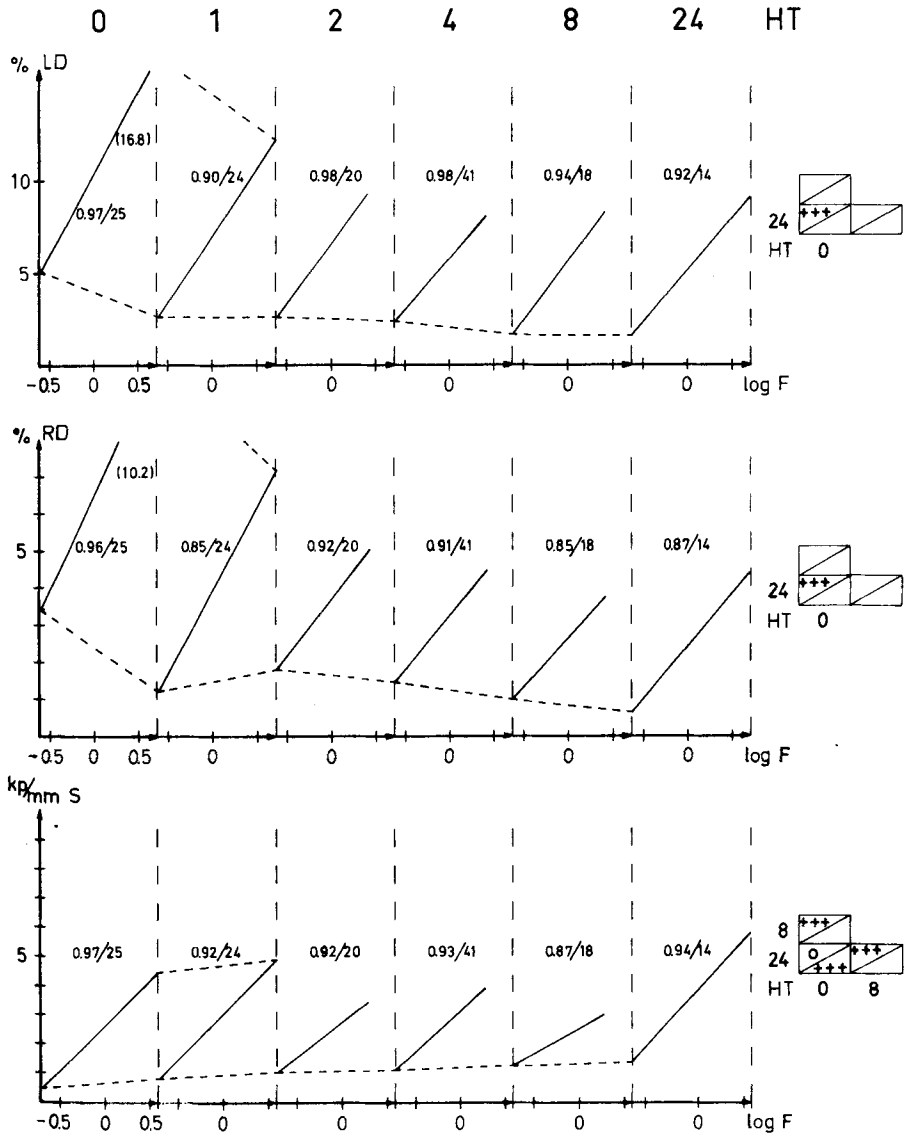


Fig 51–52. Mean regression lines for load deformation (LD), residual deformation (RD) and stiffness (S) versus log F (force in kp) in relation to healing time (HT) in weeks. Left page specimens with muscle release and interrupted sutures on undivided tendons (procedure nr 2).



Right page specimens with muscle release and criss-cross sutures on undivided tendons (procedure nr 3). For details see legend to fig 41–42.

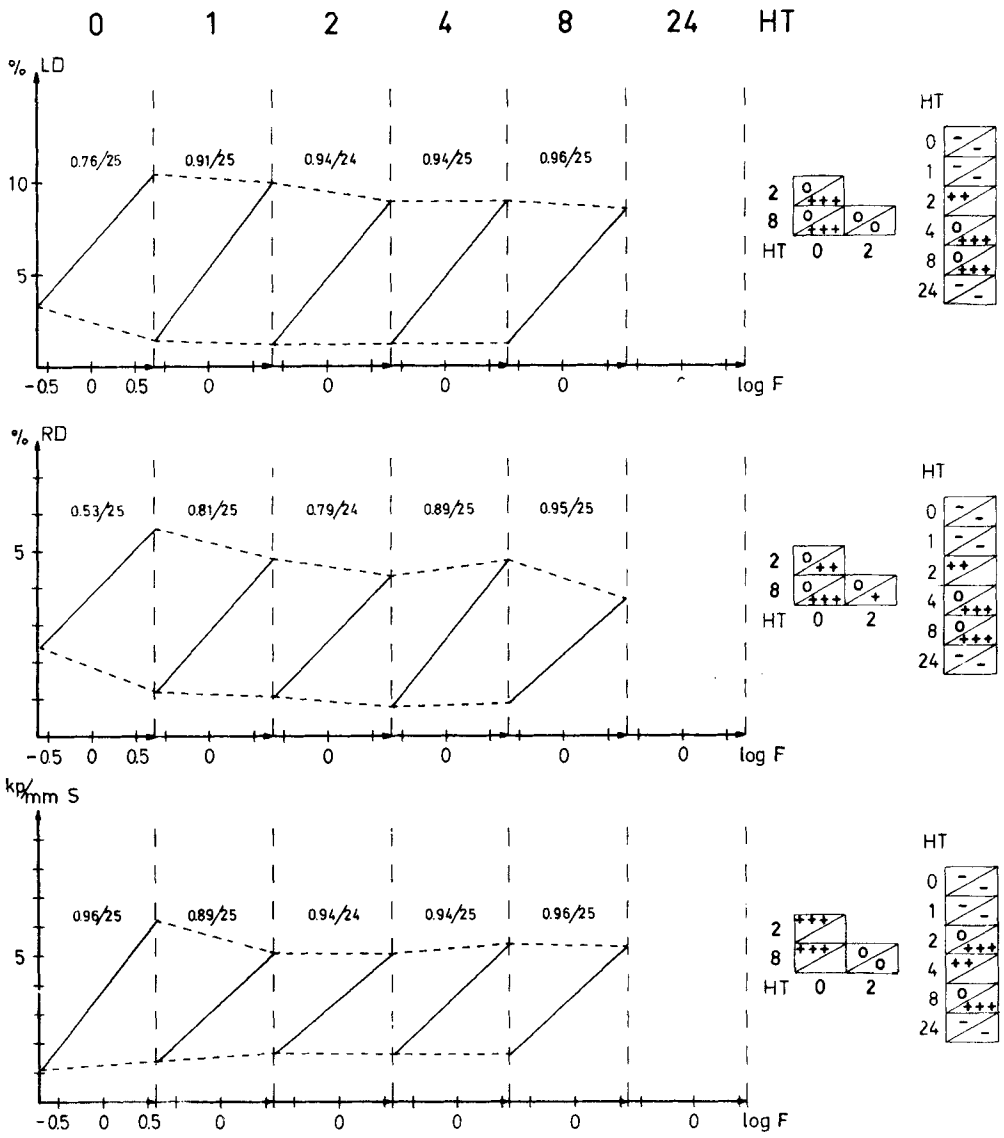
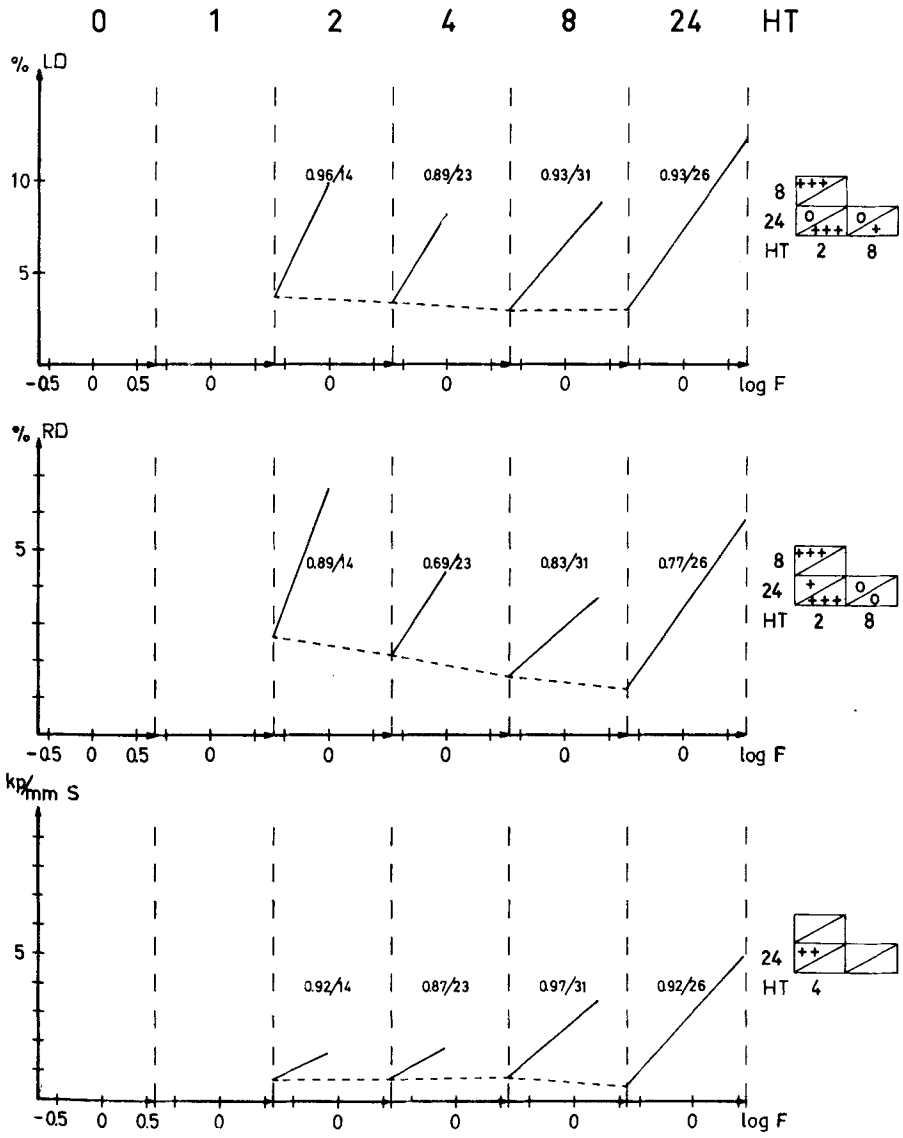


Fig 53–54. Mean regression lines for load deformation (LD), residual deformation (RD) and stiffness (S) versus log F (force in kp) in relation to healing time (HT) in weeks. Left page specimens with muscle release and interrupted sutures on undivided tendons (procedure nr 2).



Right page specimens with muscle release and interrupted sutures on divided tendons (procedure nr 4). For details see legend to fig 41 -42.

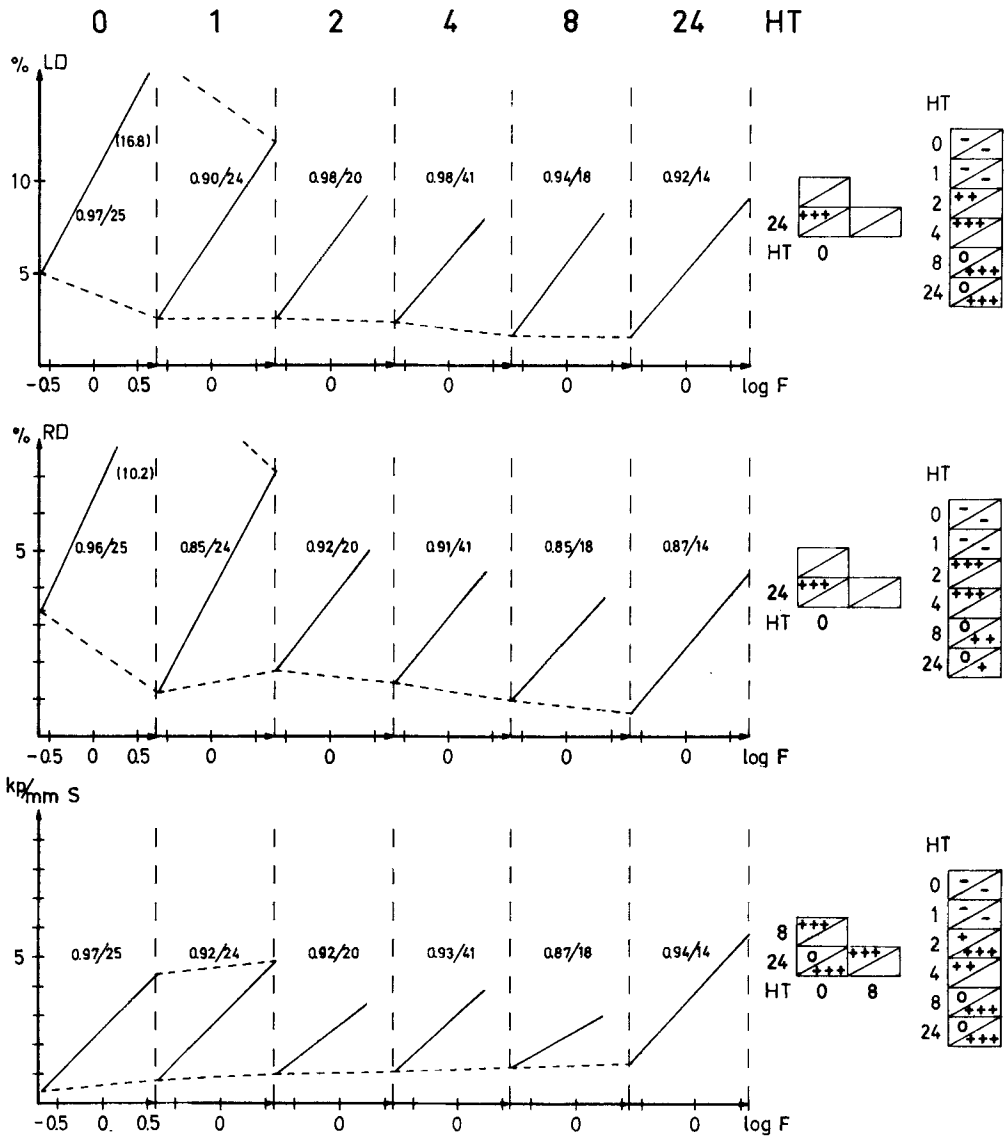
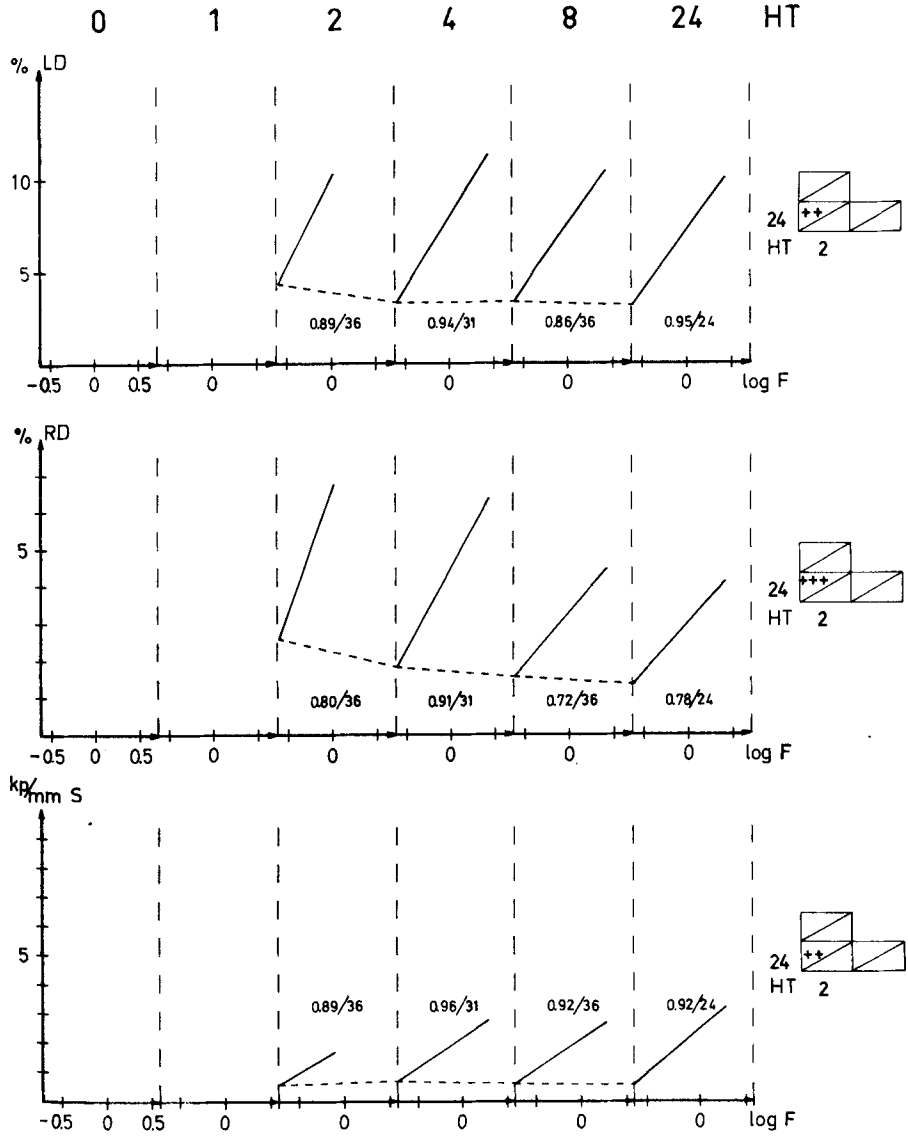


Fig 55–56. Mean regression lines for load deformation (LD), residual deformation (RD) and stiffness (S) versus log F (force in kp) in relation to healing time (HT) in weeks. Left page specimens with muscle release and criss-cross sutures on undivided tendons (procedure nr 3). Right



page specimens with muscle release and criss-cross sutures on divided tendons (procedure nr 5). For details see legend to fig 41–42.

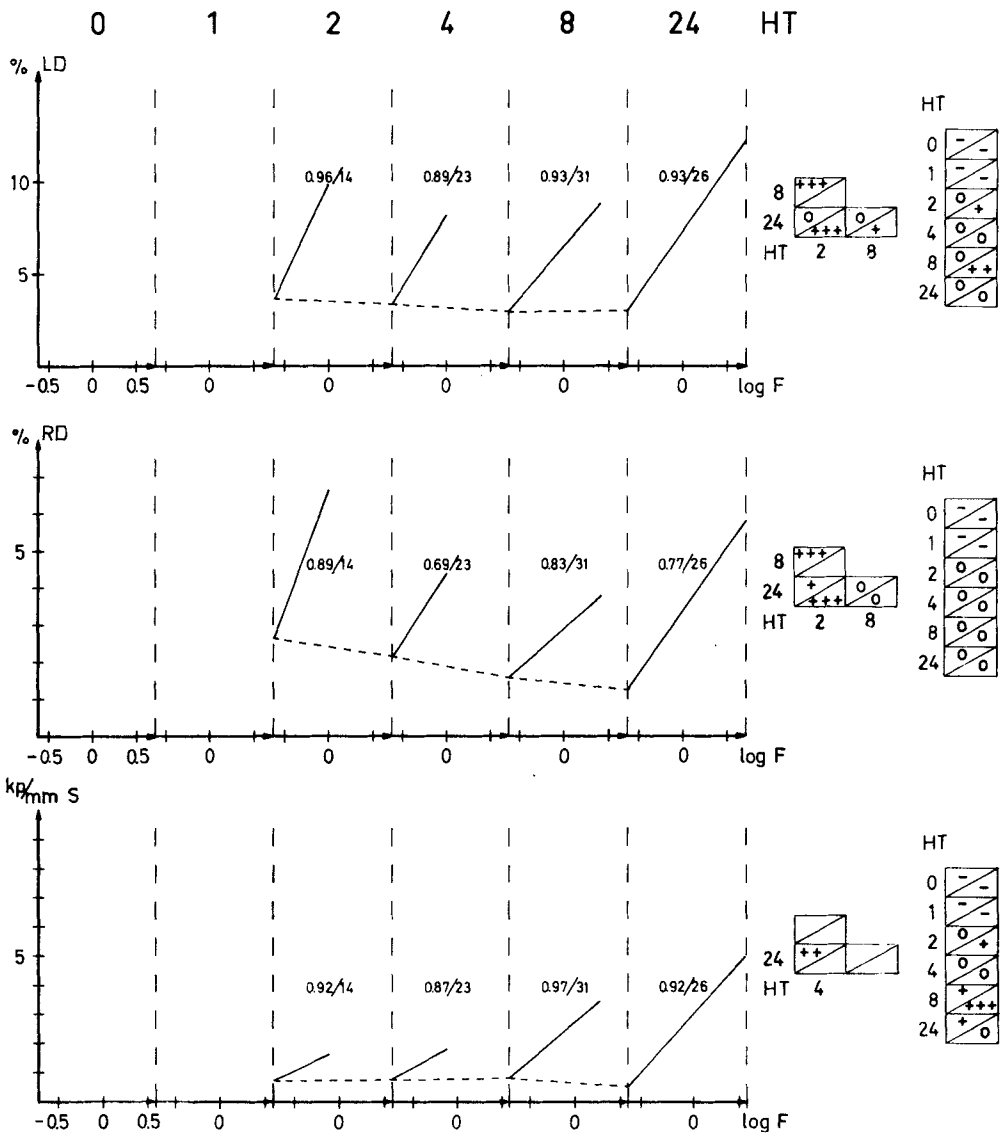
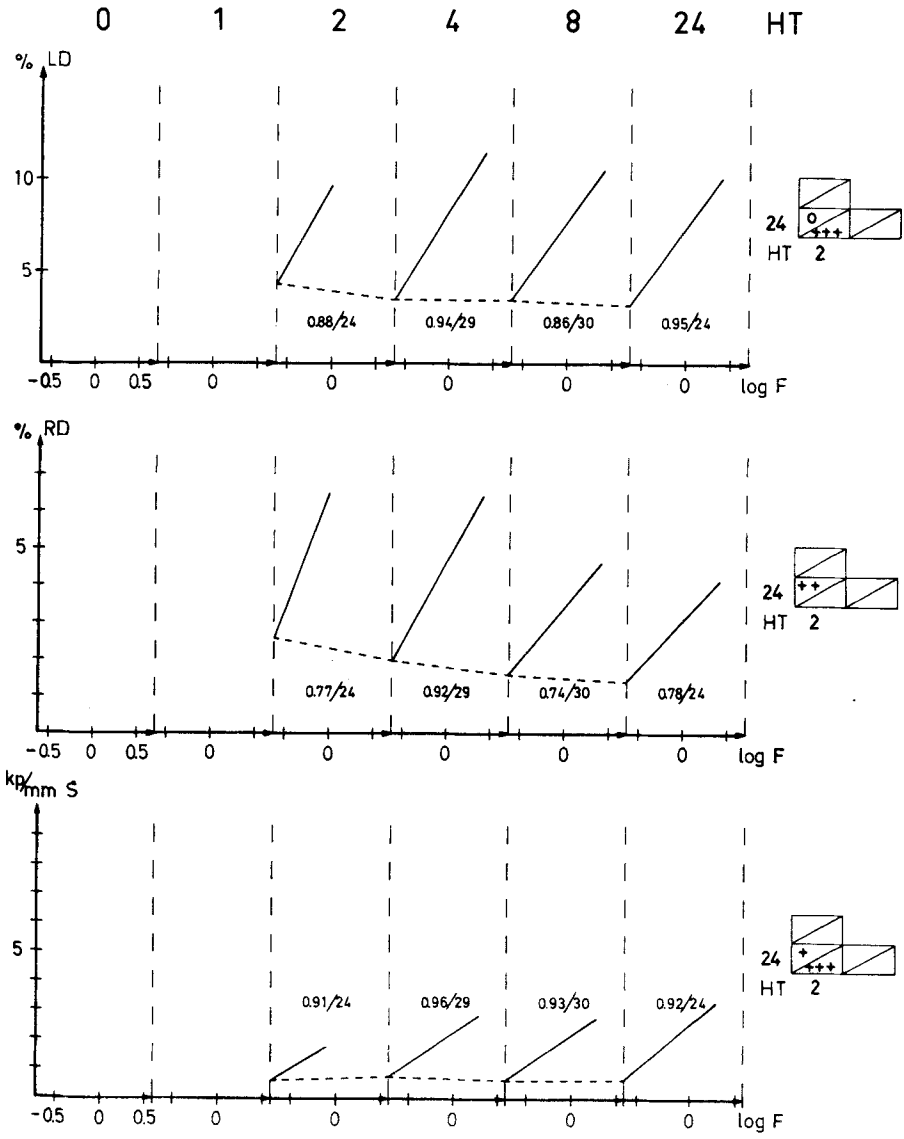


Fig 57–58. Mean regression lines for load deformation (LD), residual deformation (RD) and stiffness (S) versus log F (force in kp) in relation to healing time (HT) in weeks. Left page specimens with muscle release and interrupted sutures on divided tendons (procedure nr 4). Right



page specimens with muscle release and criss-cross sutures on divided tendons (procedure nr 5). For details see legend to fig 41–42.

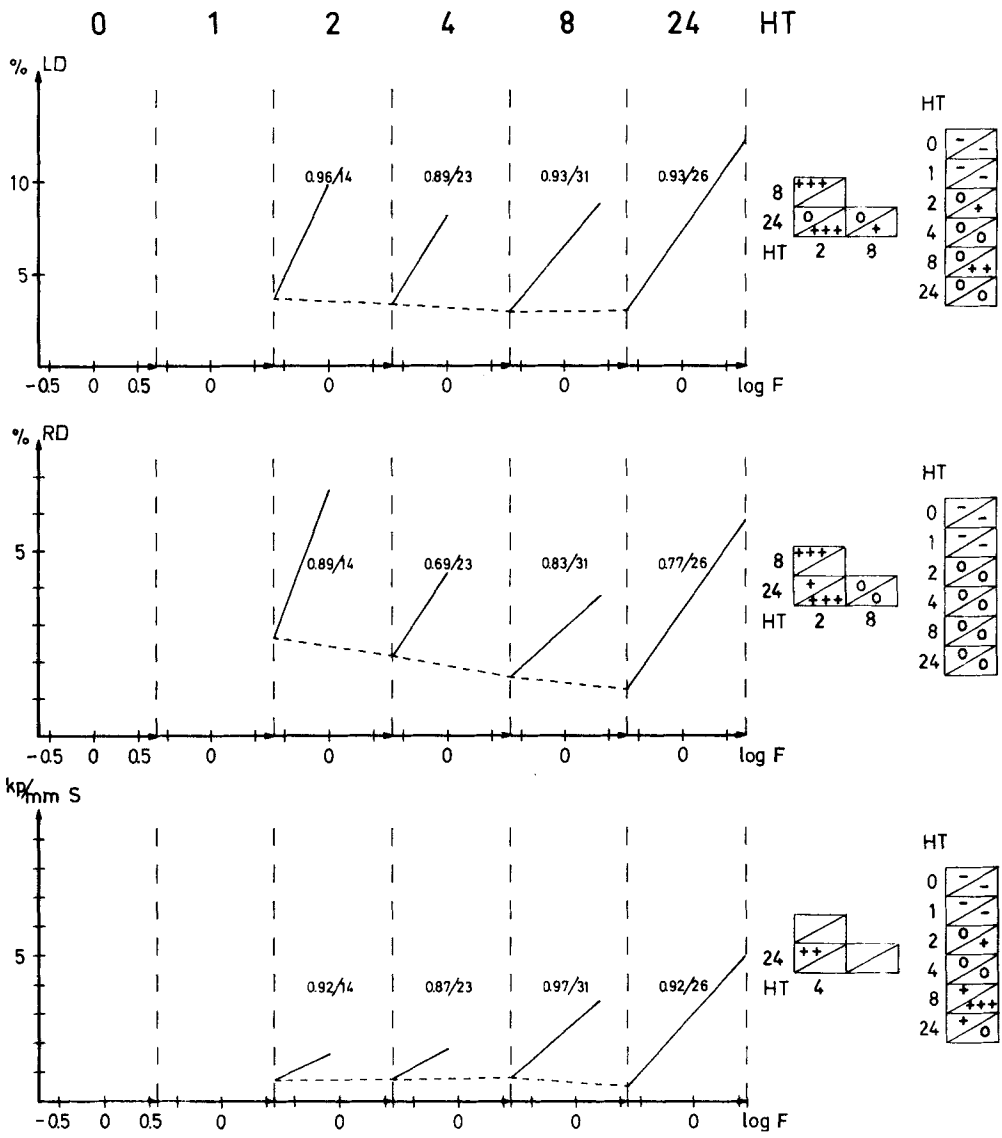
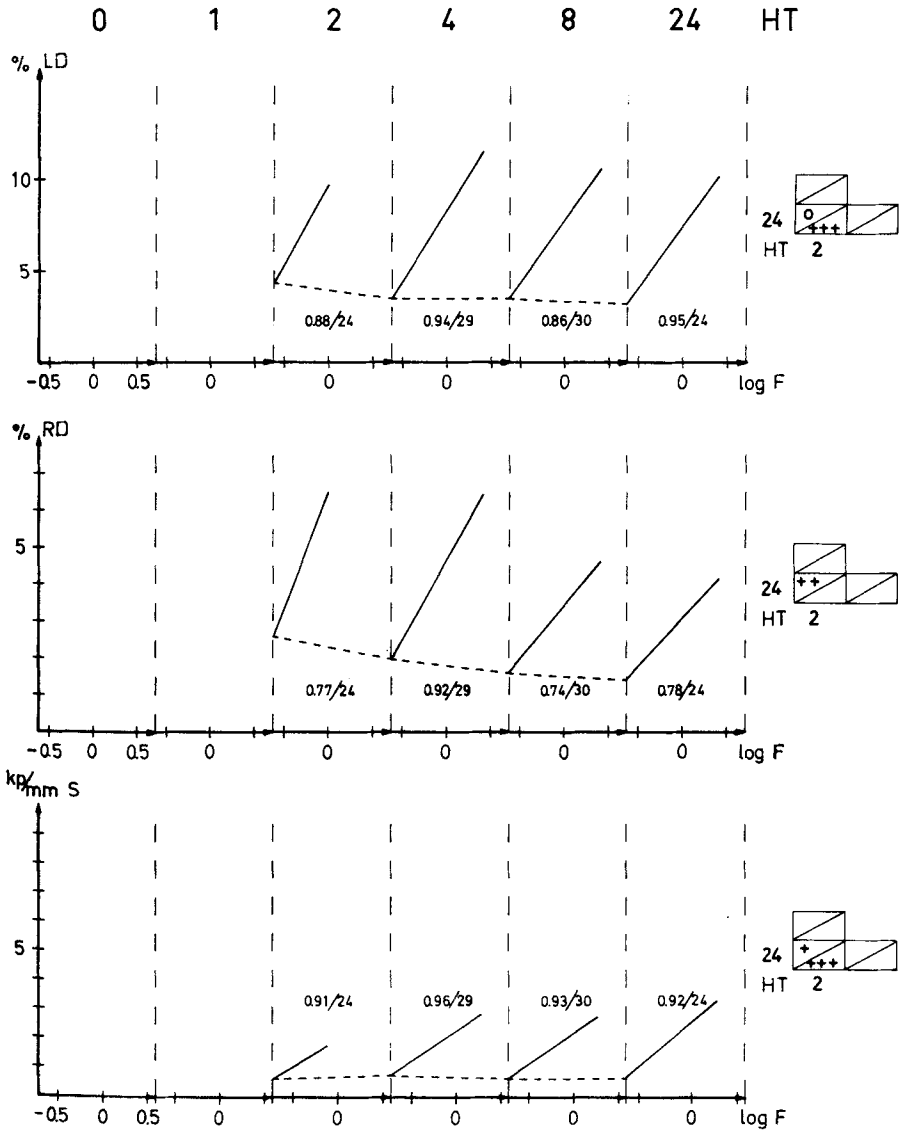


Fig 57–58. Mean regression lines for load deformation (LD), residual deformation (RD) and stiffness (S) versus log F (force in kp) in relation to healing time (HT) in weeks. Left page specimens with muscle release and interrupted sutures on divided tendons (procedure nr 4). Right



Page specimens with muscle release and criss-cross sutures on divided tendons (procedure nr 5). For details see legend to fig 41–42.

Fig 59–60. Mean regression lines for creep versus log t (time in sec) at varying load levels and in relation to HT (healing time in weeks). Left page intact specimens (procedure nr 0), right page specimens with muscle release only (procedure nr 1). Match after procedure number (at the top) = matched groups, see page 50. HT for intact tendons relates to the muscle release performed on the contralateral leg.

The ordinate is repeated 5 times corresponding to load levels noted to the right just above the abscissa.

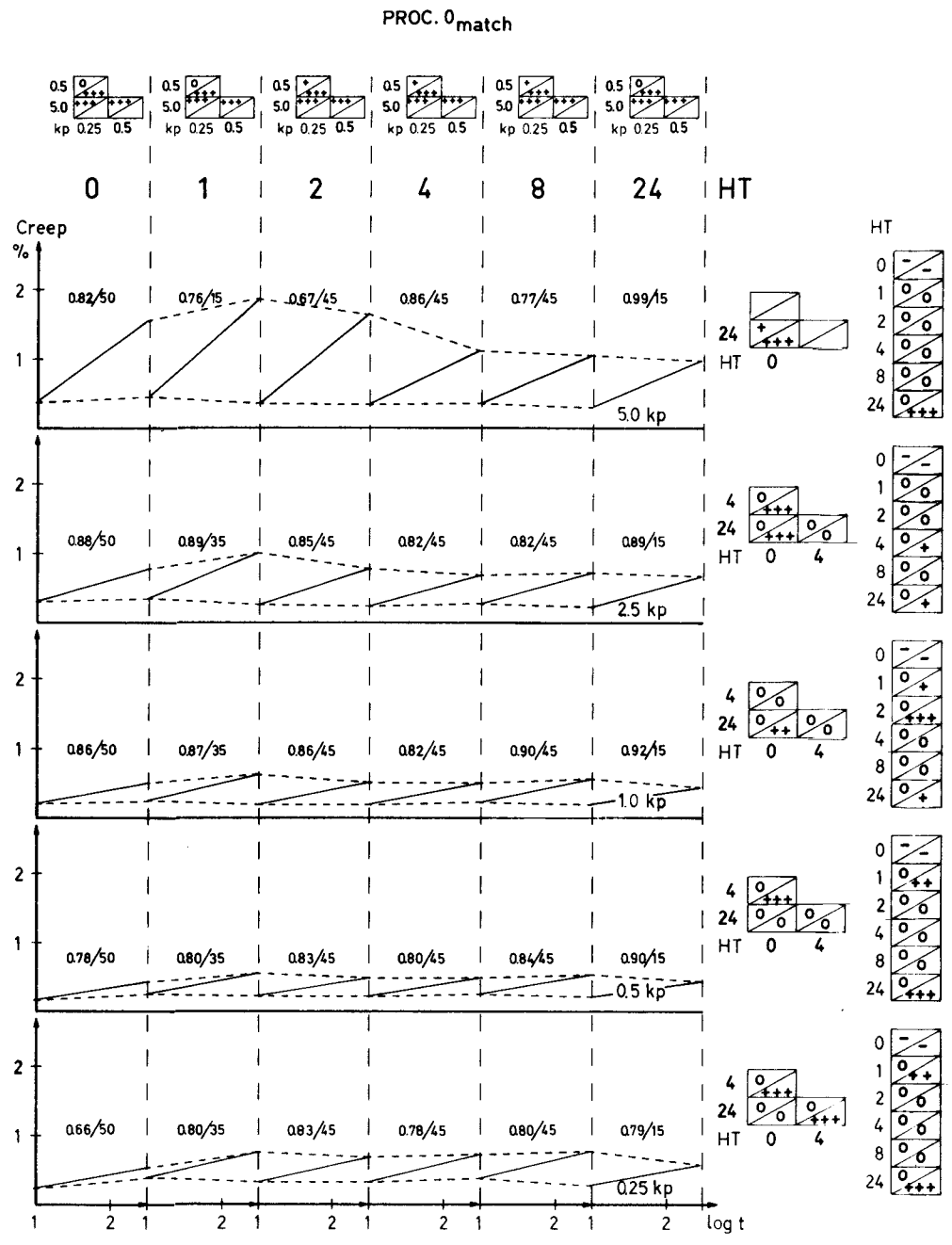
The abscissa is repeated 6 times as indicated by the vertical broken lines and corresponding to various HT noted at the top in bold figures.

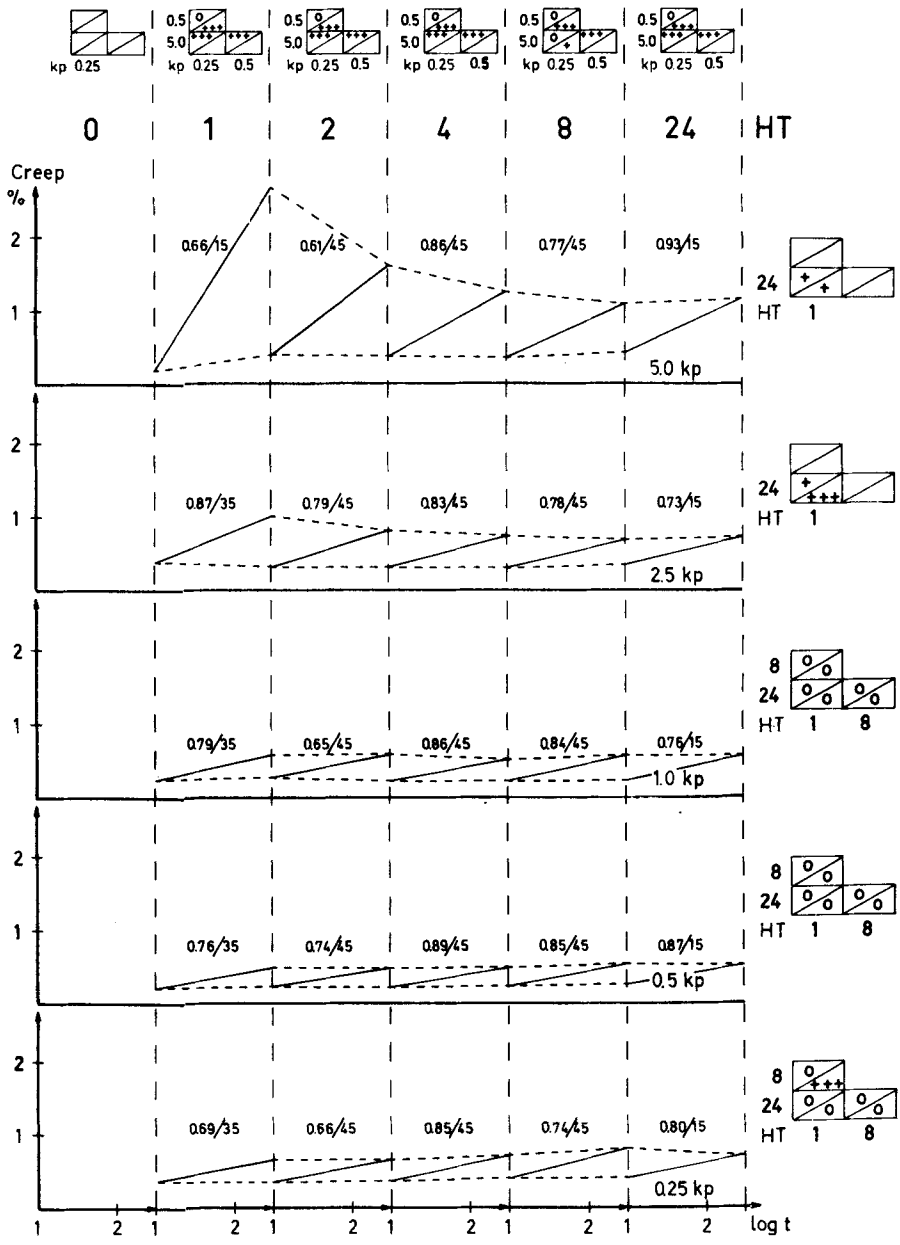
With each regression line a fraction is given. The numerator = coefficient of correlation = r, the denominator = number of observations = n.

Results of statistical analysis comparing *different load levels* for the *same HT* in the *same procedure* are given in scoreboards at the top. Signs in the scoreboards: 0 = $p > .05$, +, ++, +++ = $p \leq .05$, .01, .001 respectively. Statistical differences for coefficients of regression = b are given in the upper left triangle, and for mean values of the ordinate = intercept = a in the lower right triangle. (For instance when comparing .25 and .5 kp for HT 24 in proced nr 0 b is equal indicated by 0 in the upper left triangle and a is lower for .5 kp, +++ in the lower right triangle.)

Results of statistical analysis comparing *different HT* at the *samt load level* in the *same procedure* are given in scoreboards to the right. (For instance when comparing HT 0 and 24 on load level .25 kp in proced nr 0 both b and a are equal indicated by 0 in both triangles.)

Results of statistical analysis *comparing procedures* for *equal HT and load level* are given in the vertical column in the middle. (For instance, when comparing regression lines at load level 1.0 kp at HT 1 b is equal = 0 in the upper left triangle and a is lower for proced nr 1= + in the lower right triangle.)




kp 0.25
0.5
5.0
kp 0.25 0.5
0
1
2
4
8
24
HT
Creep
%
0.66/15
0.61/45
0.86/45
0.77/45
0.93/15
5.0 kp
0.87/35
0.79/45
0.83/45
0.78/45
0.73/15
2.5 kp
0.79/35
0.65/45
0.86/45
0.84/45
0.76/15
1.0 kp
0.76/35
0.74/45
0.89/45
0.85/45
0.87/15
0.5 kp
0.69/35
0.66/45
0.85/45
0.74/45
0.80/15
0.25 kp
log t

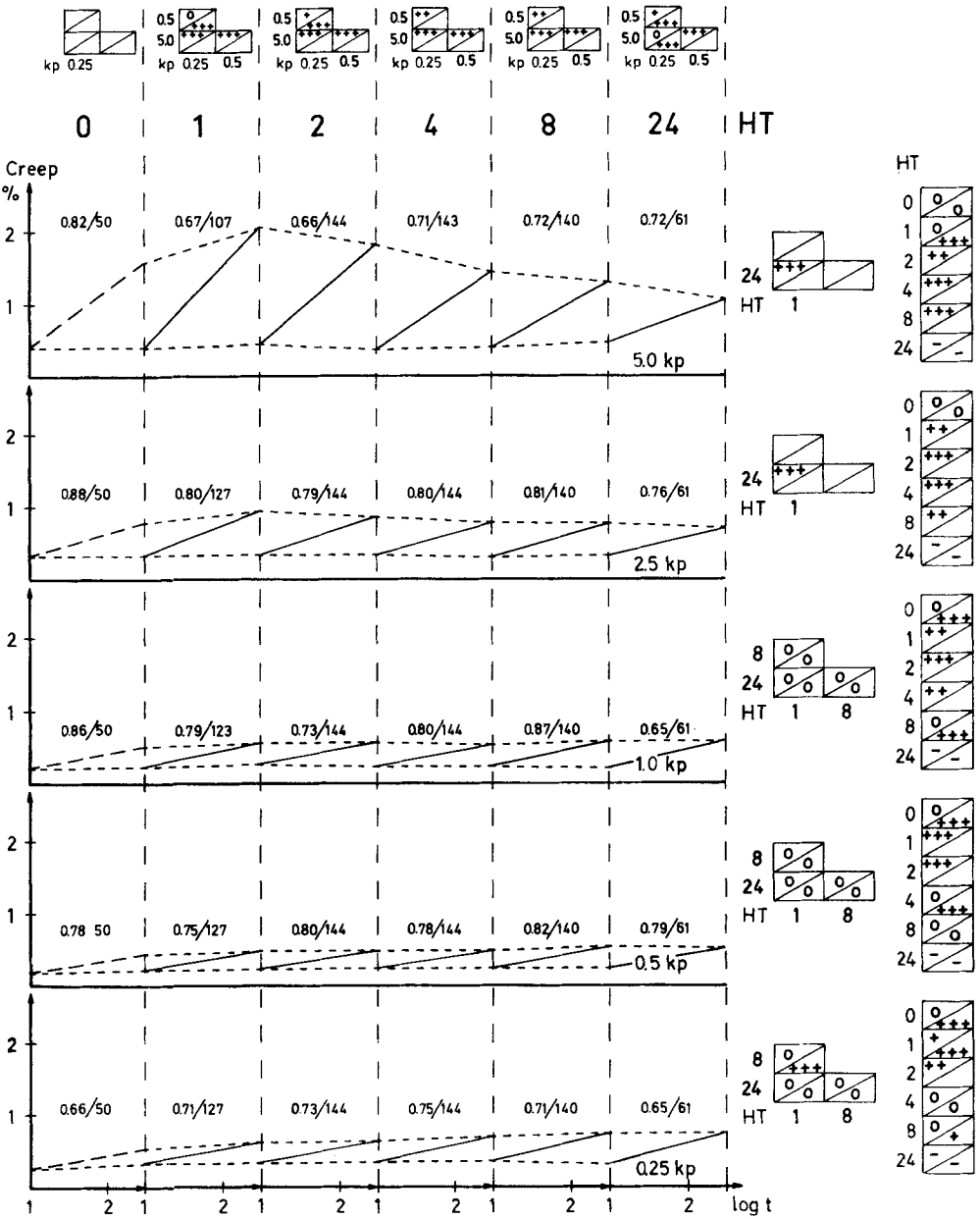
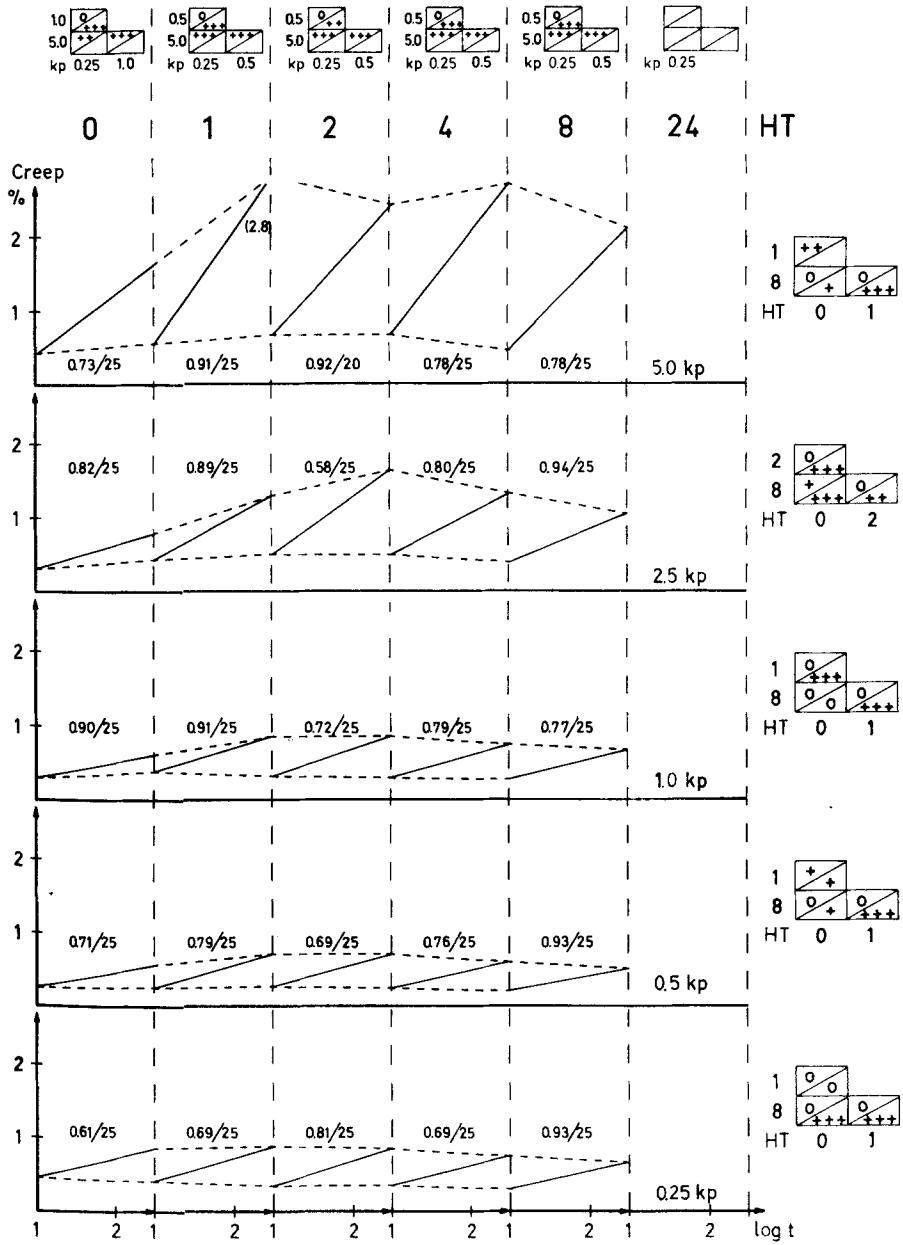


Fig 61–62. Mean regression lines for creep versus log t (time in sec) at varying load levels and in relation to HT (healing time in weeks). Left page control specimens (procedure nr 0+1). Right page



specimens with muscle release and interrupted sutures on undivided tendons (procedure nr 2). For details see legend to fig 59 - 60.

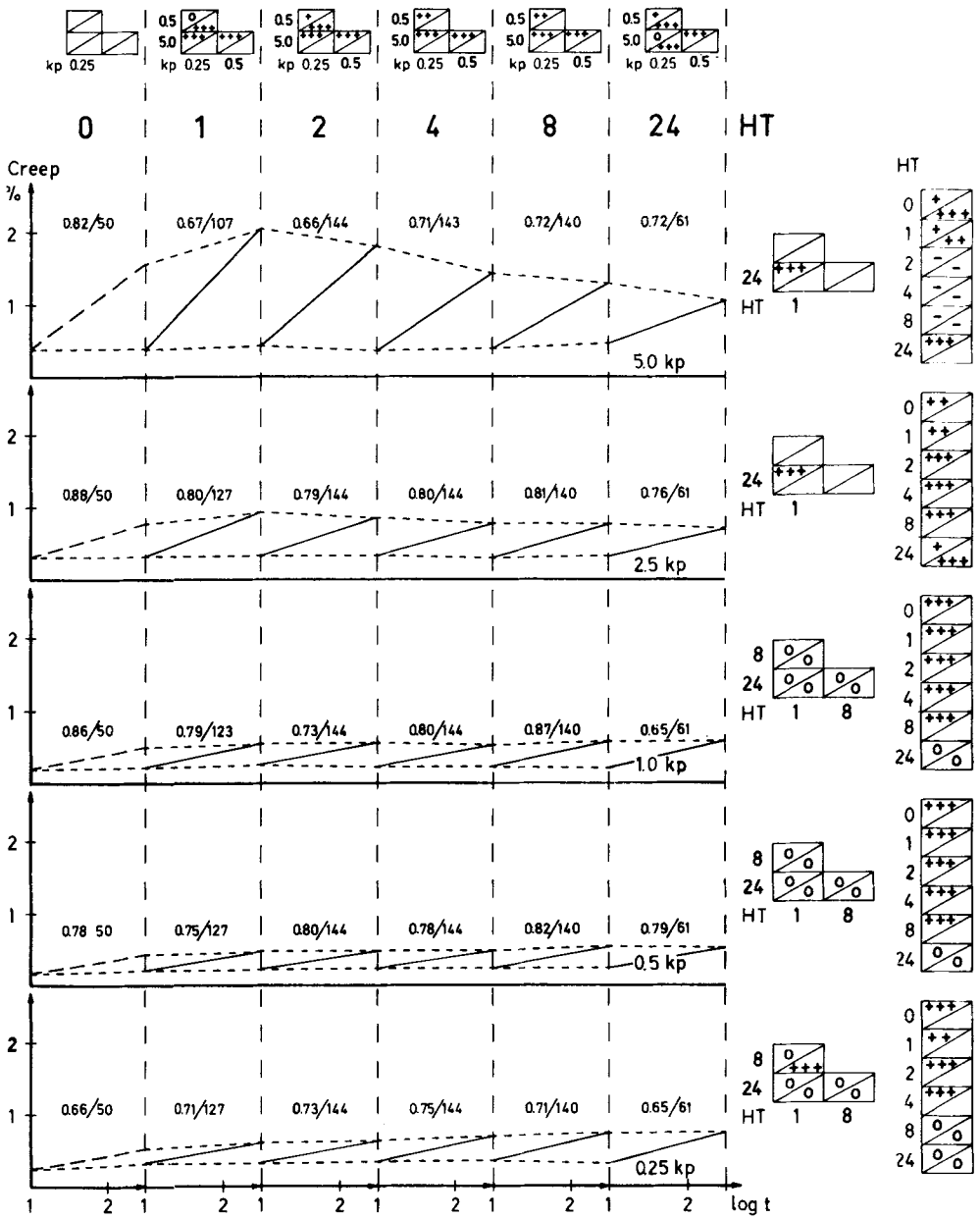
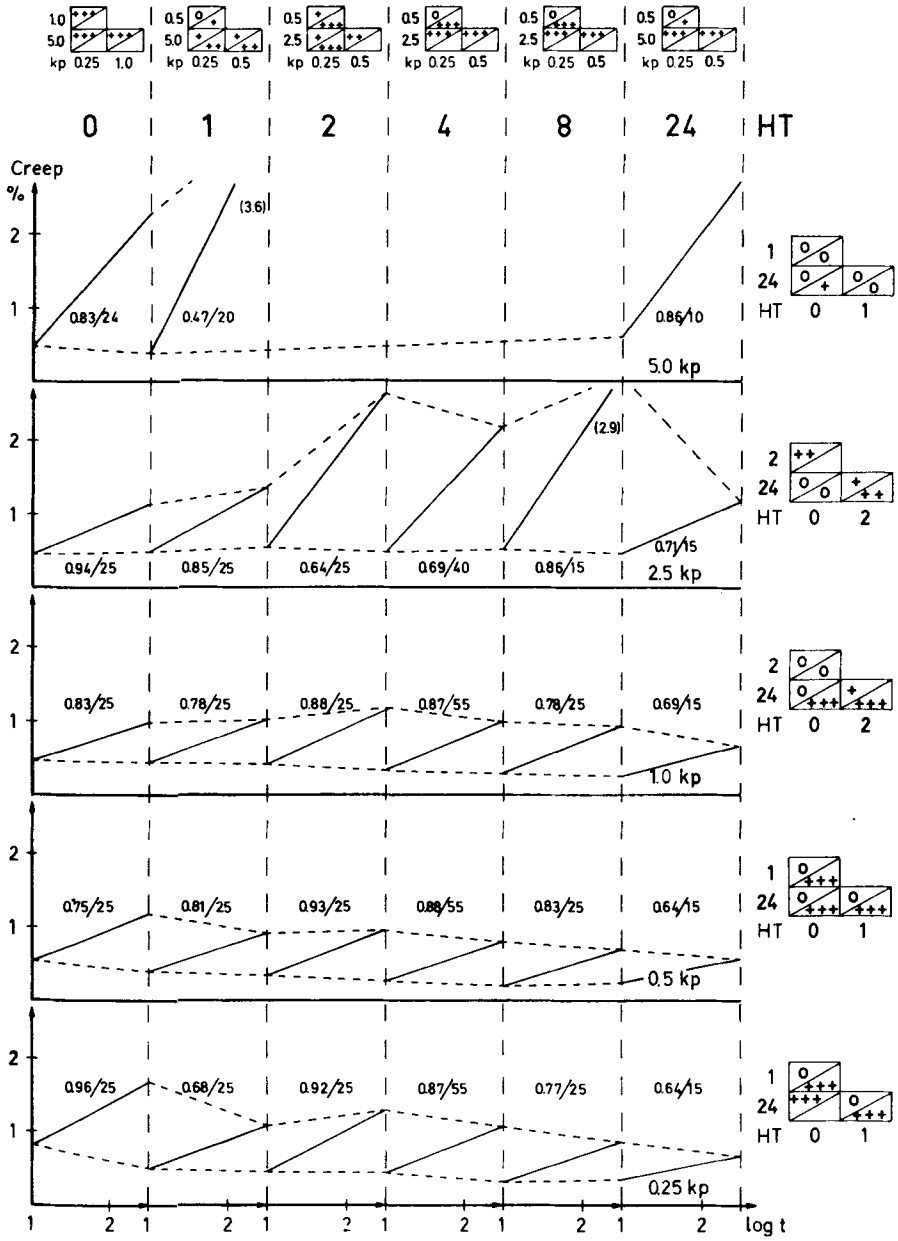


Fig 63–64. Mean regression lines for creep versus log t (time in sec) at varying load levels and in relation to HT (healing time in weeks). Left page control specimens (procedure nr 0+1). Right page



specimens with muscle release and criss-cross sutures on undivided tendons (procedure nr 3). For details see legend to fig 59 - 60.

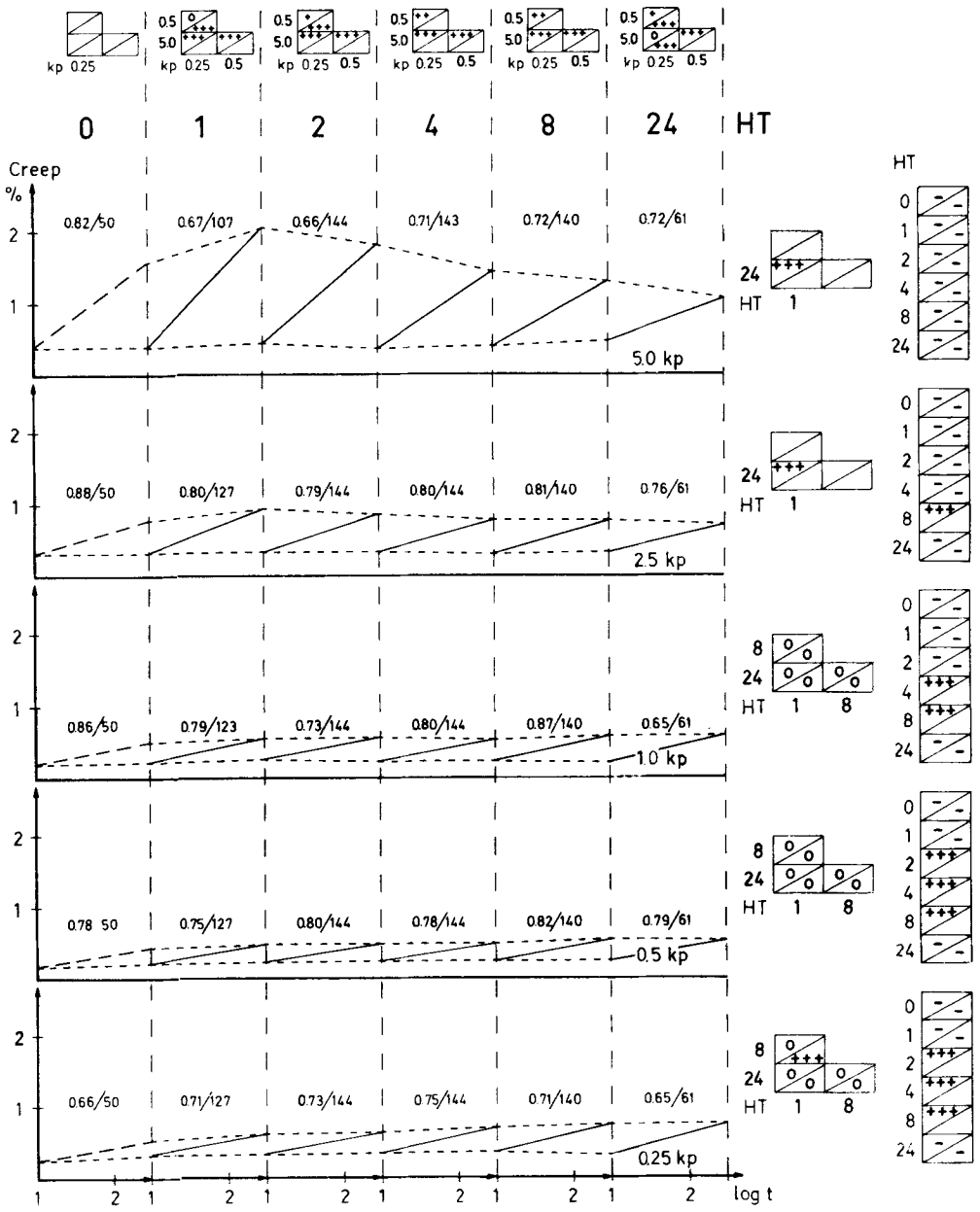
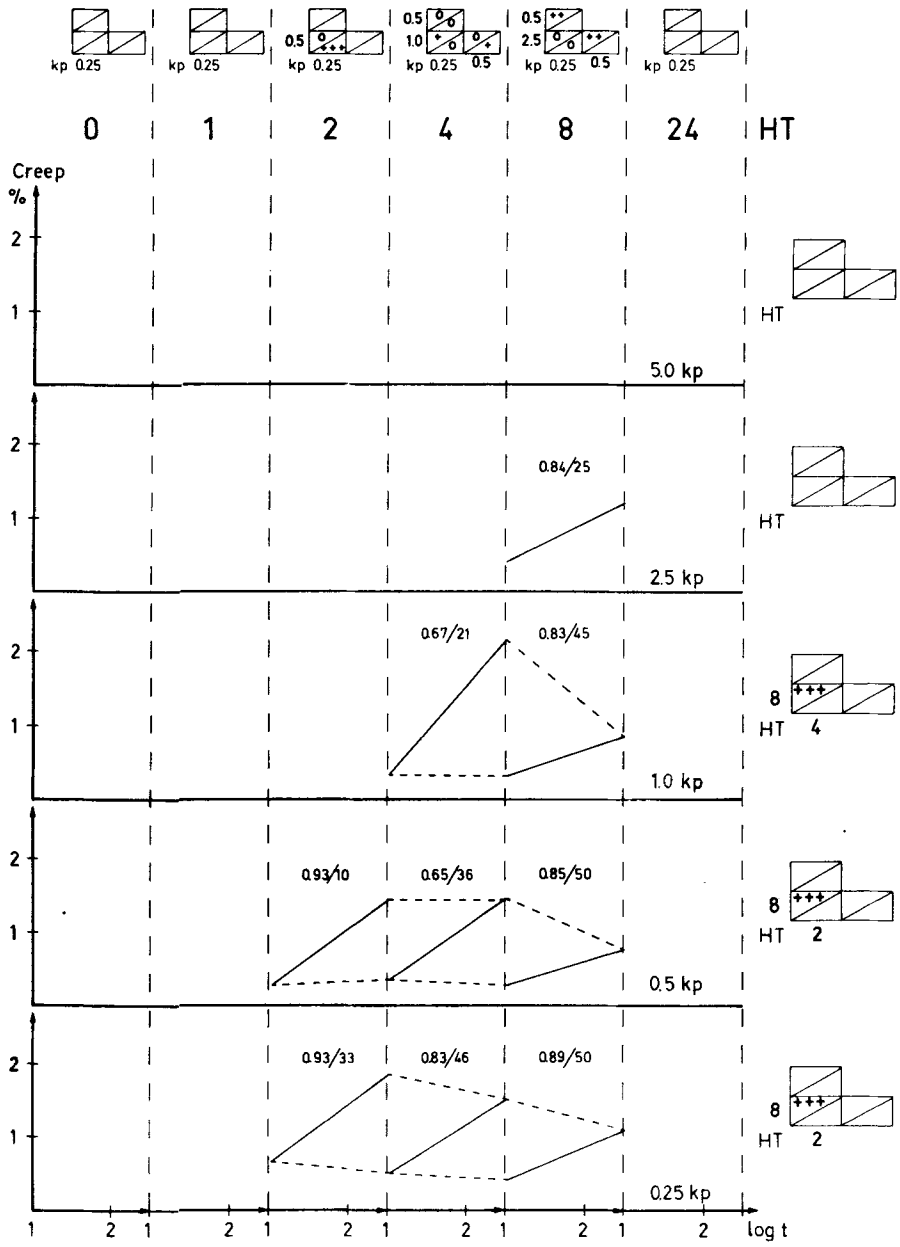


Fig 65–66. Mean regression lines for creep versus log t (time in sec) at varying load levels and in relation to HT (healing time in weeks). Left page control specimens (procedure nr 0+1). Right page



specimens with muscle release an interrupted sutures on divided tendons (procedure n 4). For details see legend to fig 59–60.

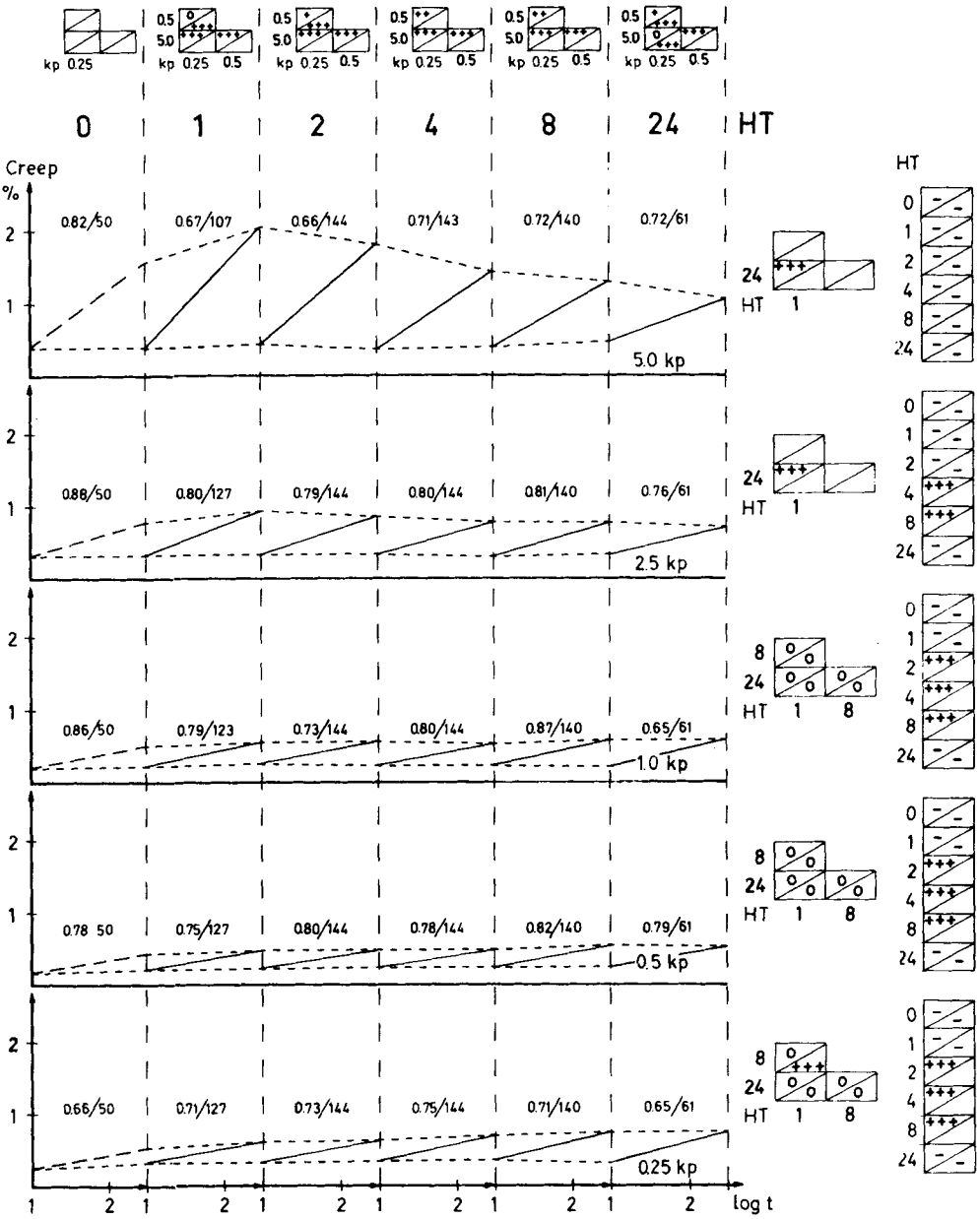
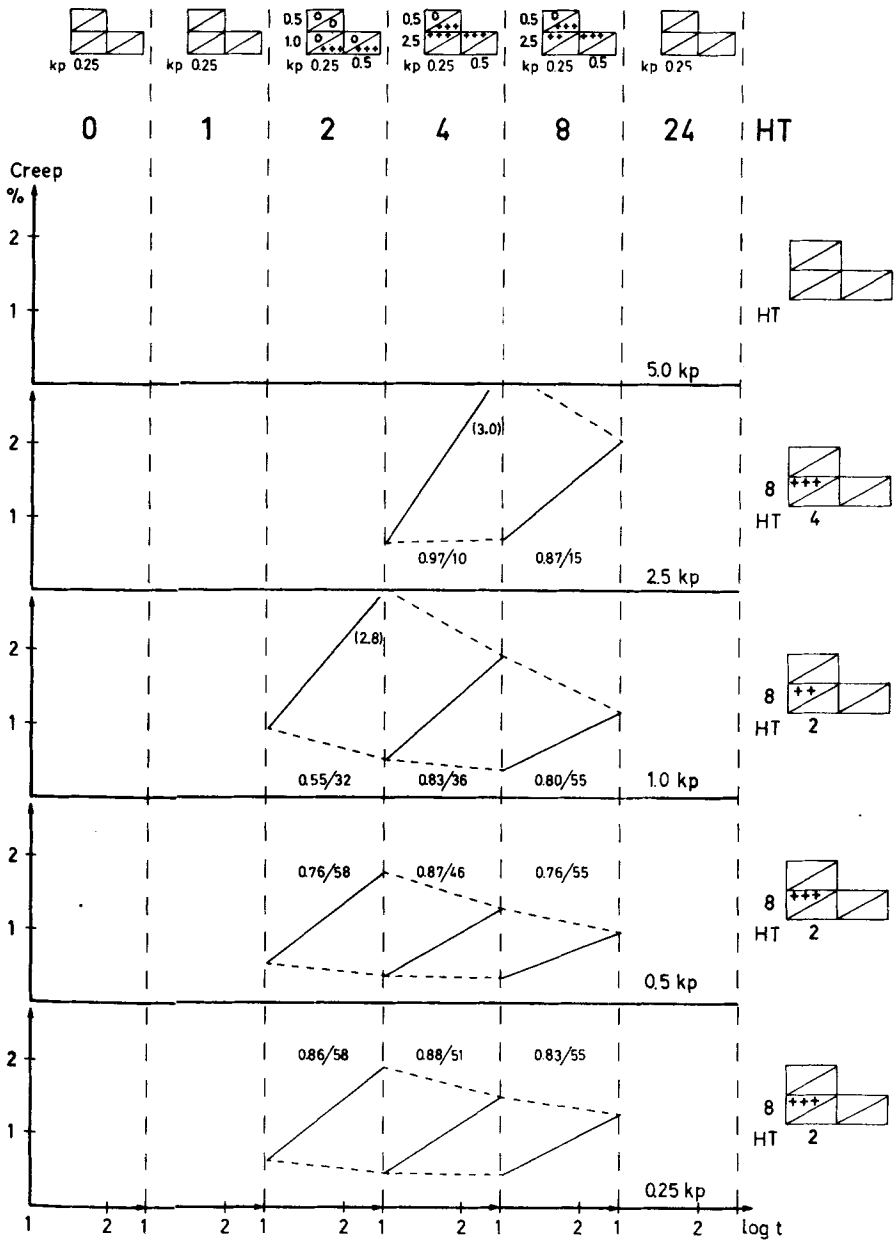


Fig 67–68. Mean regression lines for creep versus log t (time in sec) at varying load levels and in relation to HT (healing time in weeks). Left page control specimens (procedure nr 0+1). Right page



specimens with muscle release and criss-cross sutures on divided tendons (procedure nr 5). For details see legend to fig 59–60.

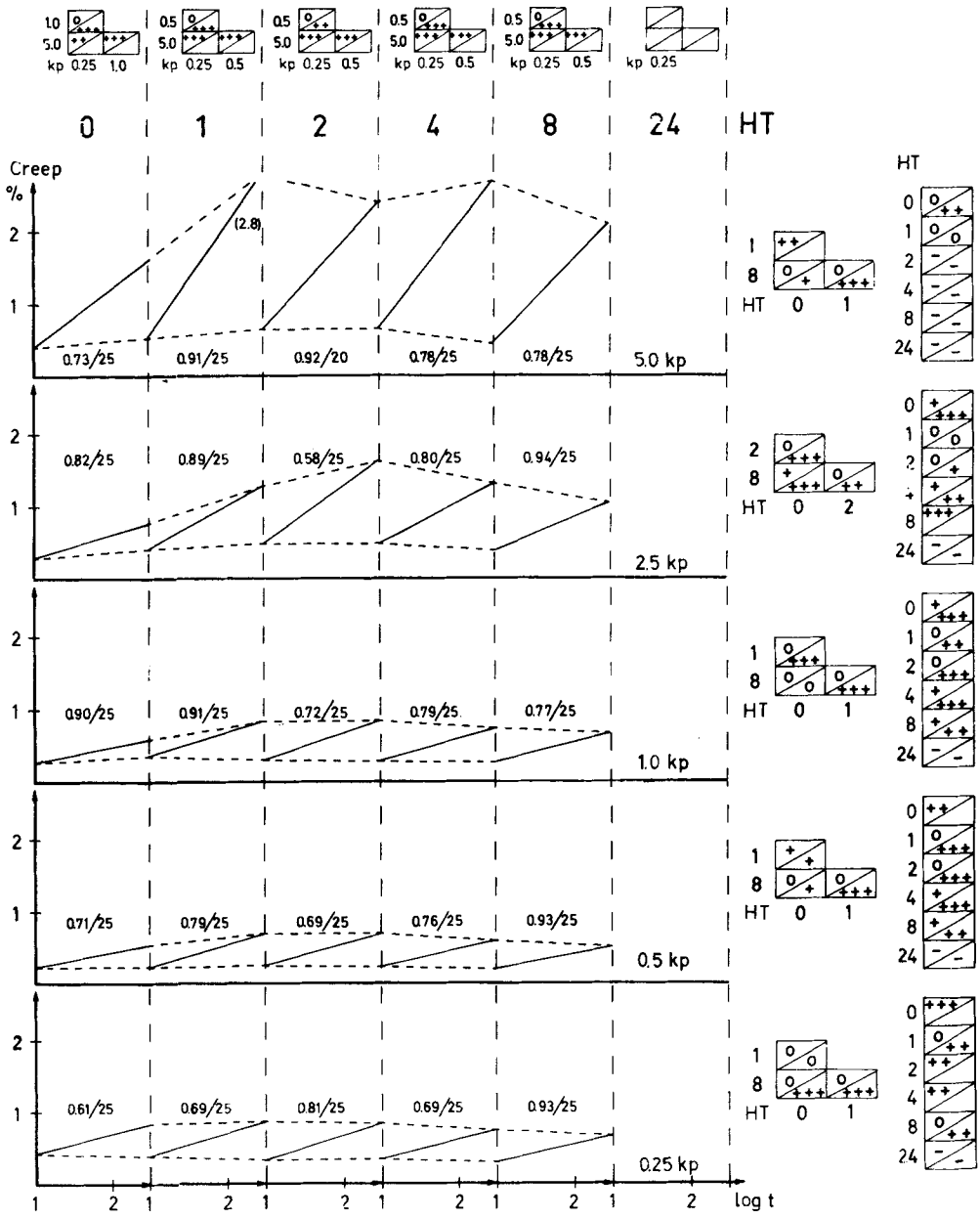
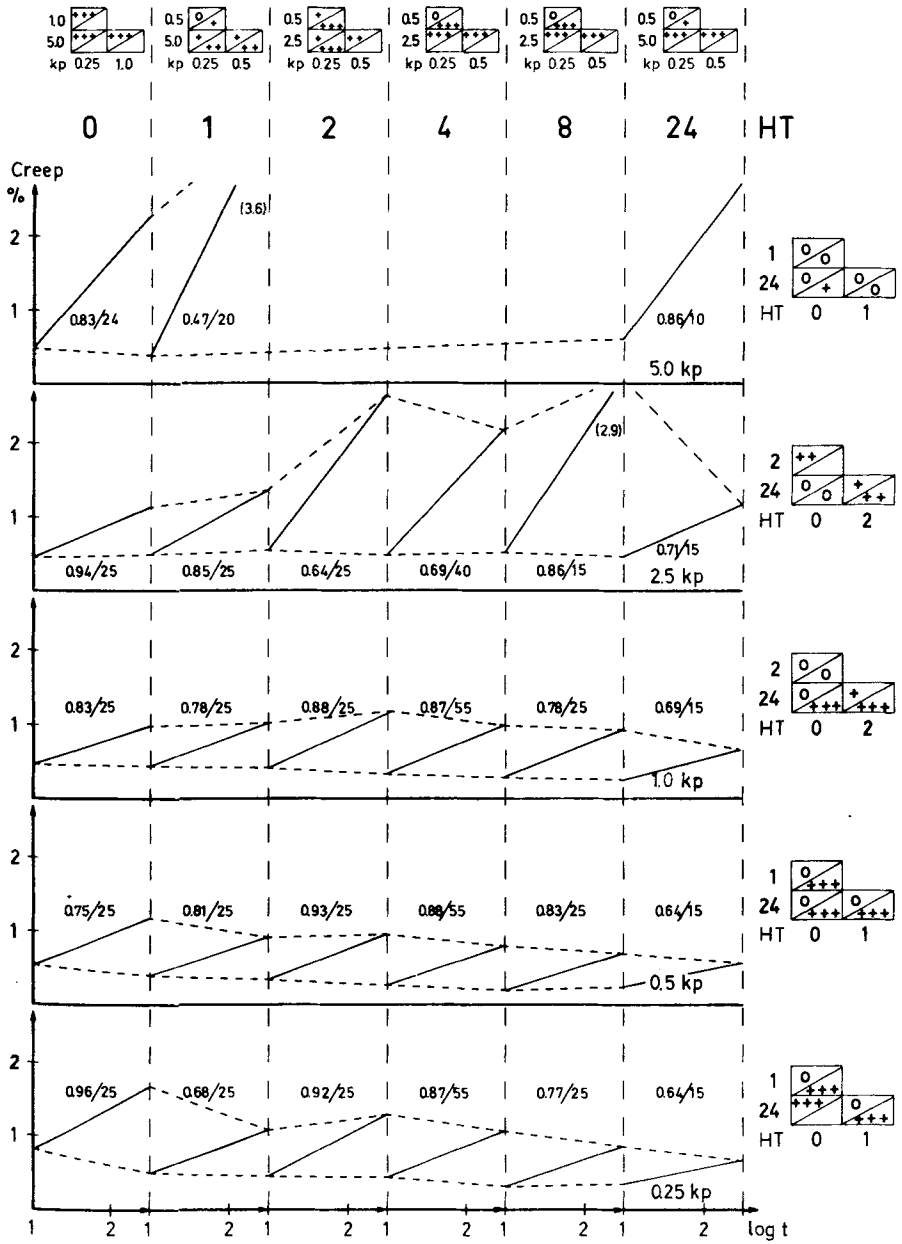


Fig 69–70. Mean regression lines for creep versus log t (time in sec) at varying load levels and in relation to HT (healing time in weeks). Left page specimens with muscle release and interrupted



sutures on undivided tendons (procedure nr 2). Right page specimens with muscle release and criss-cross sutures on undivided tendons (procedure nr 3). For details see legend to fig 59–60.

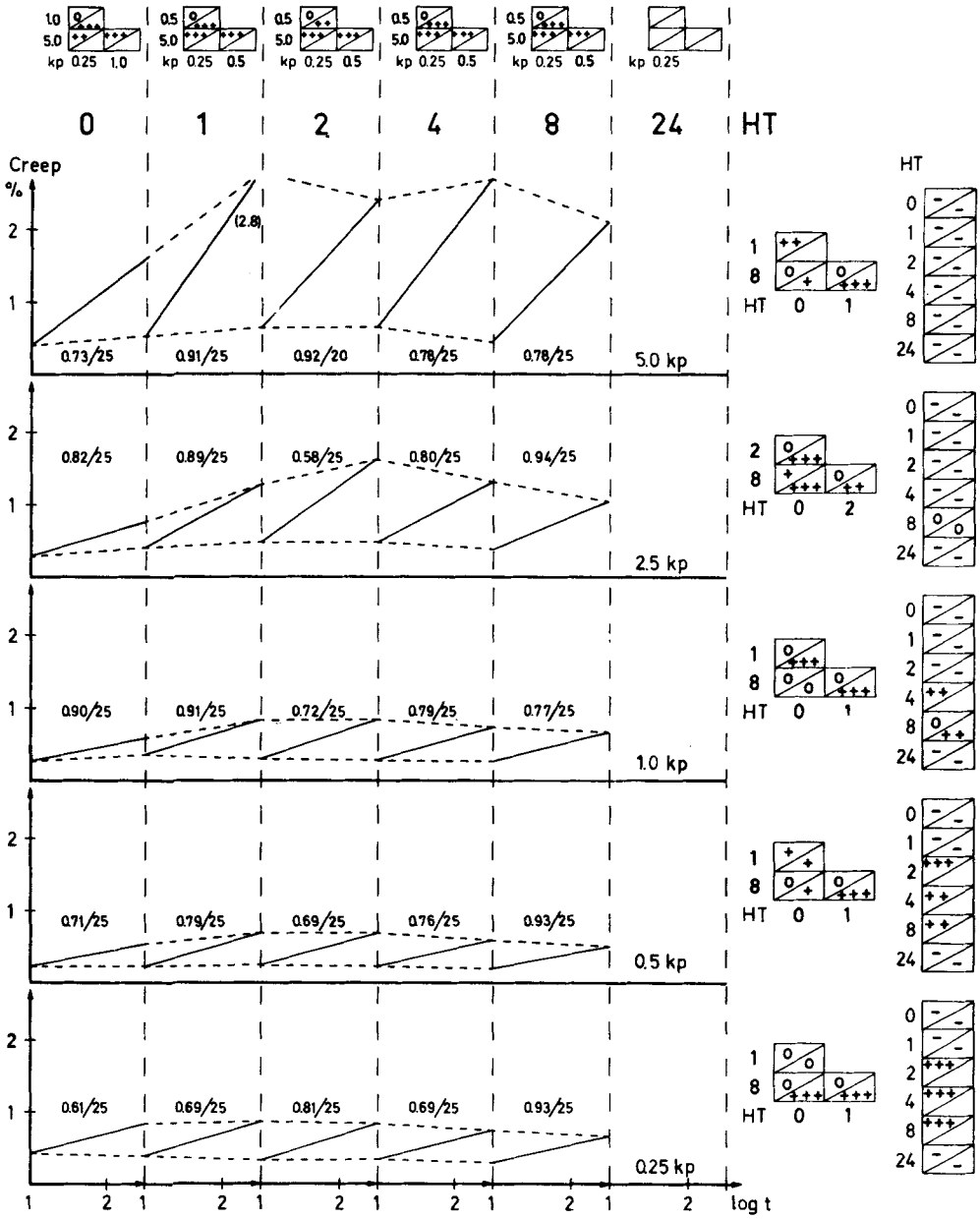
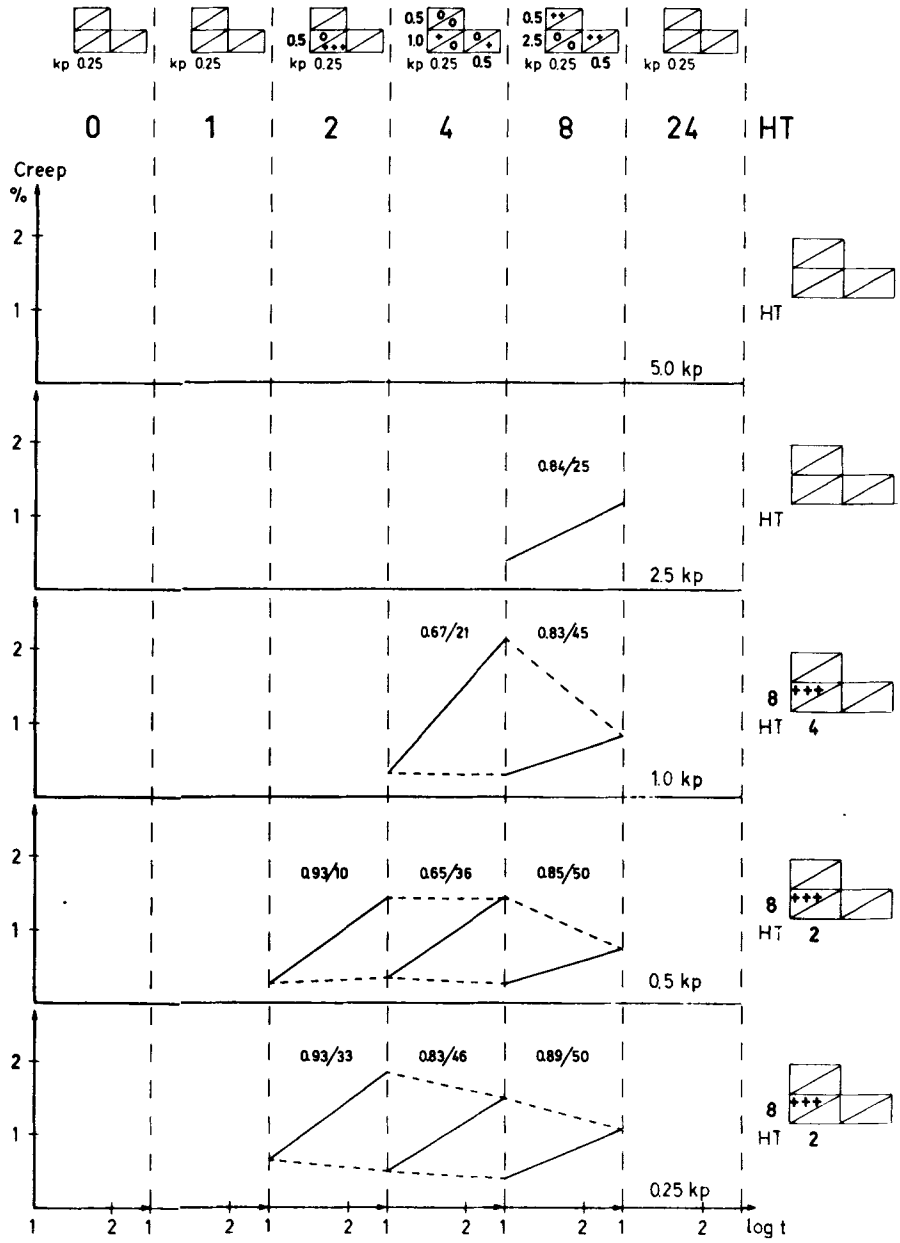


Fig 71–72. Mean regression lines for creep versus log t (time in sec) at varying load levels and in relation to HT (healing time in weeks). Left page specimens with muscle release and interrupted



sutures on undivided tendons (procedure nr 2). Right page specimens with muscle release and interrupted sutures on divided tendons (procedure nr 4). For details see legend to fig 59–60.

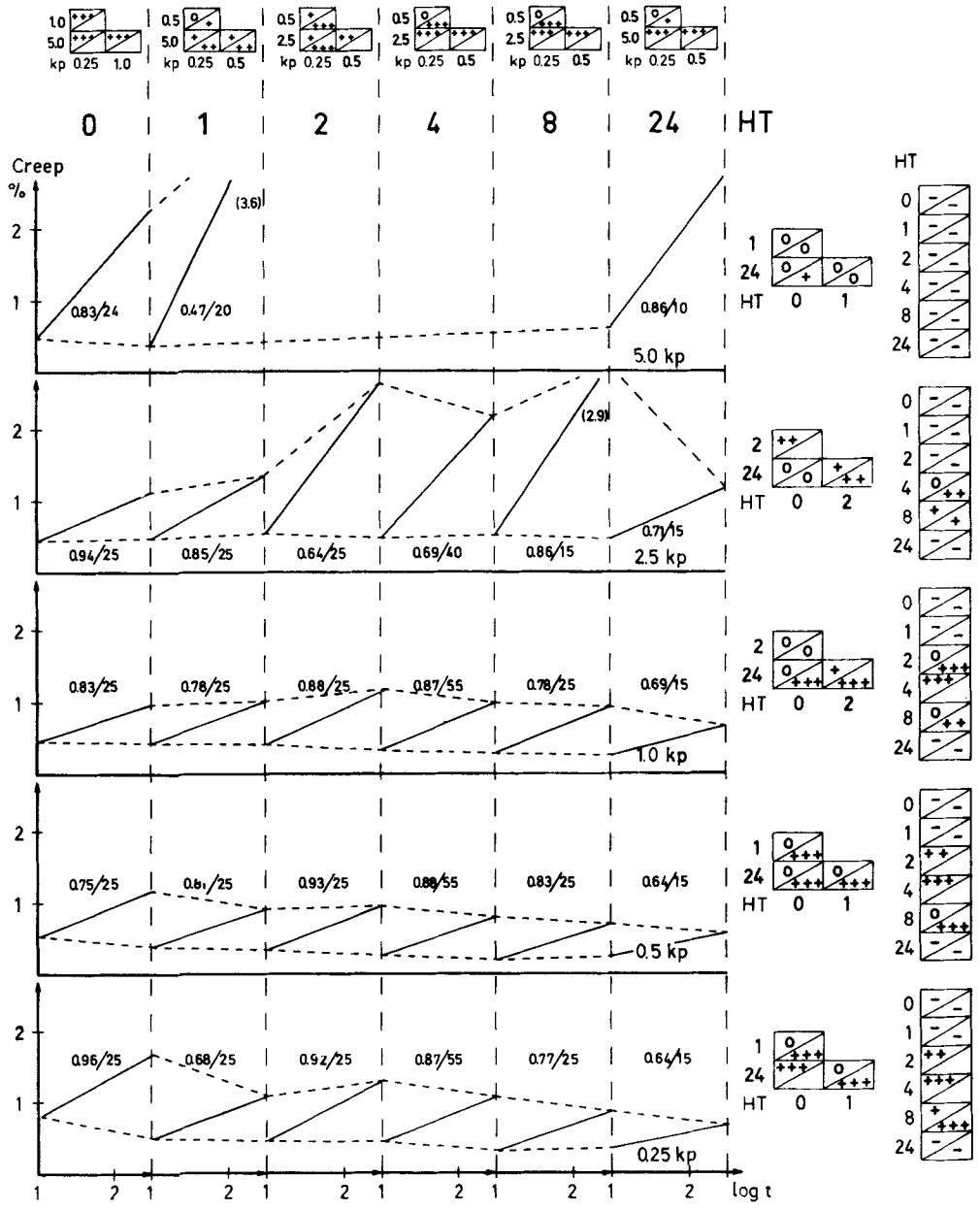
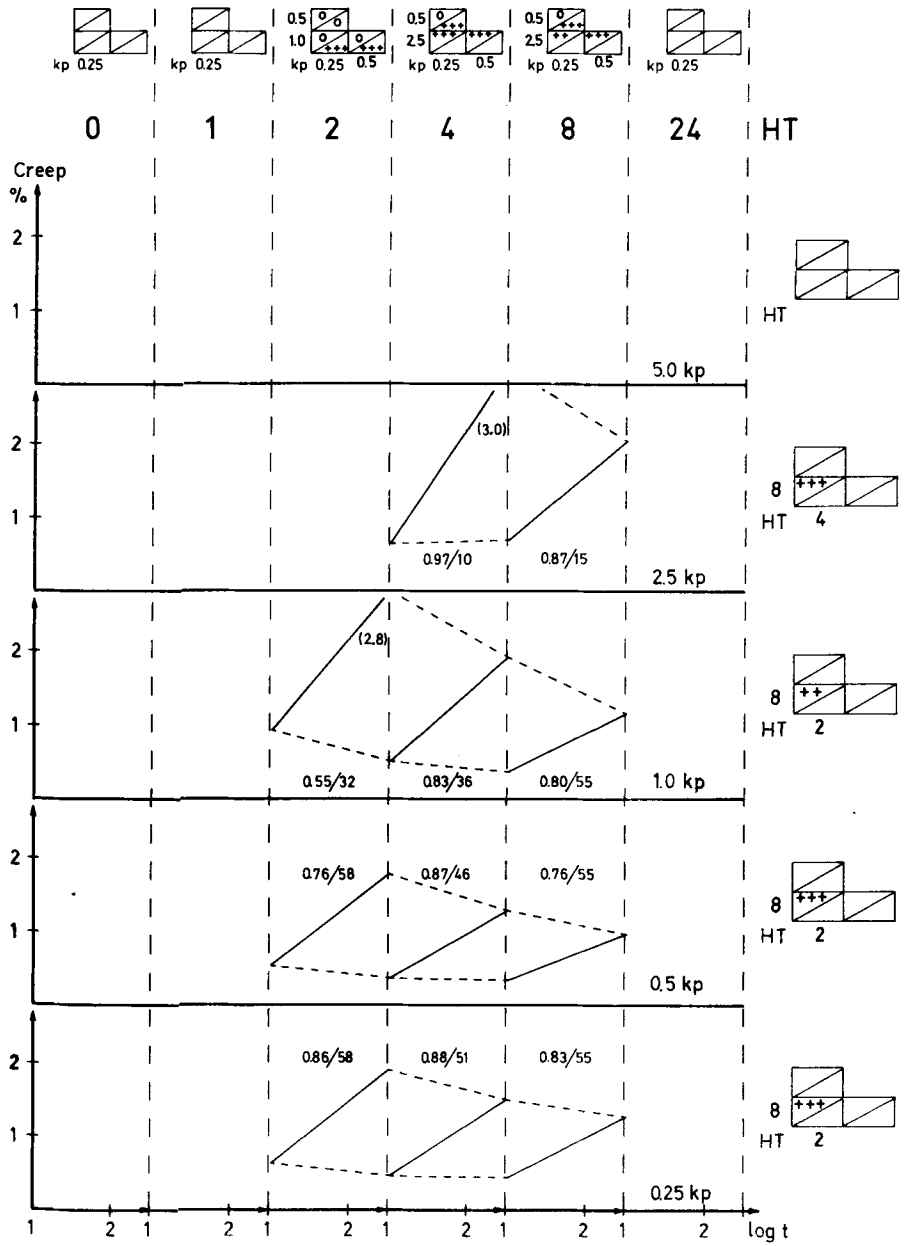


Fig 73–74. Mean regression lines for creep versus log t (time in sec) at varying load levels and in relation to HT (healing time in weeks). Left page specimens with muscle release and criss-cross



sutures on undivided tendons (procedure nr 3). Right page specimens with muscle release and criss-cross sutures on divided tendons (procedure nr 5). For details see legend to fig 59–60.

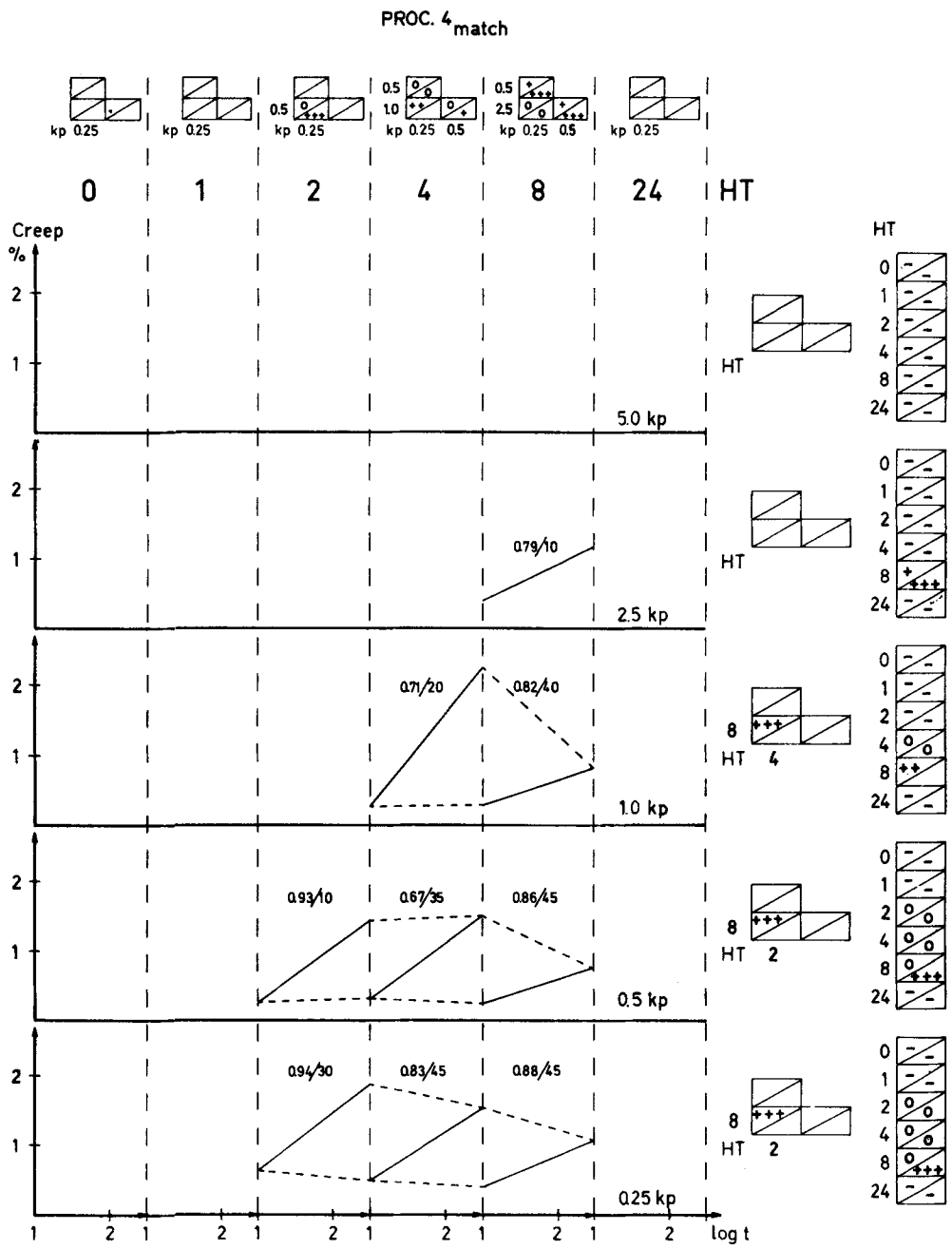
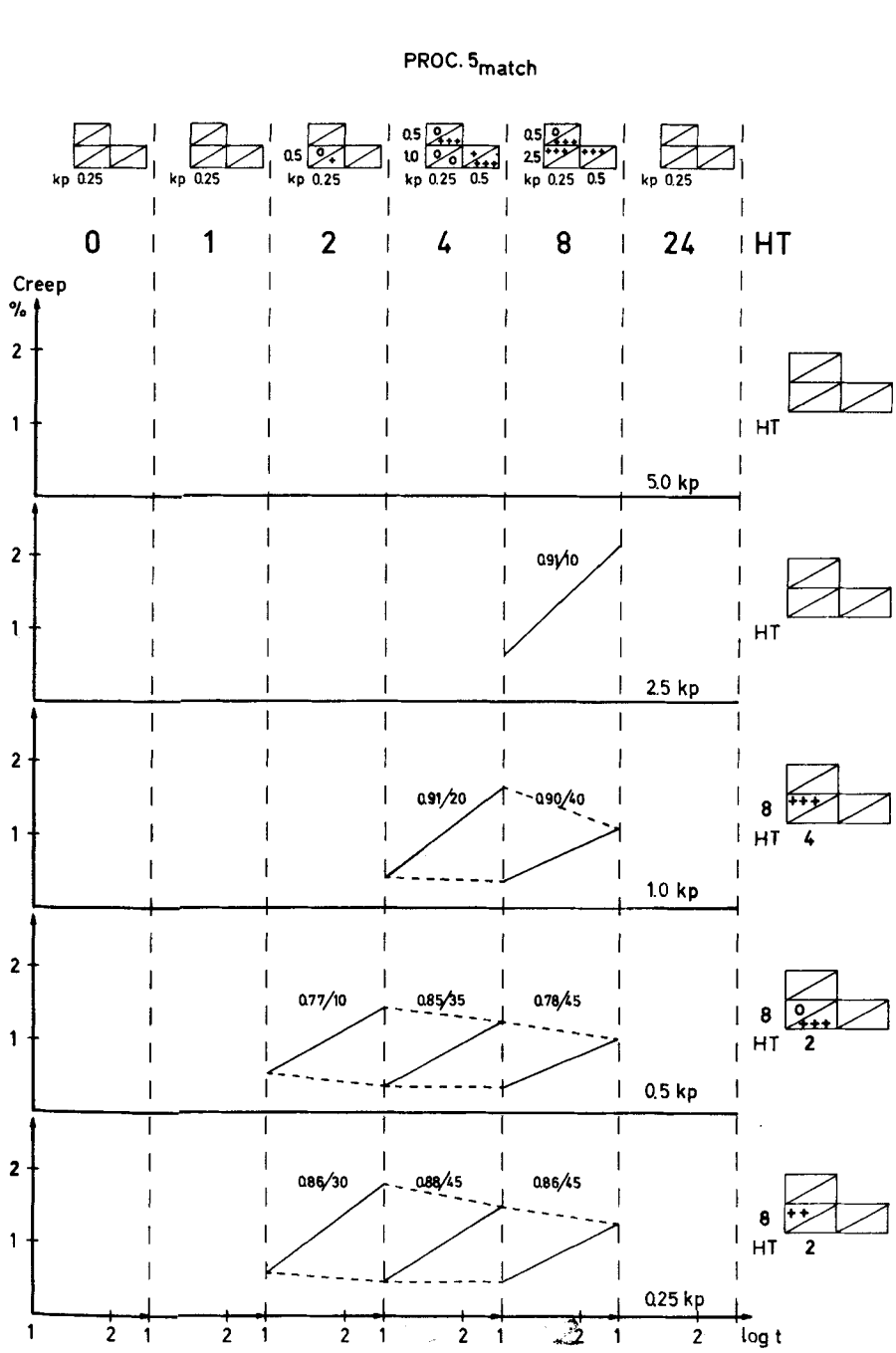


Fig 75–76. Mean regression lines for creep versus log t (time in sec) at varying load levels and in relation to HT (healing time in weeks). Left page specimens with muscle release and interrupted



sutures on divided tendons (procedure nr 4). Right page specimens with muscle release and criss-cross sutures on divided tendons (procedure nr 5). For details see legend to fig 59–60.

Fig 77–78. Mean regression lines for force-relaxation versus log t (time in sec) at varying load levels and in relation to HT (healing time in weeks). Left page intact specimens (procedure nr 0). Right page specimens with muscle release only (procedure nr 1). Match after procedure number (at the top) = matched groups, see page 50. HT for intact specimens relates to the muscle release performed on the contralateral leg.

The ordinate is repeated 5 times corresponding to load levels noted to the right just above the abscissa.

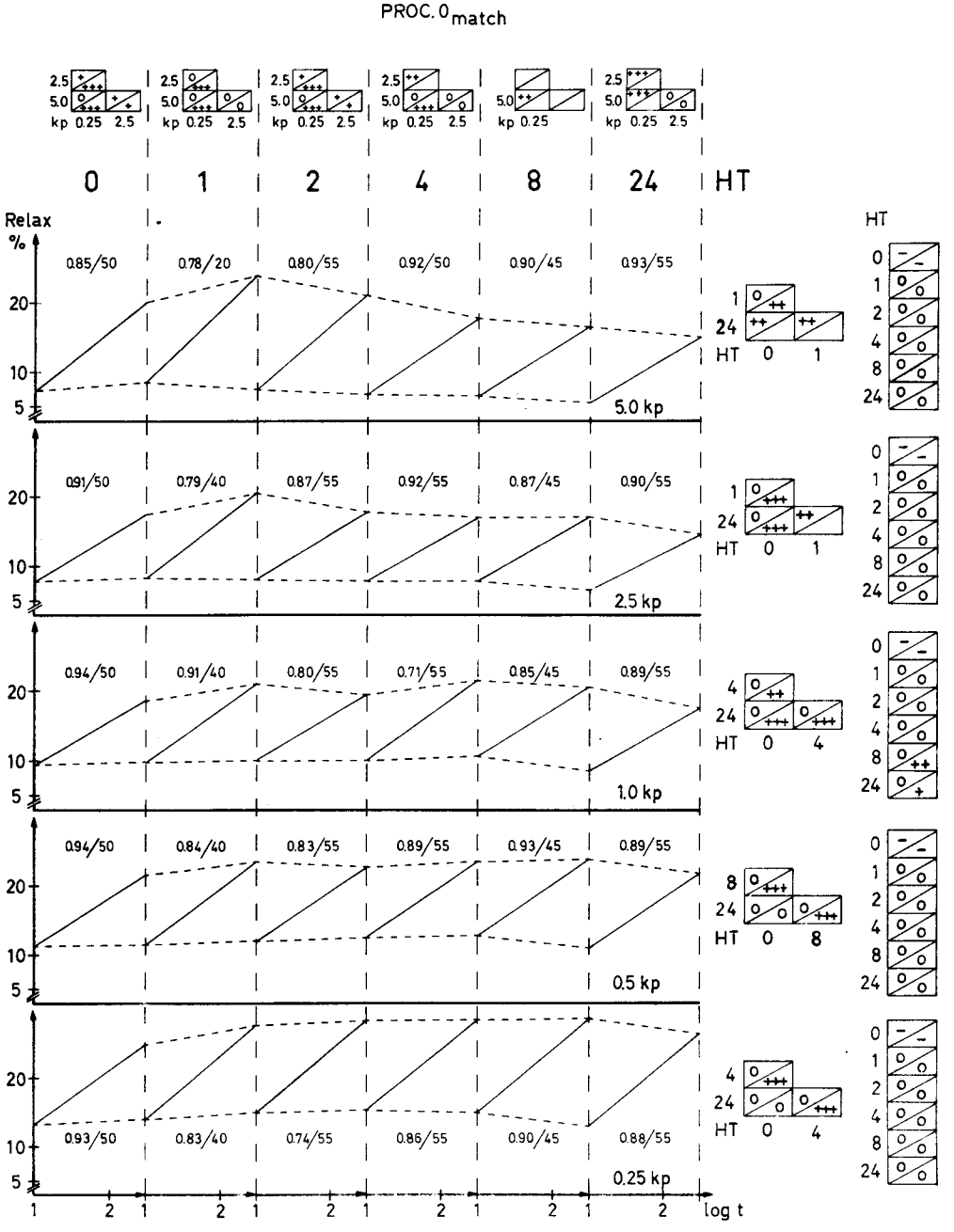
The abscissa is repeated 6 times as indicated by the vertical broken lines and corresponding to various HT noted at the top in bold figures.

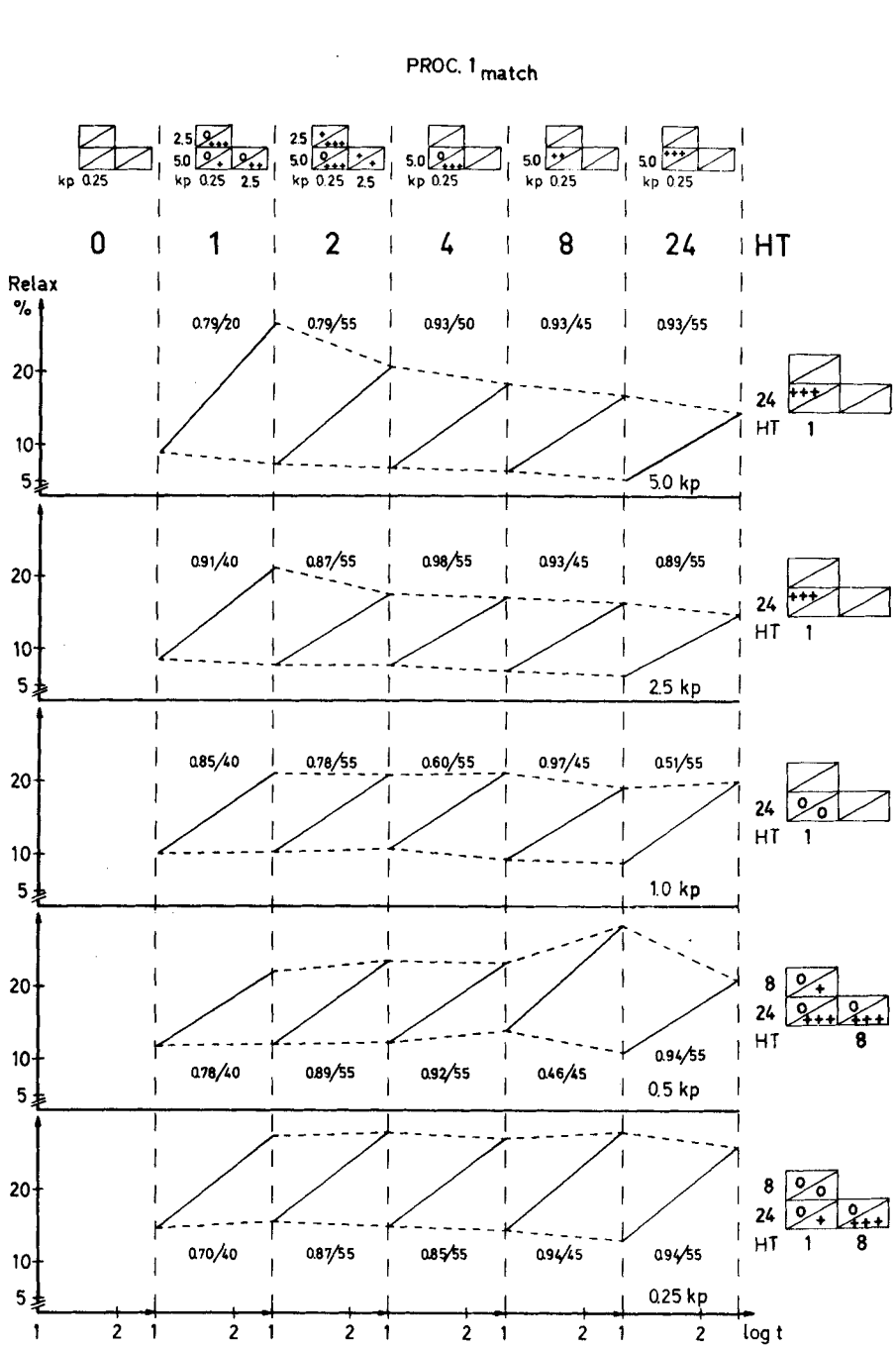
With each regression line a fraction is given. The numerator = coefficient of correlation = r, the denominator = number of observations = n.

Results of statistical analysis comparing *different load levels* for the *same HT* in the *same procedure* are given in scoreboards at the top. Signs in the scoreboards: 0 = p > .05, +, ++, +++ = p < 05, .01, .001 respectively. Statistical differences for coefficients of regression = b are given in the upper left triangle, and for mean values of the ordinate = intercept = a in the lower right triangle. (For instance, when comparing 2.5 and 5.0 kp at HT 2 in proced nr 0 b is higher for 5.0 kp indicated by + in the upper left triangle. a is also higher for 5.0 kp, + in the lower right triangle.)

Results of statistical analysis comparing *different HT* on the *same load level* in the *same procedure* are given in scoreboards to the right.

Results of statistical analysis *comparing procedures* for *equal HT and load level* are given in the vertical column in the middle.




PROC. 1 match
kp 0.25
2.5
5.0
kp 0.25 2.5
kp 0.25 2.5
5.0
kp 0.25
5.0
kp 0.25
5.0
kp 0.25
0
1
2
4
8
24
HT
Relax
%
20
10
5
0.79/20
0.79/55
0.93/50
0.93/45
0.93/55
5.0 kp
24
HT 1
0.91/40
0.87/55
0.98/55
0.93/45
0.89/55
2.5 kp
0.85/40
0.78/55
0.60/55
0.97/45
0.51/55
1.0 kp
8
0.78/40
0.89/55
0.92/55
0.46/45
0.94/55
0.5 kp
HT 8
0.70/40
0.87/55
0.85/55
0.94/45
0.94/55
0.25 kp
HT 1 8
1
2
log t

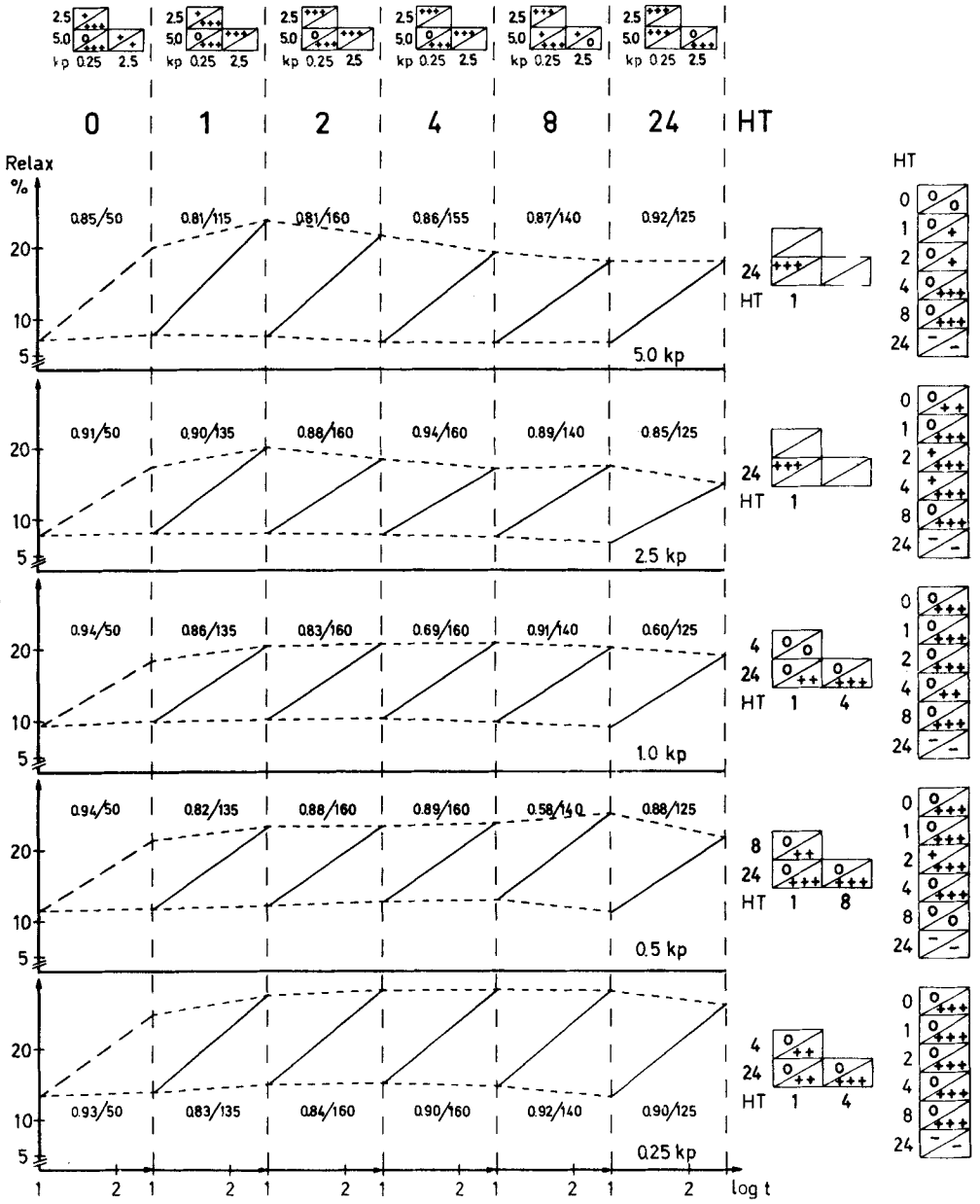
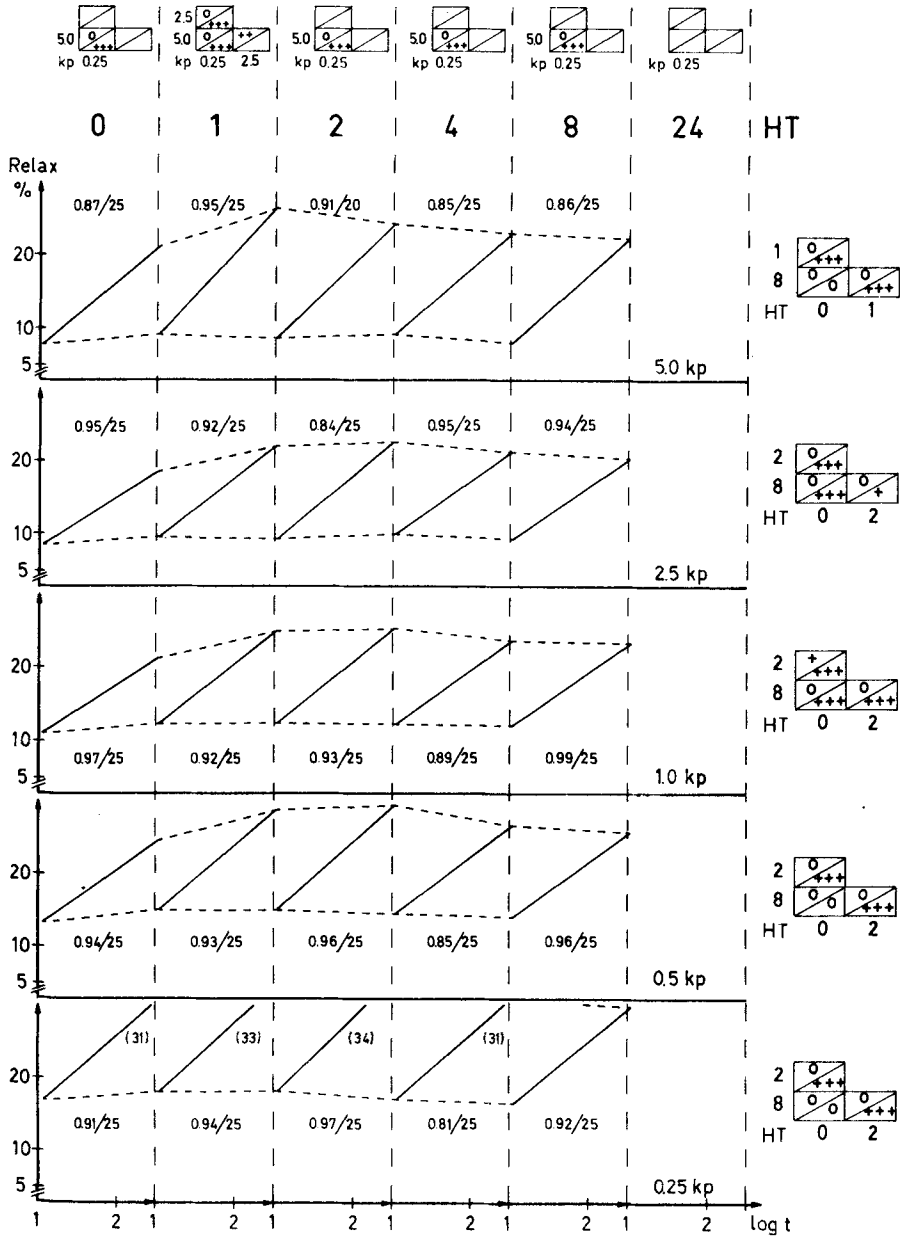


Fig 79–80. Mean regression lines for force-relaxation versus log t (time in sec) at varying load levels and in relation to HT (healing time in weeks). Left page control specimens (procedure nr



0+1). Right page specimens with muscle release and interrupted sutures on undivided tendons (procedure nr 2). For details see legend to fig 77 - 78.

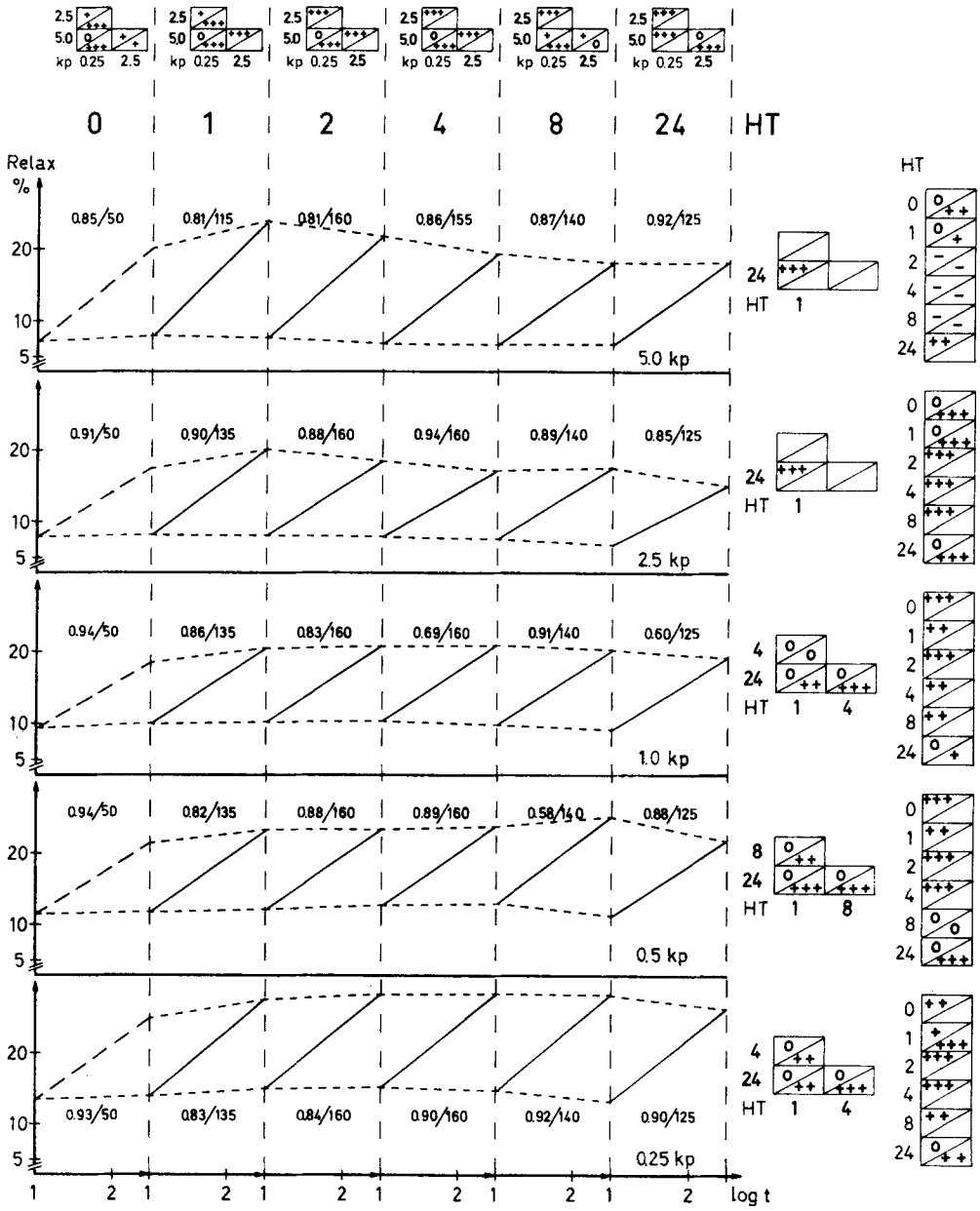
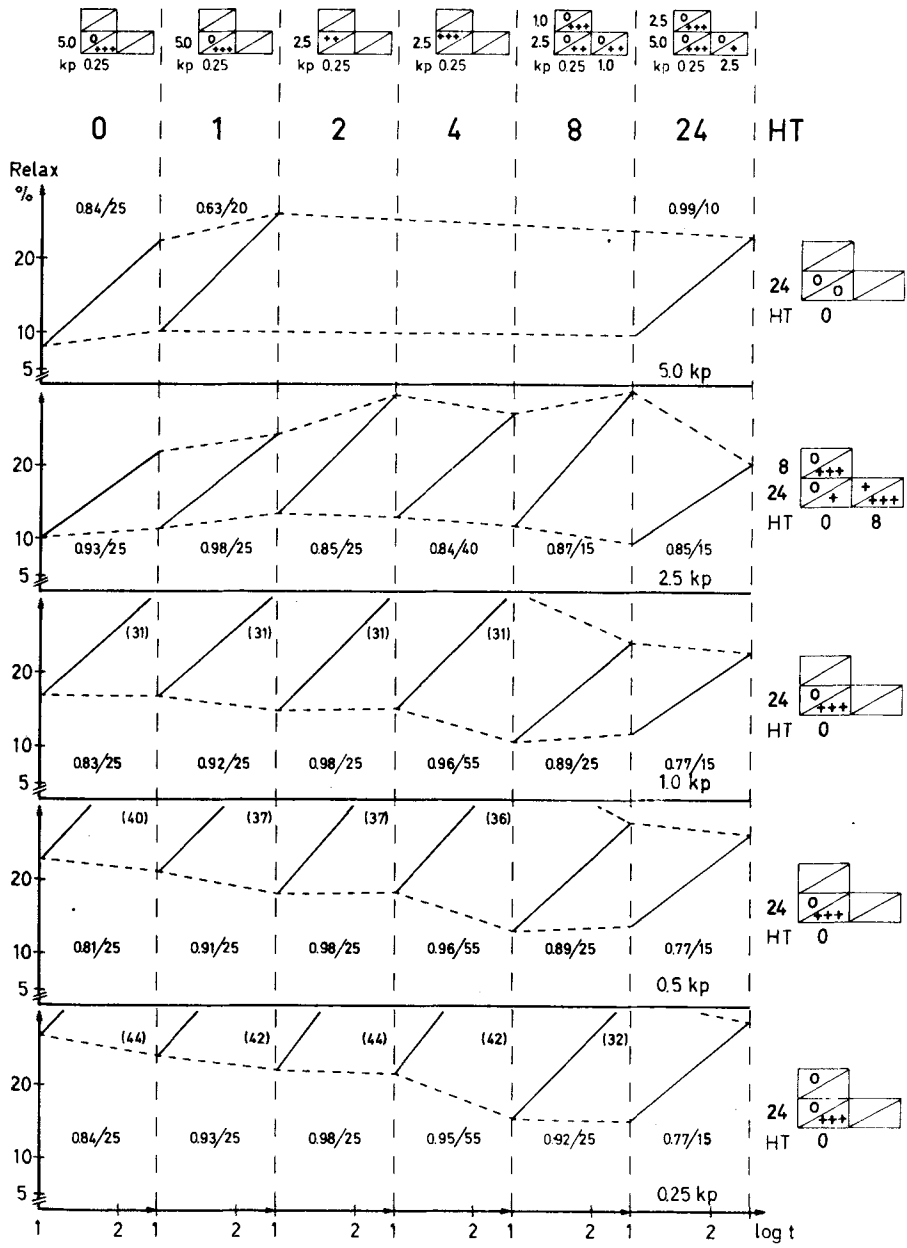


Fig 81–82. Mean regression lines for force-relaxation versus log t (time in sec) at varying load levels and in relation to HT (healing time in weeks). Left page control specimens (procedure nr 0+1).



Right page specimens with muscle release and criss-cross sutures on undivided tendons (procedure nr 3). For details see legend to fig 77–78.

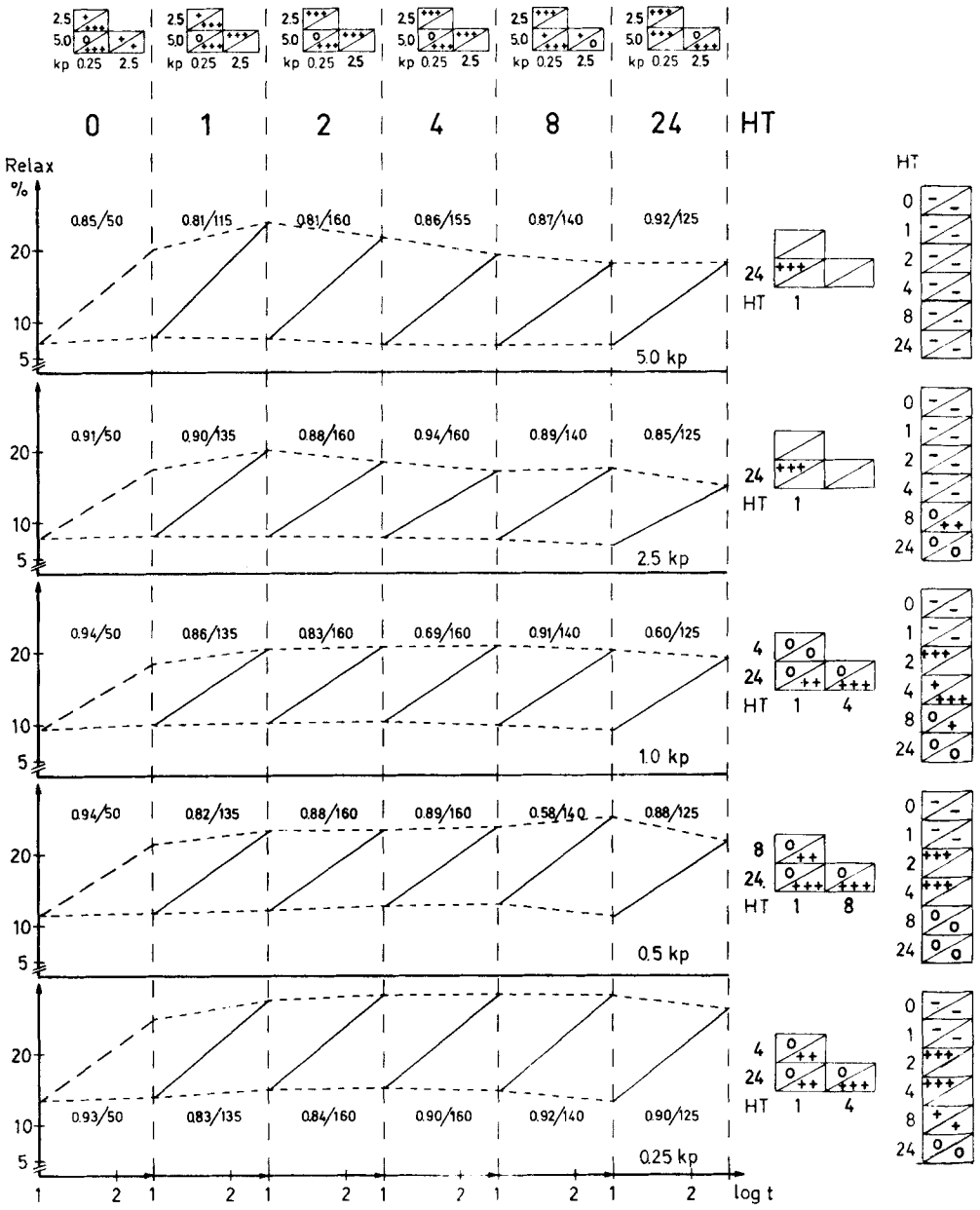
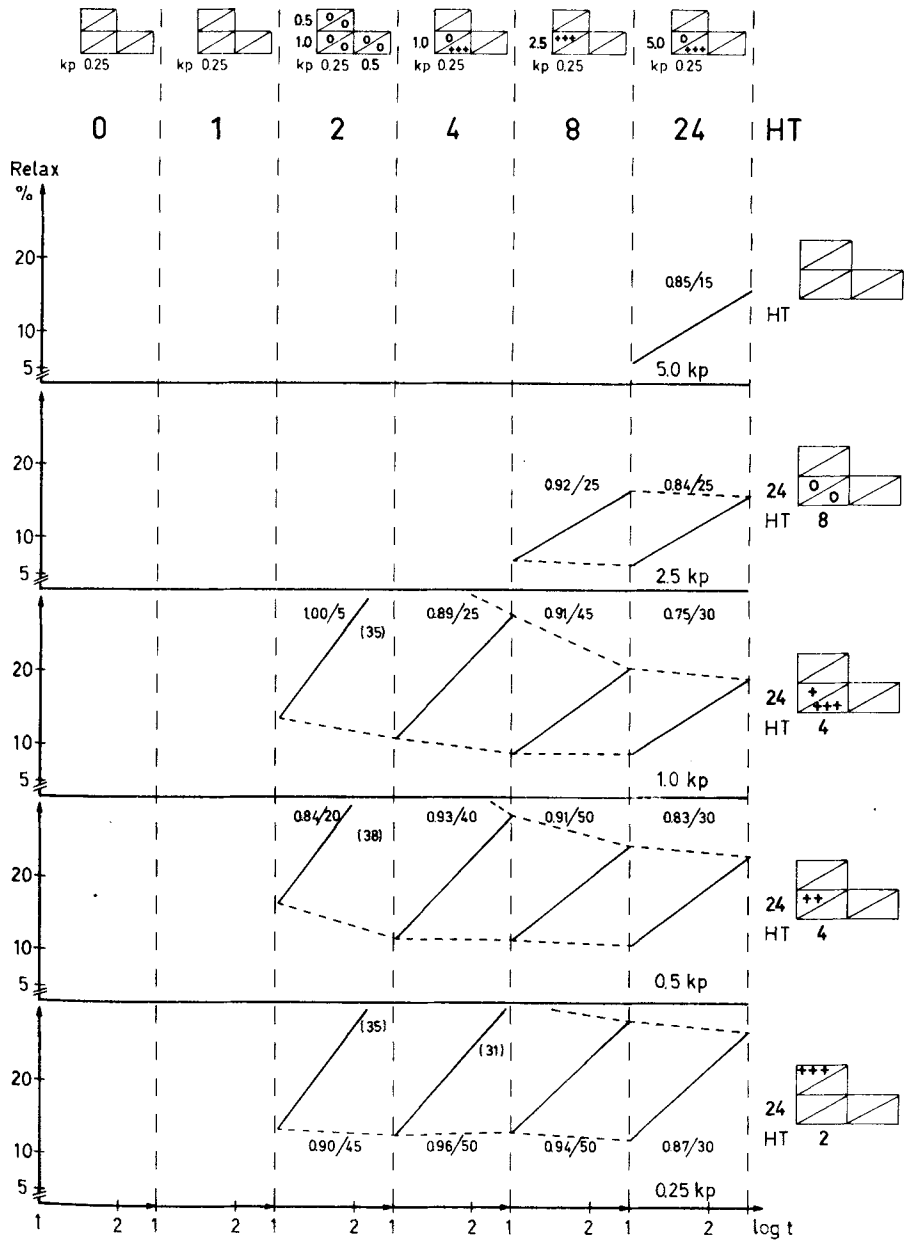


Fig 83–84. Mean regression lines for force-relaxation versus log t (time in sec) at varying load levels and in relation to HT (healing time in weeks). Left page control specimens (procedure nr 0+1).



Right page specimens with muscle release and interrupted sutures on divided tendons (procedure nr 4). For details see legend to fig 77–78.

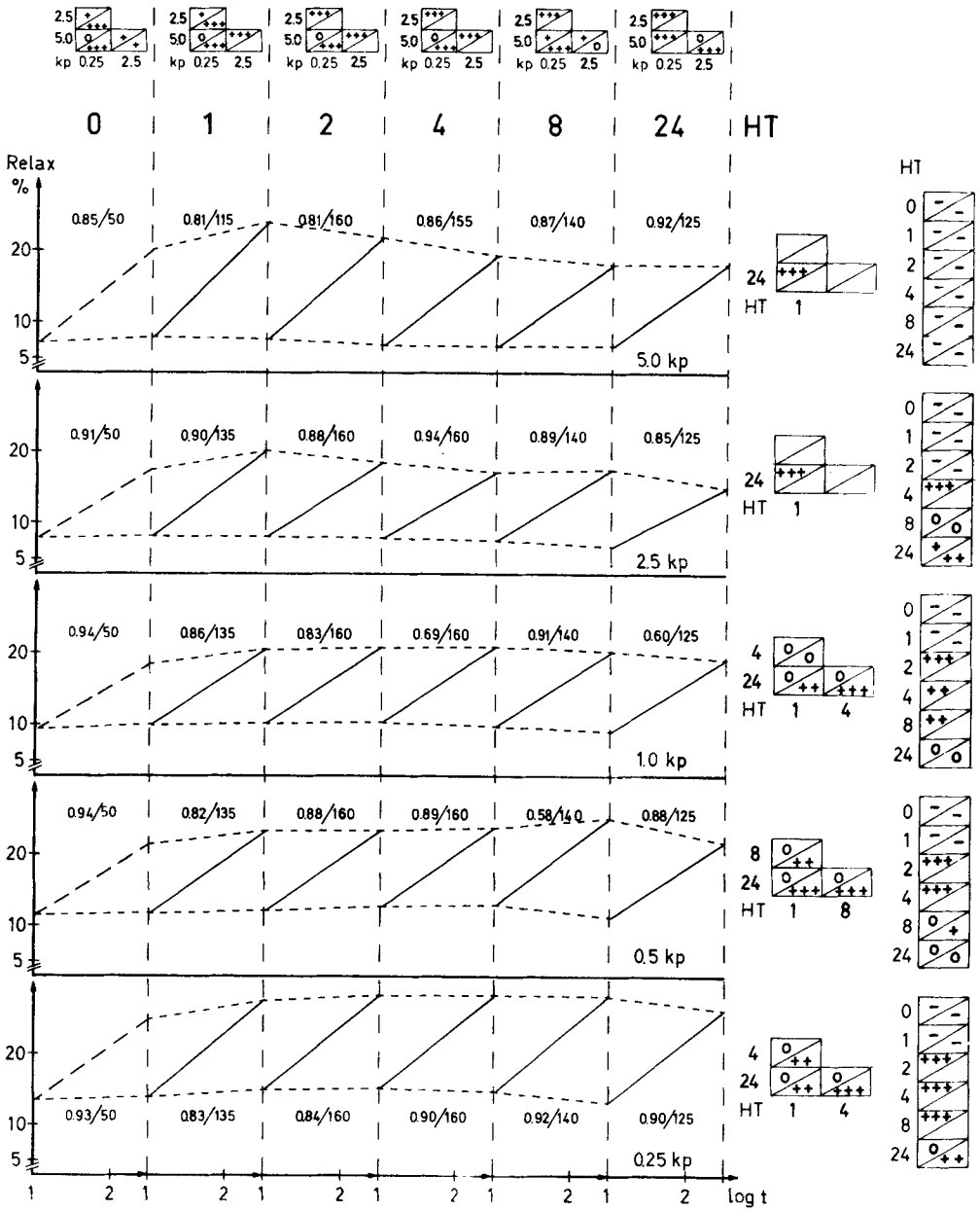
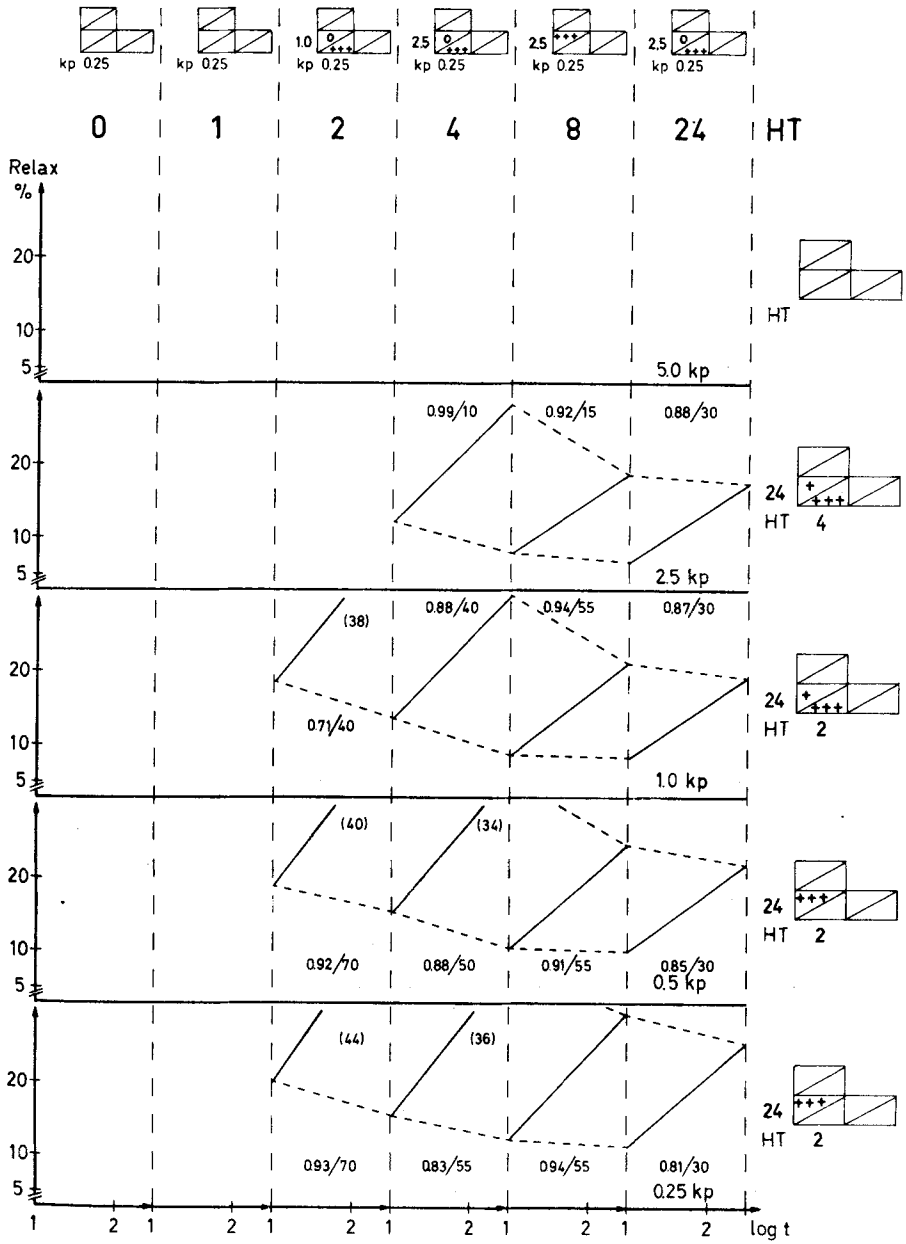


Fig 85–86. Mean regression lines for force-relaxation versus log t (time in sec) at varying load levels and in relation to HT (healing time in weeks). Left page control specimens (procedure nr 0+1).



Right page specimens with muscle release and criss-cross sutures on divided tendons (procedure nr 5). For details see legend to fig 77–78.

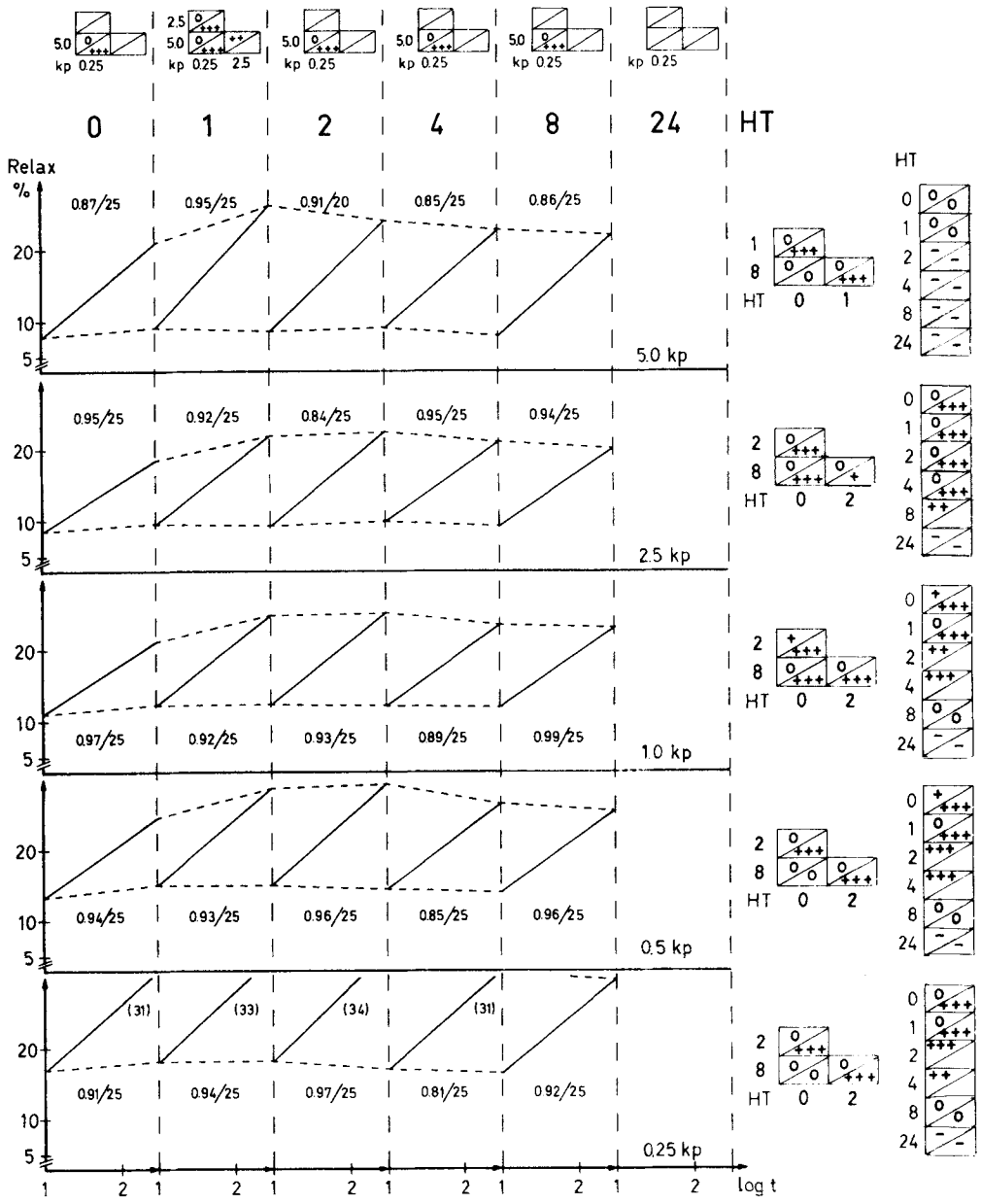
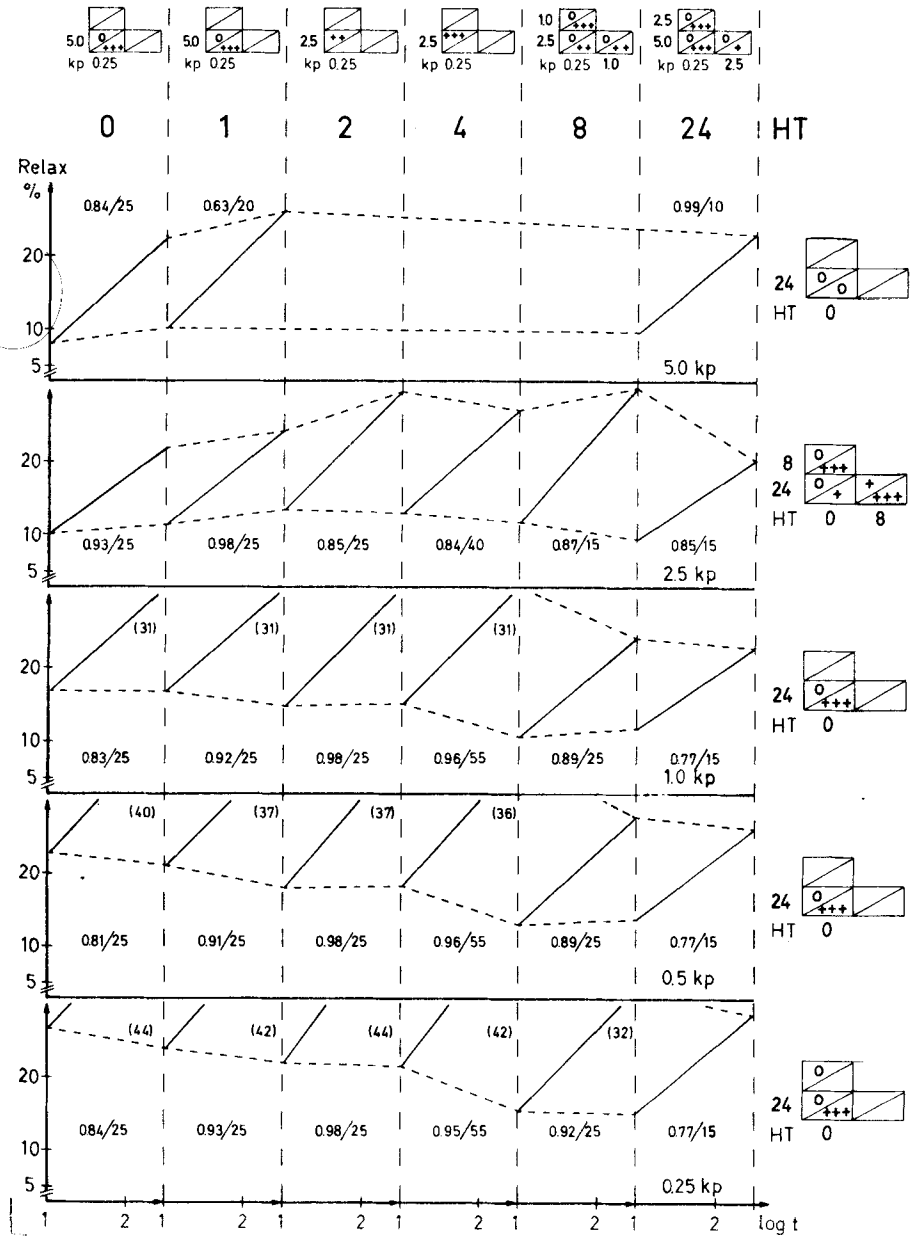


Fig 87–88. Mean regression lines for force-relaxation versus log t (time in sec) at varying load levels and in relation to HT (healing time in weeks). Left page specimens with muscle release and



interrupted sutures on undivided tendons (procedure nr 2). Right page specimens with muscle release and criss-cross sutures on undivided tendons (procedure nr 3). For details see legend to fig 77–78.

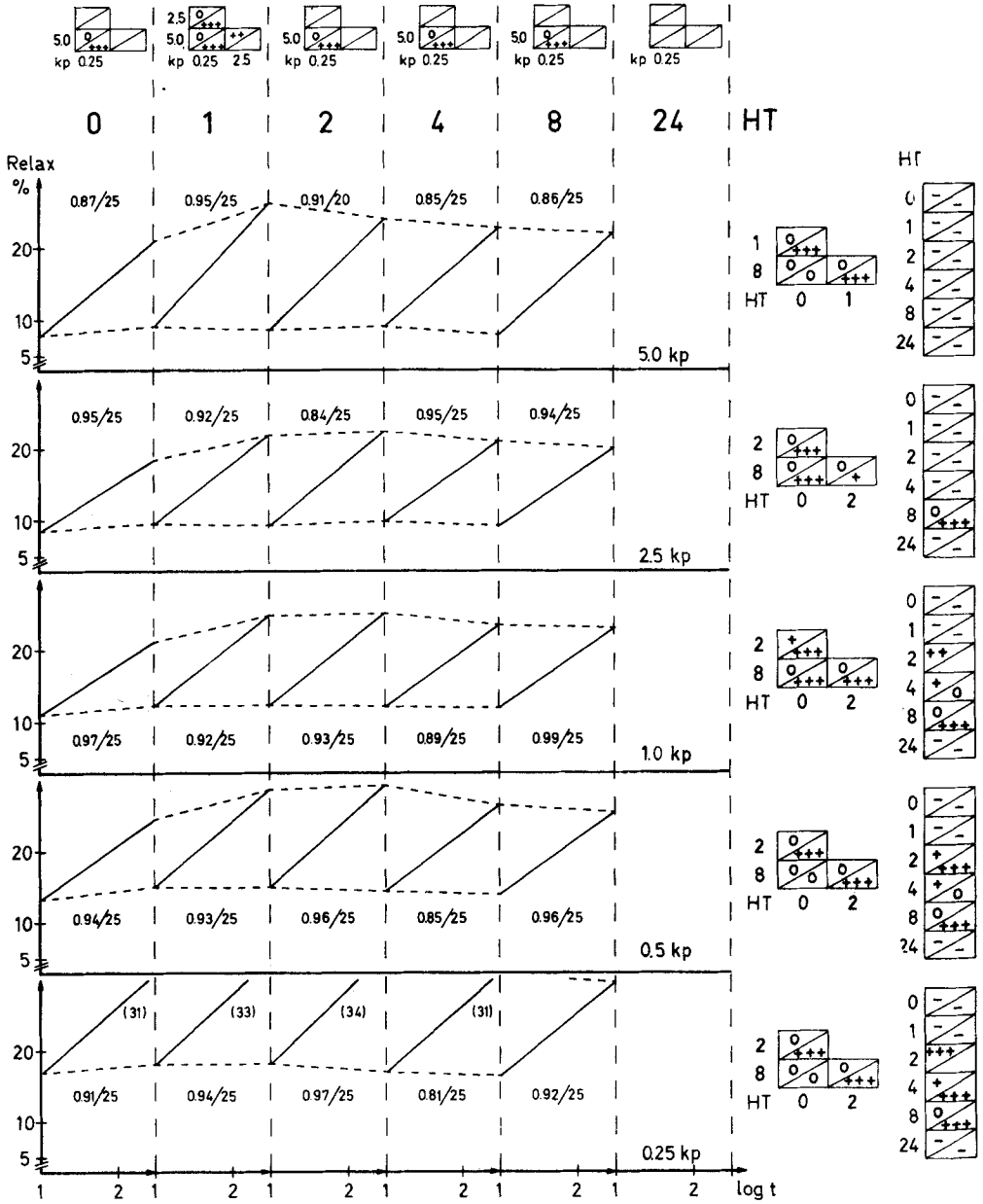
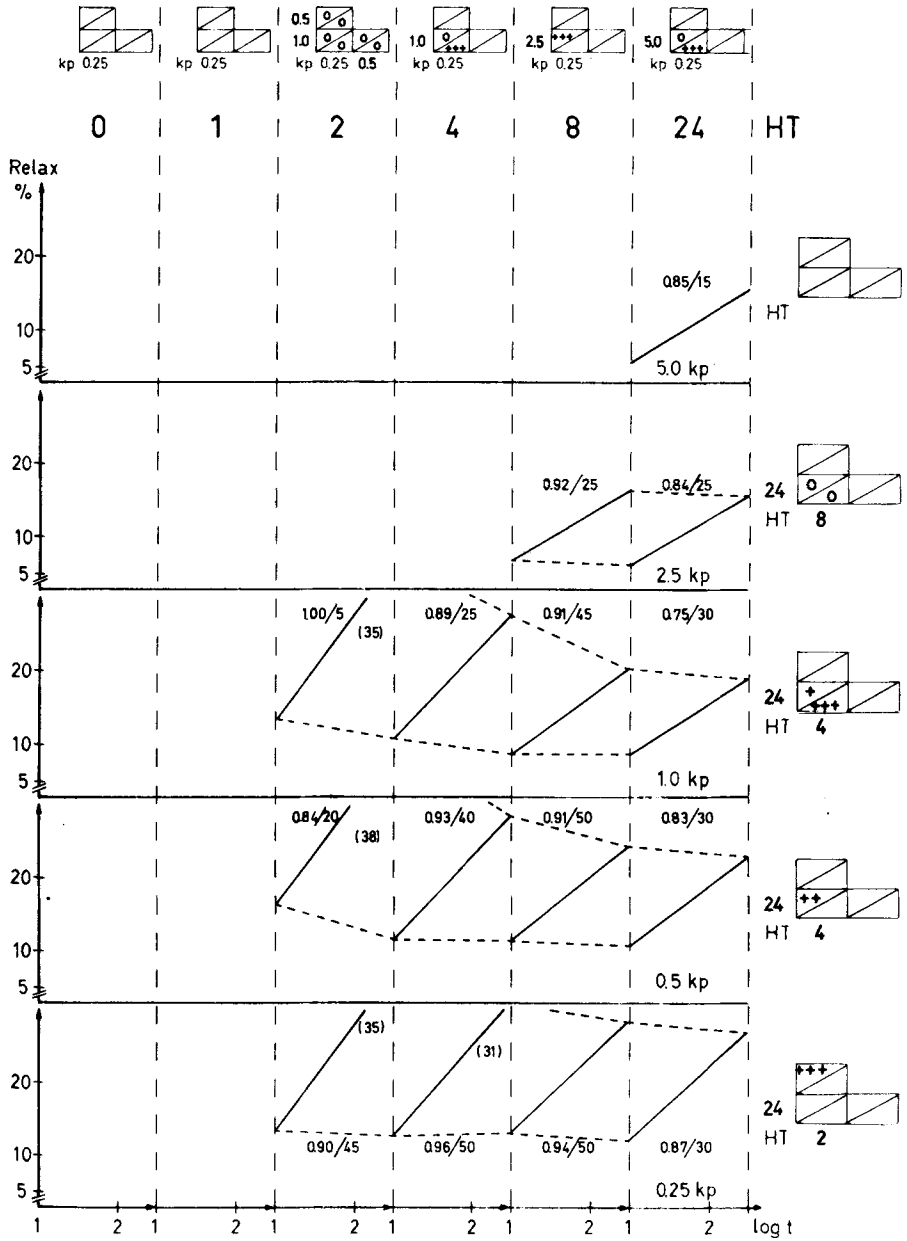


Fig 89–90. Mean regression lines for force-relaxation versus log t (time in sec) at varying load levels and in relation to HT (healing time in weeks). Left page specimens with muscle release and



interrupted sutures on undivided tendons (procedure nr 2). Right page specimens with muscle release and interrupted sutures on divided tendons (procedure nr 4). For details see legend to fig 77–78.

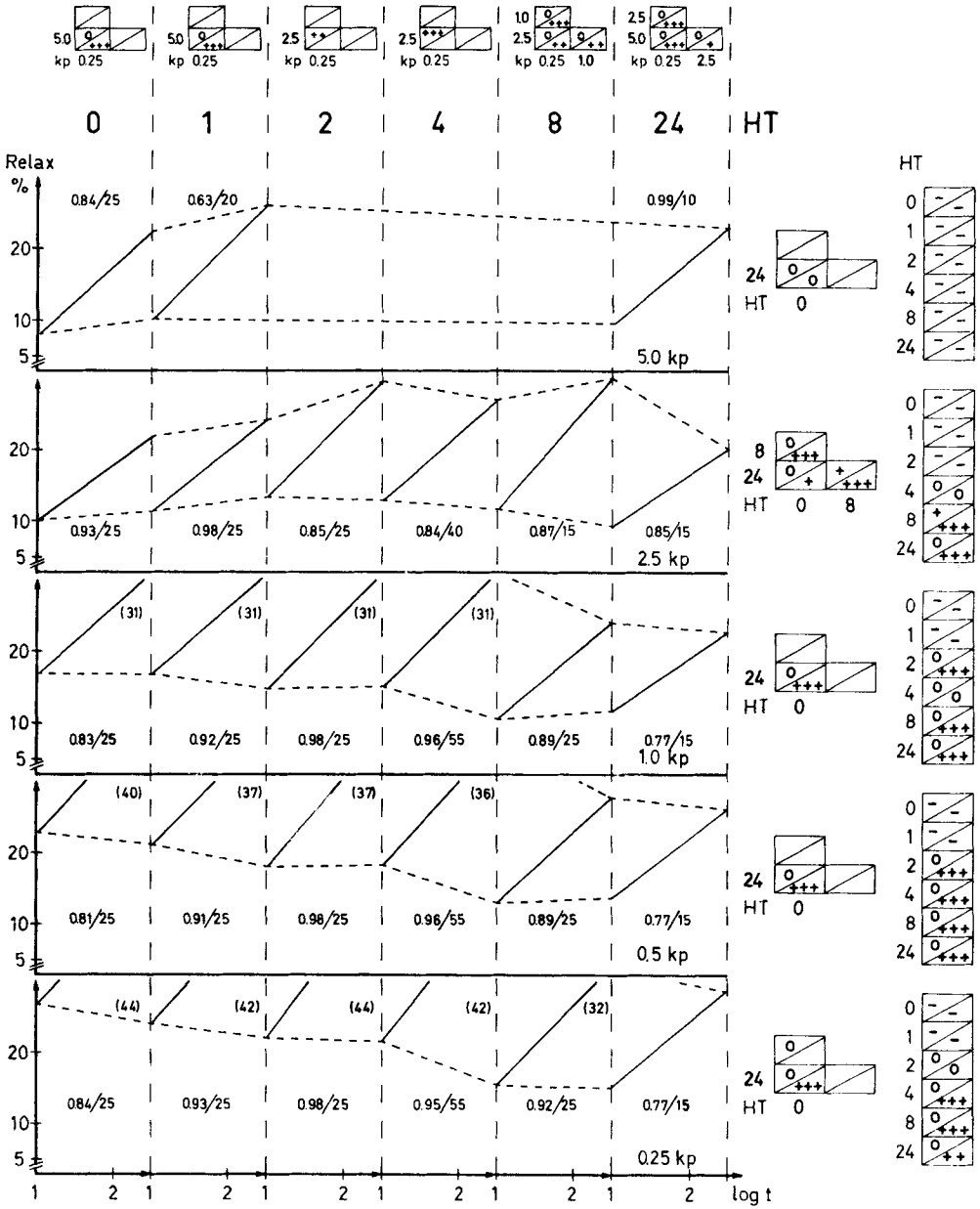
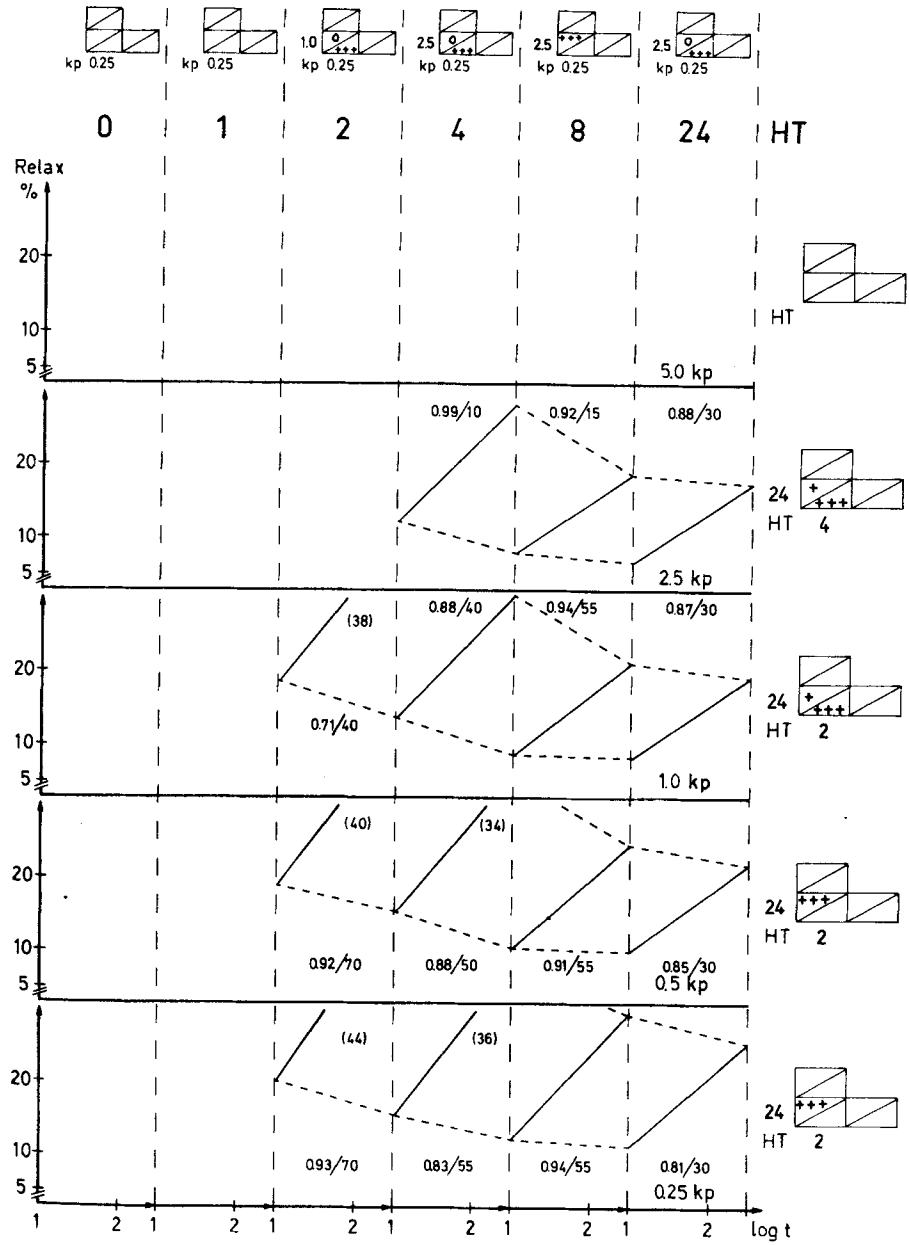


Fig 91–92. Mean regression lines for force-relaxation versus log t (time in sec) at varying load levels and in relation to HT (healing time in weeks). Left page specimens with muscle release and



criss-cross sutures on undivided tendons (procedure nr 3). Right page specimens with muscle release and criss-cross sutures on divided tendons (procedure nr 5). For details see legend to fig 77–78.

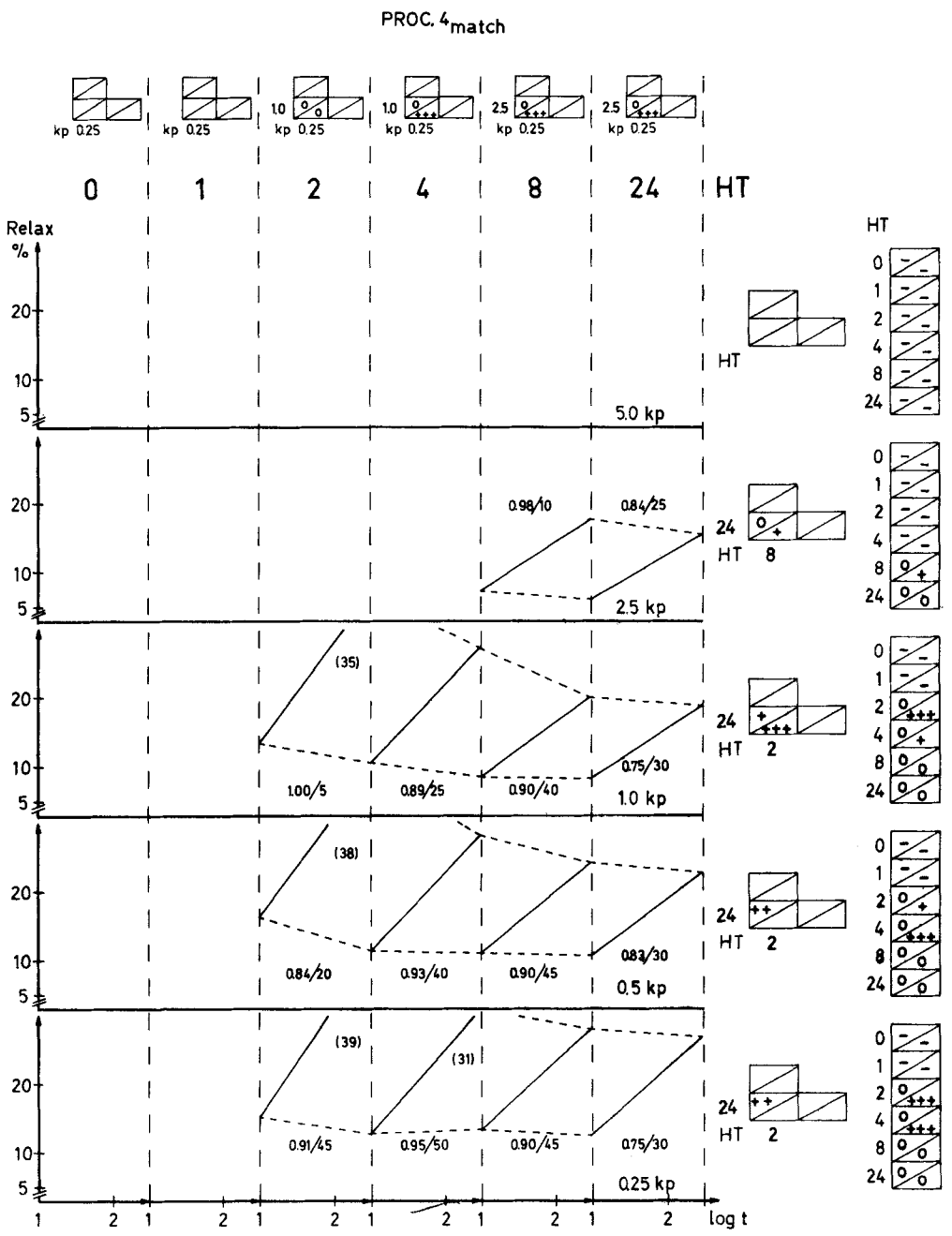
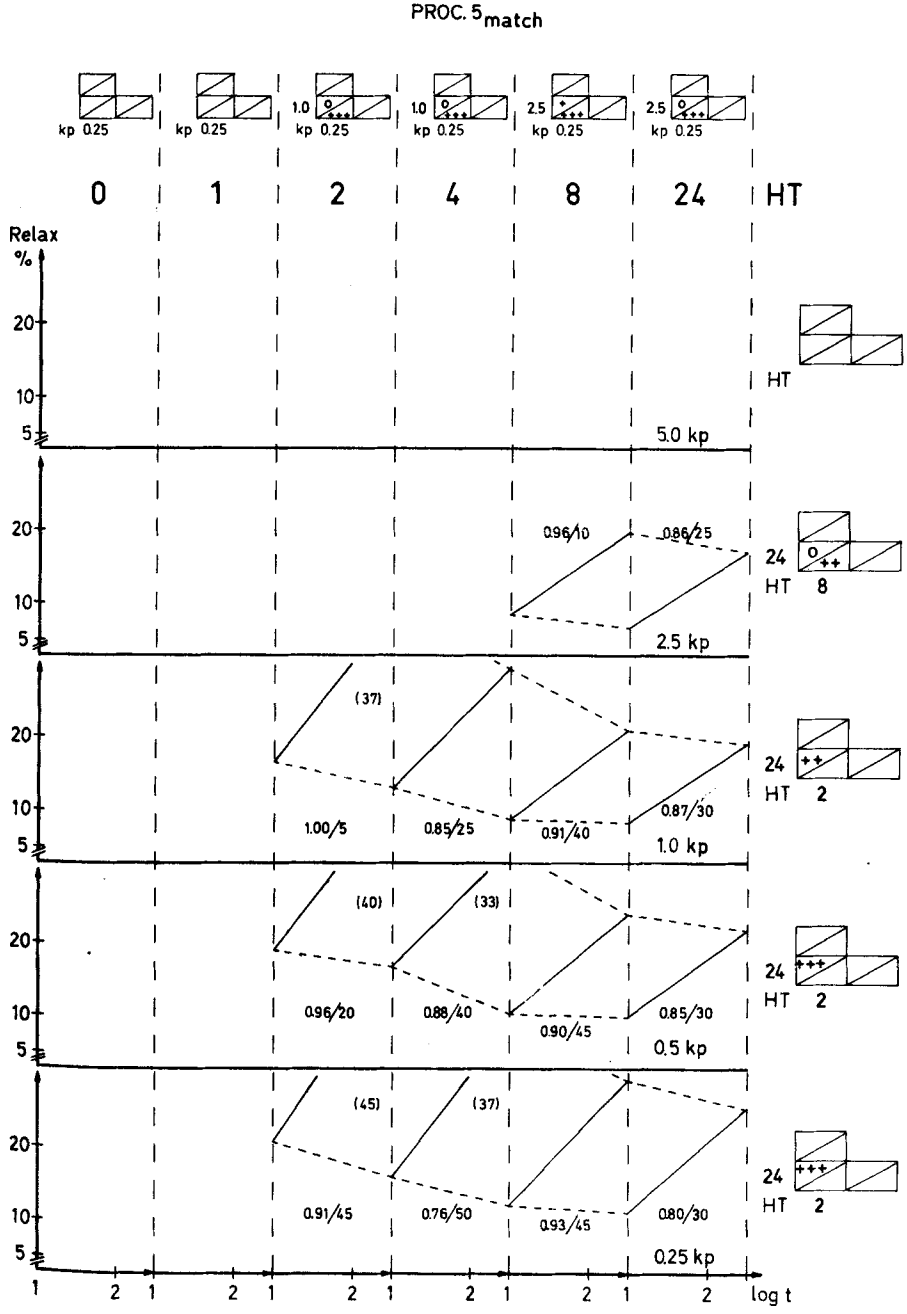


Fig 93–94. Mean regression lines for force-relaxation versus log t (time in sec) at varying load levels and in relation to HT (healing time in weeks). Left page specimens with muscle release and



interrupted sutures on divided tendons (procedure nr 4). Right page specimens with muscle release and criss-cross sutures on divided tendons (procedure nr 5). For details see legend to fig 77–78.