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STRESS–STRAIN RELATIONSHIP IN HUMAN CADAVERIC PLANTARIS TENDON: A PRELIMINARY STUDY*

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Abstract—As a part of a major experimental study of forces in muscles and tendons it became necessary, as a preliminary step, to know the stress–strain relationship in human tendon. The studies reported herein give data from thirty tests on cadaveric human plantaris tendon in three states, i.e., moist, air dried and oven dried. Results are correlated with previously published results on tendon and with published strengths of human muscle and bone. Considerable new information on tendon strength is presented and several important deductive conclusions are given. The equipment and methods are described and illustrated and an appendix is given, showing results of the individual tests.

1. INTRODUCTION

THE PRESENT study was necessitated by the almost total lack of published data on the stress–strain characteristics of tendon and the extremely wide range of values reported for the ultimate tensile strength of tendon. A survey of the literature concerning tensile stress versus strain characteristics reveals that, to date, no adequate comprehensive studies presenting quantitative data for both parameters have been published. Frog achilles tendon has been reported to stretch up to 35% of its resting length when subjected to a load of 960 g (GERSTON, 1955). The tensile strength of bovine achilles tendon has been reported as approximately 1,700 to 28,400 pounds per square inch (psi) (calculated by the present authors from data published by BRAAMS, 1960); that of human tendon, fixed and fresh, as 8,700 to 18,000 psi by CRONKITE, (1936). Cat achilles tendons have been reported to withstand forces from 106 to 170 lb (DAVIDSSON, 1954) and rabbit achilles tendons have failed to rupture upon application of forces in excess of 76 to 130 pounds (DAVIDSSON, 1954) and 22·9 to 50·6 pounds by MCMASTER (1933). The present study will report preliminary data for the stress–strain relationship and tensile strength determinations for human plantaris tendon.

2. MATERIALS AND METHODS

Tendons of the M. plantaris were obtained from the Gross Anatomy Laboratory and stored in the wetting solution used by student dissectors (5% phenol in tap water). The cadavers had been embalmed in the Tulane Gross Anatomy laboratory preparation rooms, and the fluid used was of the following composition:

33·3%	Isopropyl alcohol
8·3%	Glucarine B
2·1%	Formalin
6·7%	Phenol
0·1%	Zepharine Chloride
49·5%	Tap water
100·0%	

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The tendons were removed from cadavers utilized by gross anatomy students in their medical schooling. Other than to say that the bodies exhibited no evidence of diseases involving the tendons, that the tendons *in vivo* were not damaged and that they were carefully removed, no remarks as to their character can be made. The cadavers were of several ages at death, of both sexes, of several races, from many geographical locations in the United States, and the causes of death were various and unknown. A total of thirty tendon segments were tested, twenty immediately following removal from the wetting solution in which they were stored (Group I), five following air drying at room temperature for 24 hr (Group II) and five following oven drying at 104°F for 24 hr (Group III).

Cross sectional area of the tendons in Group I was measured using the instruments illustrated in Fig. 1. These instruments were fabricated in the Mechanical Engineering Shops and each consists of a slotted plate with a movable following bar with key machined to fit into the slot. In operation the movable bar is lowered until the key *gently* forces the irregularly shaped, pliable tendon into the rectangular space created at the base of the slot. The width of the slot is known; the height of the rectangle is measured by means of a micrometer head mounted upon the instrument. Measurements of the height of the rectangle were found to be reproducible by several operators to within 0·002 in., so that on a specimen of 0·200 in. in height, the error is less than 1%. Three instruments have been fabricated with slots of 0·066, 0·163 and 0·248 in. in width respectively, permitting measurements of tendons of a wide range of cross sectional areas.

Since they were hard and inflexible following drying, the tendons in Groups II and III could not be measured with the instruments described above. The cross sectional area of these tendons were determined from measurement of width and thickness with a vernier caliper. This method, obviously, yields an approximation of the true area of the tendon. The amount of error is less in those tendons which are broad and thin and greater in those with more oval cross sections. In all instances the measurements would indicate a cross sectional area greater than that actually existing and, hence, the figures reported for unit tensile stress would be less than that actually existing in these tendons.

Segments of tendon approximately four inches long were subjected to tensile stress in the device illustrated in Fig. 2. With the ends secured in suitable clamps (see Fig. 3), tension was applied to one end of the tendon segment by turning a hand-wheel which moves a lead-screw. The lead-screw is keyed to prevent its turning with the hand-wheel. The other end of the tendon segment was affixed to a draw-bar which is restrained from moving by the pressure of two matched springs. The deformation of the springs, measured by a dial gauge, was used to determine the force applied to the tendon. Several sets of matched springs are available, providing a variety of pressure ranges for testing tendons of varying cross sectional areas.

Measurement of elongation of the tendon was made using a dissecting microscope with an ocular micrometer having minimal divisions of 0·00863 in. when calibrated using a magnification of seven diameters against a scale graduated to 0·01 in. Reference points on the tendon were provided by two metal wound clips placed 0·216 in. apart as measured by the ocular micrometer, and affixed in a manner that did not damage the collagenous fibers of the tendon. The gauge length thus established was accomplished with the tendon in the test device adjusted so that impending tension prevailed and so that there was no slack or stress in the tendon.

3. RESULTS

Fourteen of the twenty tendon segments in Group I were stressed until the tendon ruptured. The remaining six were not carried to rupture because one end or the other slipped from the retaining wedge clamps. The tensile strength of those segments which were tested to rupture varied from 10,600 to 21,300 psi, with an average

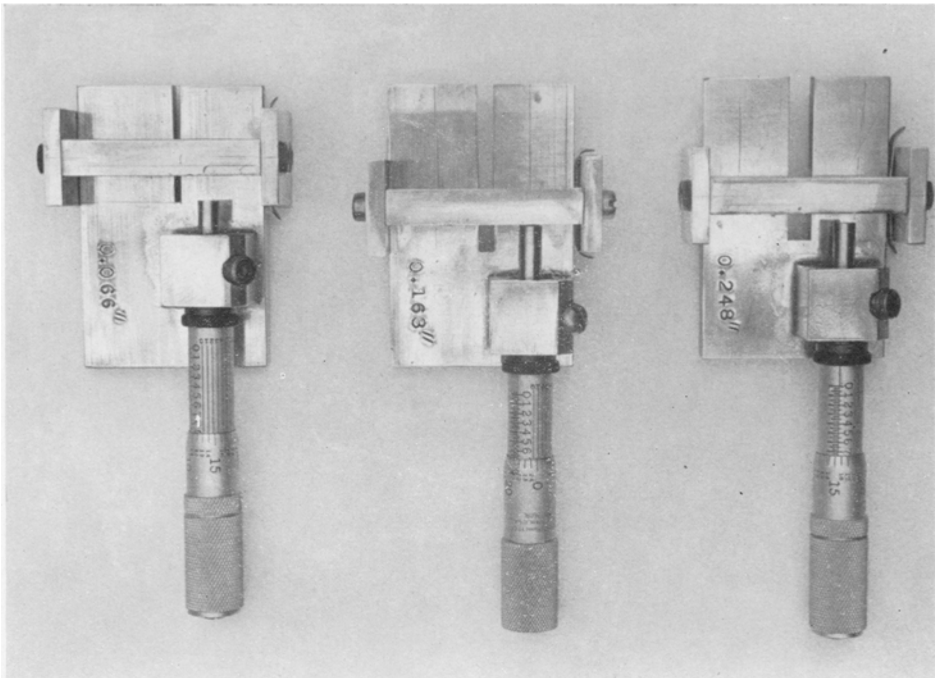
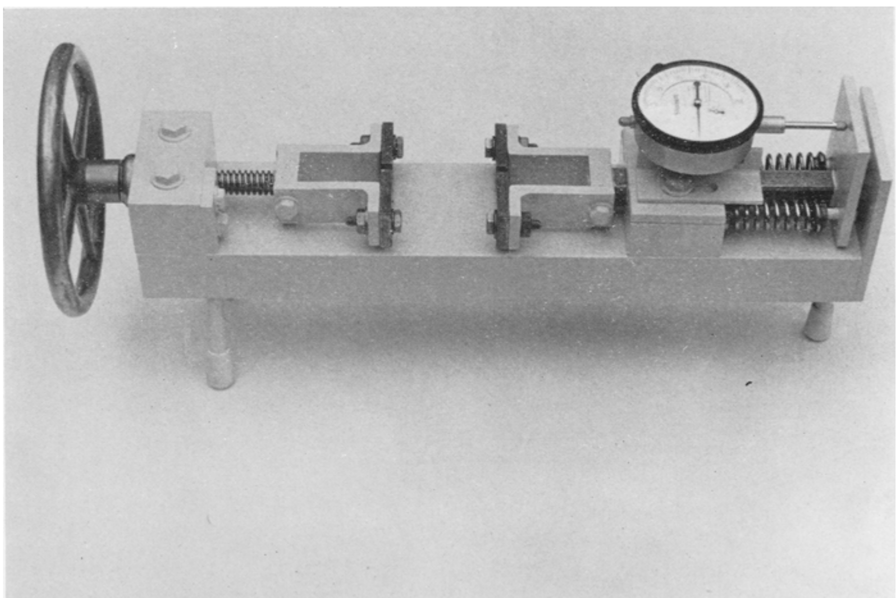


FIG. 1. Area measuring device.



(*facing p.* 32)

FIG. 2. Tension testing device.

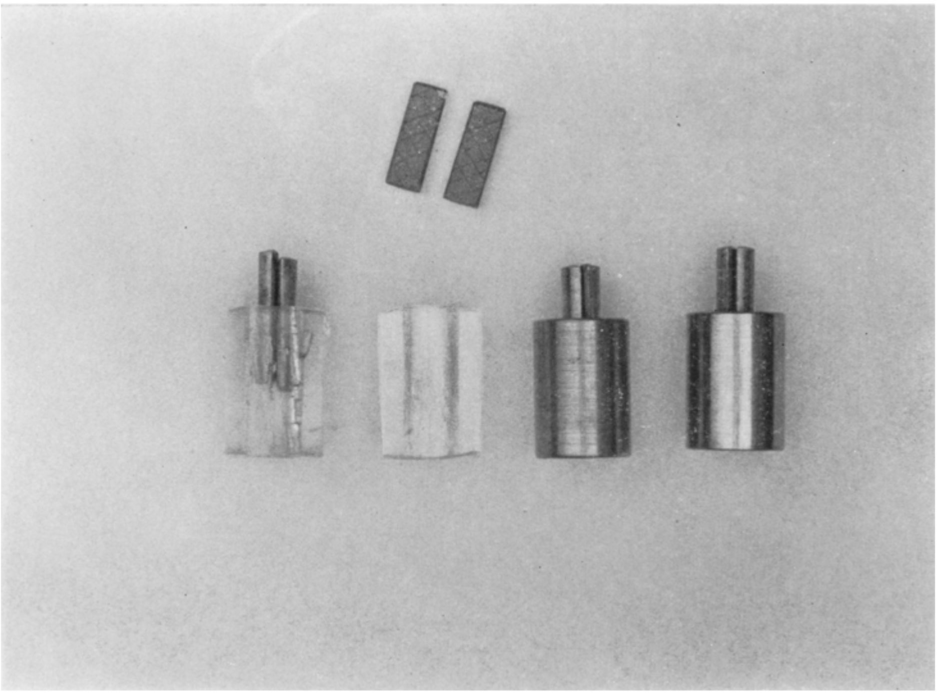


FIG. 3. Tendon clamps.

of 14,200 psi. Since the method used to determine the cross sectional area of the tendons in Groups II and III was relatively inaccurate, the tensile strength and stress-strain characteristics reported must be considered as being only fair approximations of their true values. Recall, however, that in each instance the figures reported for tensile strength are less than those which one would obtain with closer area measurements. None of the dried tendons were stressed sufficiently to cause a pure tensile failure. The tendons in this group demonstrated tensile strengths ranging from greater than 17,050 to greater than 31,750 psi, with an average of greater than 23,470 psi before they slipped from the jaws of the clamps used.

Stress–strain curves of all tendons tested are shown in Fig. 4 (Group I), Fig. 5 (Group II) and Fig. 6 (Group III). Examination of the stress–strain curves of the tendons in Group I (Fig. 4) reveals two distinct patterns. A curve characteristic of one pattern is illustrated in Fig. 7, Curve A and shows an increasing stiffness with elongation, i.e., as the tendon is elongated, it requires an increasing stress to produce unit strain. A curve characteristic of the second pattern is illustrated in Fig. 7, Curve B, and shows a period of almost linear strain per unit stress up to a strain of approximately 0·04 to 0·06 in./in., followed by a pattern of increasing strain per unit stress. The stress–strain curves characteristic of dried tendon, either air or oven dried, are similar in many respects to that illustrated by Curve A in Fig. 7. Such a curve, Fig. 7, Curve C, demonstrates in addition, an increased stiffness for these tendons.

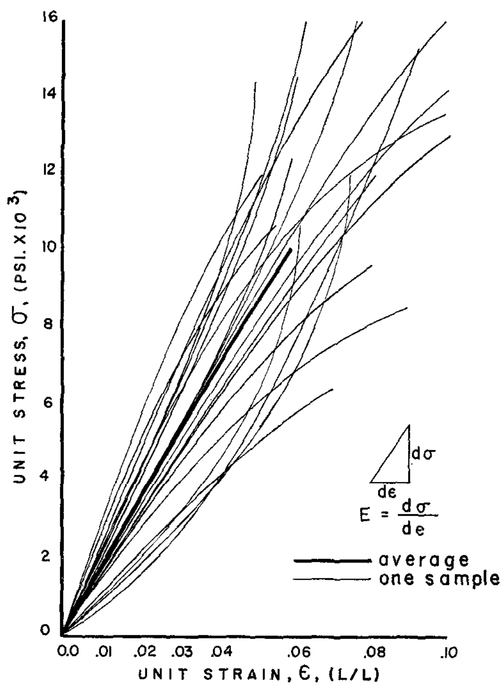


FIG. 4. Stress–strain plots for twenty moist plantaris tendon specimen.

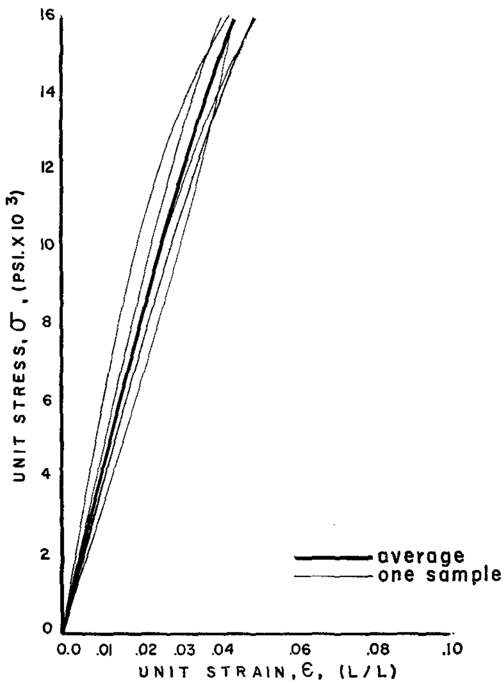


FIG. 5. Stress–strain plots for five air-dried plantaris tendon specimen.

4. DISCUSSION

The tensile strength of the plantaris tendons as determined in this study, 10,600 to 21,300 psi, are of the same order of magnitude as that reported by CRONKITE (1936) for human tendon in general, 8,700 to 18,000 psi. Although the general range of strength is slightly higher in the present series, the range of variability is

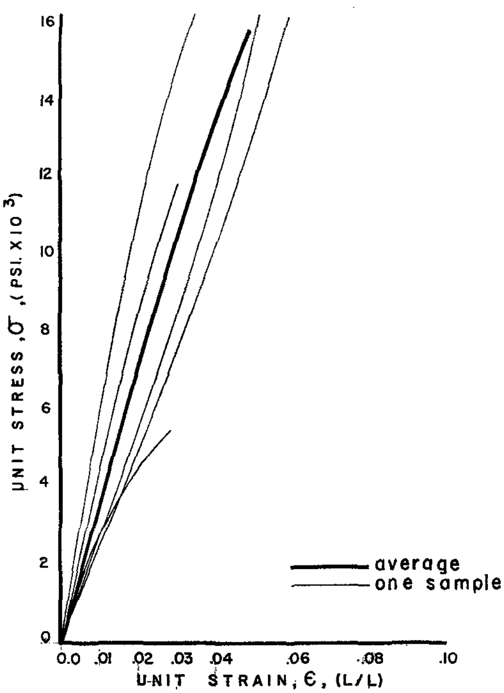


FIG. 6. Stress–strain plots for five oven-dried plantaris tendon specimen.

seen to be essentially the same. The average tensile strength reported herein, 14,200 psi is, however, considerably higher than that reported by KOCH (1917), 9,850 psi. The present results show conclusively a great increase in tensile strength of dry tendons over similar moist tendons; in fact, the average strength of dehydrated tendons is more than 50% greater than that of moist tendons. A similar increase in the tensile strength subsequent to dehydration has been reported for human bone by EVANS and LEBOW (1952). These workers demonstrated that the strength of the middle third of the human femur increased from 12,000 psi for wet specimen to 16,000 psi for dried specimen, an increase of 33%. A similarity is, however, not to be unexpected since the principal organic constituent of tendon and bone are the same, i.e., collagen. The difference in tensile strength noted may be explained on the basis of the different orientation of the collagenous fibers in tendon and bone. In tendon the fibers run a longitudinal course paralleling the principal axis of stress (the longitudinal axis of the tendon), whereas in bone the collagenous fibers are laid down in spirals of differing pitch in the lamellae of the Haversian systems. Their obliquity to the long axis of the bone would necessarily subject them to greater shearing stress when the bone is stressed in its long axis and, hence, would cause them to rupture under less unit stress in this axis.

Inspection of the stress–strain curves of all tendons tested indicates immediately that those tendons which were dried differ rather markedly from the moist tendons. In addition to exhibiting greater tensile strength, as discussed above, the dry tendons were stiffer, i.e., exhibited less strain per unit stress than did the moist tendons. EVANS and LEBOW (1952) demonstrated that dried human bone elongated approximately 0·65% at rupture, whereas wet human bone elongated essentially twice as much, or 1·25%. This increased elongation in wet bone was correlated with its ability to absorb more energy when stressed. In the present study the maxi-

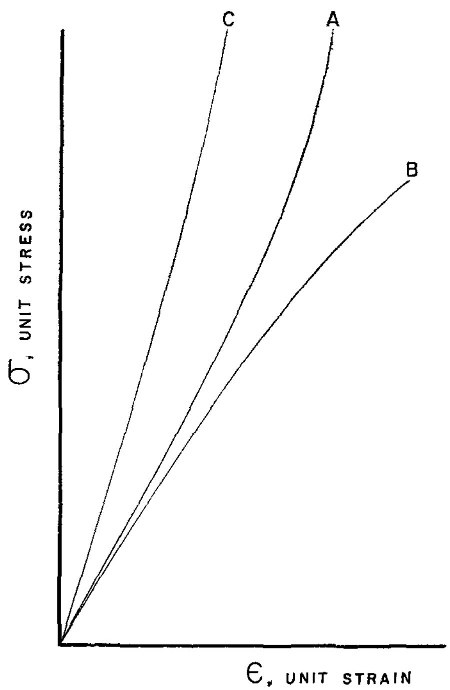


FIG. 7. Characteristic curves of stress vs. strain in plantaris tendons.

mum elongation observed in moist tendons was 10%, whereas the dried tendons were seen to elongate less than 5%. Since one of the described functions of tendon as a component of the series-elastic component of muscle (HILL, 1956), is to act as a cushion to the sudden development of force in the muscle, one would expect that normally hydrated tendon would have the ability to absorb at least as much energy as bone as well as transmit forces of muscular contraction to the bone.

Curves A and B, Fig. 7, are typical of the two patterns of stress–strain curves for moist tendons in this study. Both tendons develop strain of essentially the same magnitude per unit stress until a stress of 3,000 to 4,000 psi is reached. At this point the development of strain begins to differ. Curve A indicates an increasing stiffness whereas Curve B indicates a decreasing stiffness. The significant fact, in the opinion of the authors, is that the stress–strain curves do not differ significantly during the application of the initial one-fourth of the stress. The divergence of the two beyond this point is believed to be related to events in the tendon during testing. The apparent decrease in stiffness is believed to be due principally to the serial failure of individual collagenous fibers or small fascicles of collagenous fibers at weak points along their length. In corroboration, although the tendons chosen for testing were devoid of major defects, such as torn or frayed areas a number of tendons showed evidence of having been bent or folded during manipulation by student dissectors. During tests, rupture of small fascicles of collagenous fibers was seen to occur at transverse markings indicative of this previous folding or bending. The number of fibers failing was never large enough to cause any apparent abrupt change in the stress-strain curve, but, their rupture is believed to have weakened the tendon gradually, resulting in an apparent gradual decrease in stiffness seen in the plotted stress–strain curves.

With reference to the relatively slight variation demonstrated in the stress–strain curves during the application of approximately one-fourth of the stress required to rupture the tendons, and to the well known fact that normal, untraumatized tendon is seldom, if ever, seen to rupture, we believe that it is safe to assume that under normal circumstances tendons are rarely subjected to stresses greater than about one-fourth that required to rupture them. In corroboration, KOCH (1916) demonstrated a safety factor of approximately 5 in a dynamically loaded, fresh, human femur and a static safety factor of approximately 10. Tendon must have a safety factor greater than this, for, in the studies of DAVIDSSON (1954), muscles were pulled from their origins with fragments of bone attached, tendons were pulled from their insertions with fragments of bone attached and femurs were fractured, but, never in his studies did a normal tendon rupture. In the same study, tendons which had been partially severed failed to rupture until at least one half the fibers had been severed. Furthermore, MCMASTER (1933) reported that tendons which had three-fourths of their fibers severed experimentally were never ruptured during the normal activities of his rabbits which were allowed to recover and move about voluntarily. Therefore, we believe that the stress–strain characteristics of cadaveric human plantaris tendon in normal use is best represented by that portion of our curves which lie below a stress of approximately 4,000 psi. Inspection of the curves at this level of stress reveals that, although the moist tendons elongate approximately twice as much as dry tendons for a given stress, elongation in each is approximately one-fifth of the ultimate elongation as seen in these tests. Dry tendons elongated 1·25% whereas moist tendons elongated 2·5% at 4,000 psi.

It has been demonstrated by CALABRISI and SMITH (1951) that the compressive strength of human bone is reduced 13% by embalming. On the assumption that the tensile strength of bone is reduced by the same amount and if we may assume, because of the similarities in tensile characteristics of bone and tendon demonstrated above, that tensile strength of tendon is similarly reduced by embalming, then the findings reported herein for the wet specimen may be increased by 13% and used as a fair approximation of the tensile strength of normal, human plantaris tendon. Continuing studies will confirm or deny this postulate.

During the course of the tests it was noted that at any level of strain the prevailing load could be allowed to remain on the tendon for a period of up to five minutes with no change in the amount of elongation. This lack of detectable flow was noted for all tendons, dry or wet. This observed absence of a flow effect was noted also in tendons which, having slipped from the clamps during the course of a test, were subjected to a second period of stress. In addition, the stress–strain relationships were observed to change very little when curves of the second tests were compared with curves plotted for the initial tests. The maximum change in strain per unit stress was observed to occur in the moist tendons and amounted to approximately 10%. When the dry tendons were subjected to a second period of stress, the stress–strain curves were observed to be practically indentical.

5. CONCLUSIONS

General results may be summarized as conclusions, among which are:

(*a*) The stress–strain ratio for human cadaveric plantaris tendons (stressed to one-fourth their ultimate strength) may be taken as:
for moist tendons, 180,000 psi;
for dried tendons, 400,000 psi.

(*b*) Ultimate strengths for moist tendon varies from 10,600 psi to 21,300 psi, averaging 14,200 psi.

(*c*) Plantaris tendon in normal maximum use in the living body is likely stressed to about one-fourth the rupture level, say, to 3,500 × 113% or 4,000 psi; associated unit strain would be about 2%, i.e., $\varepsilon = 0{\cdot}02$.

(*d*) Dry tendon is stiffer and stronger than moist tendon.

(*e*) The tendons were observed to be free of plastic flow, and, as evidenced by the efficiency of use of tendon in the living body and a few observations taken in these tests, they appear to rebound to original dimensions again and again. Studies of the time element in this elastic rebound have not been made.

(*f*) There is strong correlation between strength and stiffness of tendons to strength and stiffness of bone, in the various test conditions. The common constituent, collagen, seems to be the clue.

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APPENDIX

Individual test results

Group	Specimen number	Condition	Area (In^2.)	Highest load applied (lb)	Highest stress (psi)	Remarks
I	1	Moist	0·0040	48·0	12,000	Ruptured in tension
	2	Moist	0·0033	21·8	6,720	Ruptured at clamp
	3	Moist	0·0018	19·0	10,650	Ruptured in tension
	4	Moist	0·0012	10·5	8,790	Ruptured at damaged point
	5	Moist	0·0030	43·0	14,320	Ruptured in tension
	6	Moist	0·0028	32·8	11,700	Ruptured in tension
	7	Moist	0·0038	41·2	10,830	Slipped from clamps
	8	Moist	0·0017	24·5	14,410	Ruptured in tension
	9	Moist	0·0020	24·2	12,100	Ruptured in tension
	10	Moist	0·0024	20·5	8,550	Slipped from clamps
	11	Moist	0·0023	30·2	13,120	Ruptured in tension
	12	Moist	0·0028	46·5	16,650	Ruptured in tension
	13	Moist	0·0043	65·9	15,325	Ruptured in tension
	14	Moist	0·0018	26·3	14,610	Slipped from clamps
	15	Moist	0·0023	38·2	16,600	Slipped from clamps
	16	Moist	0·0028	34·7	12,400	Slipped from clamps
	17	Moist	0·0018	26·0	14,410	Slipped from clamps
	18	Moist	0·0020	24·0	12,000	Ruptured at clamp
	19	Moist	0·0023	48·8	21,300	Ruptured in tension
	20	Moist	0·0033	54·4	16,480	Ruptured in tension
II	21	Air Dried	0·0022	41·2	18,450	Slipped from clamps
	22	Air Dried	0·0018	30·4	17,050	Slipped from clamps
	23	Air Dried	0·0020	63·5	31,750	Slipped from clamps
	24	Air Dried	0·0018	40·0	22,200	Slipped from clamps
	25	Air Dried	0·0010	21·6	20,600	Slipped from clamps
III	26	Oven Dried	0·0054	30·0	5,530	Slipped from clamps
	27	Oven Dried	0·0011	25·4	23,600	Slipped from clamps
	28	Oven Dried	0·0024	48·6	20,100	Slipped from clamps
	29	Oven Dried	0·0019	22·8	11,850	Slipped from clamps
	30	Oven Dried	0·0022	56·3	26,000	Slipped from clamps

RELATION CHARGE–TENSION DANS LE TENDON PLANTAIRE HUMAIN PRELEVE PAR AUTOPSIE: UNE ETUDE PRÉLIMINAIRE

Sommaire—En abordant une large étude expérimentale sur les forces agissant dans les muscles et les tendons, une étude préliminaire de la relation charge-tension s'est avérée nécessaire. Le présent exposé porte sur l'information recueillie à partir de 30 expériences faites sur le tendon plantaire humain, prélevé par autopsie. Ces expériences ont été menées dans des conditions différentes: tendon humide, tendon séché à l'air, tendon séché à l'étuve. Une corrélation a été etablie entre les résultats ainsi obtenus et ceux publiés précédemment sur le comportement des tendons et sur les mesures déjà établies des forces agissant dans le muscle et le tendon. Un nombre considérable de renseignements nouveaux concernant la force du tendon est fourni par la présente étude, et plusieurs conclusions significatives en sont tirées par déduction. L'équipement et les méthodes employés y sont également décrits et illustrés.

DAS VERHÄLTNIS BELASTUNG–SPANNUNG IN FUSSOHLENSEHNEN VON LEICHEN: EINE VORLÄUFIGE UNTERSUCHUNG

Zusammenfassung—Bei einer größeren experimentellen Untersuchung über die in Muskeln und Sehnen wirkenden Kräfte, erwies sich eine Kenntnis des Verhältnisses Belastung-Spannung in menschlichen Sehnen als unerläßlich. Die hier vorliegenden Studien bringen Daten aus über 30 Testfällen mit sezierten Sohlensehnen in drei verschiedenen Zuständen: feucht, luftgetrocknet und ofengetrocknet. Die Ergebnisse werden mit kürzlich veröffentlichten Erkenntnissen über Sehnen und mit Angaben über die Stärke von menschlichen Muskelgeweben und Knochen in Beziehung gebracht. Es werden neue Informationen über Sehnenstärke und einige Folgerungen dargestellt. Die Versuchsanordnung und die Methoden werden beschrieben und abgebildet.

ОТНОШЕНИЕ НАГРУЗКА-ДЕФОРМАЦИЯ ДЛЯ ПЛАНТАРНОГО СУХОЖИЛИЯ ТРУПА ЧЕЛОВЕКА: ПРЕДВАРИТЕЛЬНЫЕ ЭКСПЕРИМЕНТЫ

Резюме — Для намечаемого исследования сил в мышцах и сухожилиях необходимо в качестве предварительной ступени изучить отношение нагрузка-деформация для сухожилия человека. Сообщенные данные относятся к тридцати испытаниям плантарного сухожилия трупов, проведенным для трех состояний; влажного, высушенного на воздухе и высушенного в сушильной печи. Результаты сопоставляются с ранее опубликованными данными о сухожилиях и прочности мышц и костей человека. Представлены существенно новые сведения о прочности сухожилий и даны некоторые важные выводы. Описаны и иллюстрированы оборудование и методы.