Mechanical properties of Achilles tendons and age

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Abstract

I investigated the mechanical properties of rabbit Achilles tendon from birth to senescence. The cross-sectional area and maximum load increased with growth and aging. These changes may be influenced by increase in body weight. Though the tensile strength of mature tendon (67 MPa) was much higher than that of immature tendon (23 MPa), we found no clear difference when it was compared to that of old tendon (66 MPa). The average elastic modulus of mature tendon (618 MPa) was higher than that of immature (281 MPa) and old (530 MPa) tendon. The averages of elongation at failure were approximately 16% strain for Achilles tendon from birth to senescence. These results suggest that rabbit Achilles tendon becomes much stronger and stiffer through growth, then becoming less stiff from maturity to senescence.

Introduction

Injuries to the Achilles tendon through sport or physical activity occur frequently emphasizing the importance of prevention. The mechanical properties of the tendon play an important role in the aetiology of sports medicine and health science.

Limited investigation on the effect of exercise training on the tensile strength of Achilles tendon has been reported. Viidik (1982) has reported that the avulsion force at the calcaneous (muscle-tendon complex) and the ultimate load of isolated Achilles tendon increased after 40-weeks of training in rabbits. Brafred (1971) showed a higher ultimate load of Achilles tendon for wild rats as compared to domestic rats. Also, Vilarta et al. (1989) found that the Achilles tendon of rats that had undergone exercise showed higher tensile strength values than that of control rats. It seems that these authors used rather inaccurate methods for mechanical testing; and in addition, these reports don't analyze the tensile properties of the tissue substance of the Achilles tendon.

It is well known that tensile strength increases in the tendon with growth. Shadwich (1990) has reported that mature digital tendon becomes much stronger, stiffer, less extensible, and more resilient than at birth. Walker et al. (1976) demonstrated increased strength and stiffness with age in canine leg tendon, as did Haut and Little (1972) for rat tail tendon during aging. Similar data for the digital tendon of miniature swine has been proposed by Woo et al. (1980). The mechanical properties of Achilles tendon are an important aspect in crash or injury research, but age-dependent changes in the mechanical properties of Achilles tendon remain unknown. Woo et al. (1980, 1982) measured strain with a video dimension analyzer and showed the tensile strength of isolated digital tendon in miniature swine using newer approaches and theories. We have made similar measurements on rabbit Achilles tendon.

The purpose of this study is to examine the mechanical properties of rabbit Achilles tendon from birth to senescence.

Materials and Methods

Immature [$n=4$, age 3wk, weight 380 ± 28 (SE) g], mature ($n=4$, 8–10 month, 4.1 ± 0.3 kg), and old ($n=5$, 4–5 yrs, 5.1 ± 0.2 kg) Japanese white rabbits were obtained from Aging Colony from Hakkaido University and were treated according to their guide book for the care and use of laboratory animals. The rabbits were maintained individually in cages (30×48×35 cm). They were housed at an ambient temperature of 23°C, placed on a 12 : 12 hour light-dark cycle, and provided with standard rabbit chow and water ad libitum. The animals were anesthetized with pentobarbital sodium (5 mg/100 g) injected into an ear vein. After sacrifice, their left hindlimbs were resected, wrapped in gauze soaked in a saline solution, given a further wrapping of plastic film, and then stored at −32°C until testing. To prepare for testing, the specimens were first thawed overnight at 4°C and then at room temperture on the test date. The Achilles tendon was then cut at the calcaneus and muscle-tendon junction in about 5 cm (mature and old tendons) and 2.5 cm (immature) lengths to be used as test specimens and the surrounding tissues were removed. Care was taken to keep the tendon moist at all times during measurement.

The cross-ssectional area of the isolated Achilles tendon was measured at a uniform pressure of 0.12 MPa using an area-micrometer at the proximal, middle, and distal regions, and then the average cross-sectional area was calculated (Yamamoto et al. 1992). Each section of tendon was marked with a center line crosswise to it's length, followed by two more parallel lines at a distance of 5 mm both distal and proximal from this first line using a dye (nigrosine). The outer two lines were used as gauge-length markers for determining the surface strain in the substance of the tendon. Strain measurements were made using a video dimension analyzer (VDA) (HTV-C1170, Hamamatu Photonics Co.) (Fig. 1).

Special clamps were designed and used so that no slipping occured when the tendon was stretched. This clamping system was designed so that the tensile load applied directly in the longitudinal direction of the tendon substance. The tendon specimen was then clamped and mounted on a conventional tensile tester (PTM-250 W, Orientec Co., Tokyo). The grips were set at a distance of 20 mm. A preload of 0.5 N was applied so that the tendon was not lax at the beginning of the test. The Achilles tendon was subjected to 10 cycles of preconditioning for each tendon at an extension rate of 20 mm/min. Then, a tesile test was performed at the same extension. During the mechanical tests the tendon was kept moist with a saline solution at room temperature. Force was measured continuously by a strain gauge load cell. Both tensile load and strain data were recorded on an X-Y recorder. From these data, the stress-strain curves, maximum load, tensile strength, and elongation at failure were calculated. In all the tests, the tensile stress was calculated as the tensile force (in Newton) / cross-sectional area (in m^2) and expressed in megapascal ($1\ MPa = 10^6\ N/m^2$). The strain was calculated as the change in the length / initial length, as measured between the two surface markers in the tests with the video dimension analyzer. The video information was tape recorded and can be used for repeated strain analysis if necessary. The elastic modulus, a measure of the elastic stiffness of the tendon, was calculated as the gradient of the stress-strain curve (using the linear of the toe part) and expressed in magapascal.

Since Achilles tendon is composed of three separete tendons (medial and lateral gastrocnemius tendons and soleus tendon), tensile tests were performed for each tendon. For each section of tendon a portion of 10 mm in length was cut lengthwise from both the right and left sides between the nigrosine markes made previously in order to cause failure of substance. The tendon thickness remaining between them measured about 1 mm in width. For the whole Achilles tendon, the maximum load was shown as the sum of the average values of the three separate tendons; the other mechanical properties was shown in the three separate average values.

Student's paired t-test was used for the statistics. $P<0.05$ was taken as statistically significant.

Results

In all the tensile tests, failure of midsubstance in the tendon occured. Figs. 2–7 show the data for each mechanical property. The measurement of tendon size and maximum load showed an increase during age (Figs. 3 and 4). The cross-sectional area and maximum load of tendon was higher ($p<.01$) in mature tendon than in immature tendon, but lower in old tendon. Fig. 2 shows the average stress-strain data for immature, mature and old tendon. The stress-strain curve exhibited a linear toe region. After an approximately 3–7% strain, the stress-strain curve is characterized by low stiffness (i.e, a relatively large increase in strain with a small increase in stress). All the regions showed a gradual increase in stiffness with increasing strain. The elongation at failure obtained from tendon are shown in Fig. 5. There were no significant differences in elongation at failure among the three groups. For tensile strength, significant differences were observed in tendon substance between the immature and the other two groups ($p<.01$). The average tensile strength in the mature (67 MPa = 682 kg/cm^2) group was higher than that in immature (23 MPa = 235 kg/cm^2) and old (66 MPa = 673 kg/cm^2) groups (Fig. 6). The elastic modulus is shown by the slope of the stress-strain curve in Fig. 7. There were no significant differences among the three groups. The average elastic modulus was highest in mature tendon (618 MPa) compared to that in immature (281 MPa) and

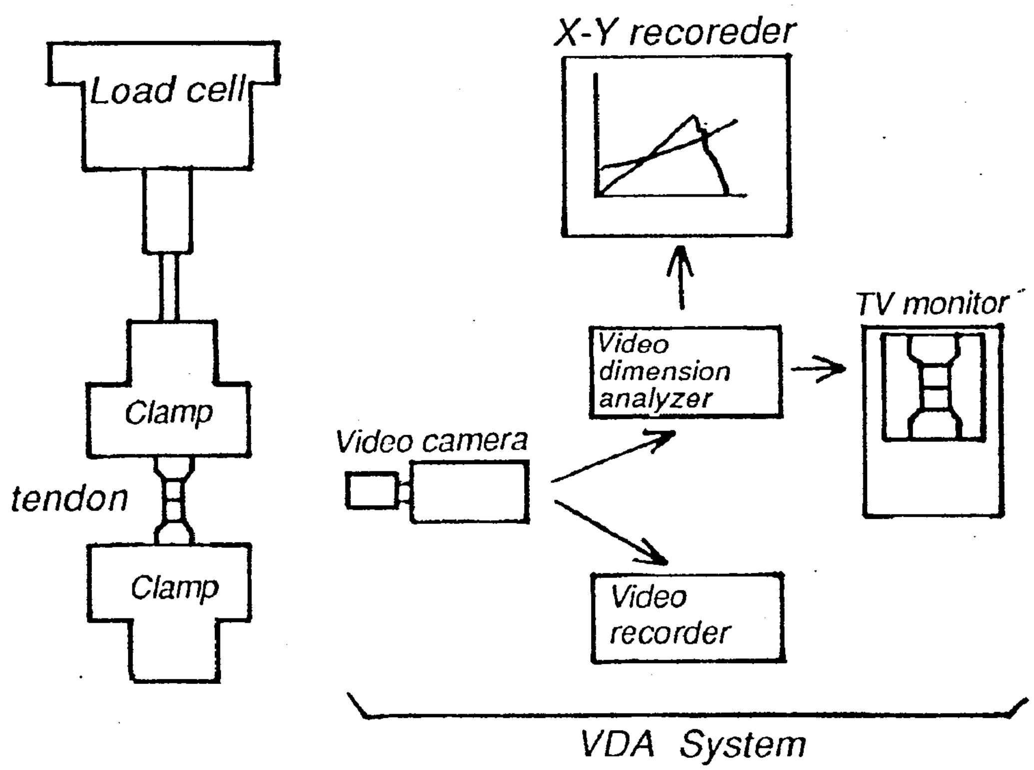

Fig. 1 Experimental apparatus used to determine the mechanical properties of Achilles tendon.

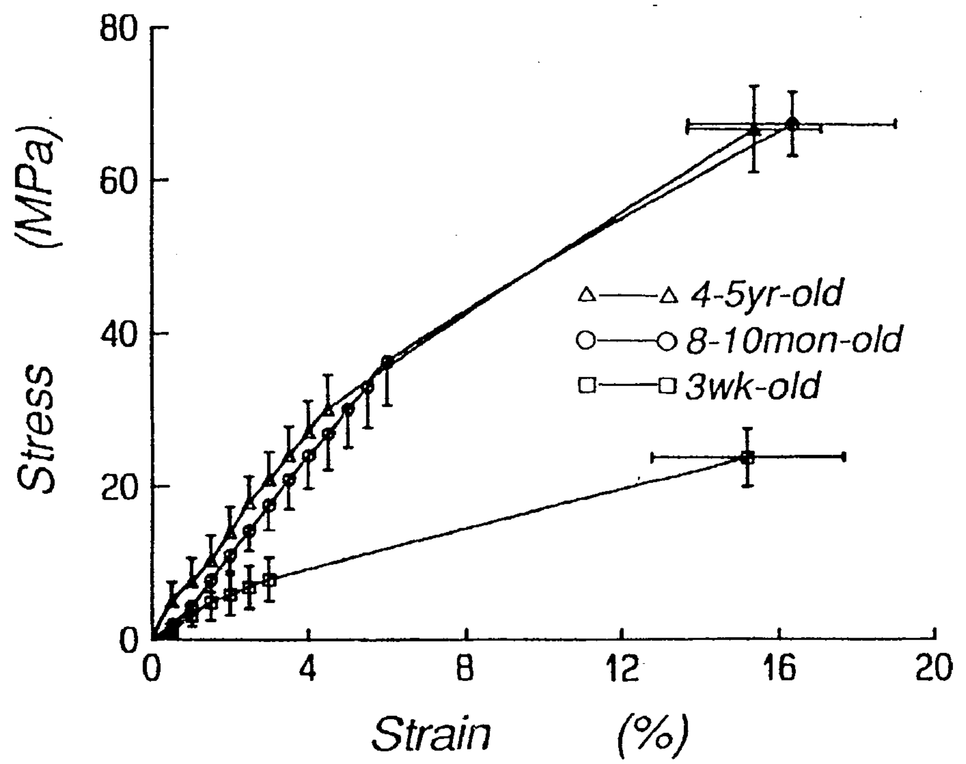

Fig. 2 Stress-strain curves of the mechanical properties of Achilles tendon with aging. Values are expressed as mean and standard error.

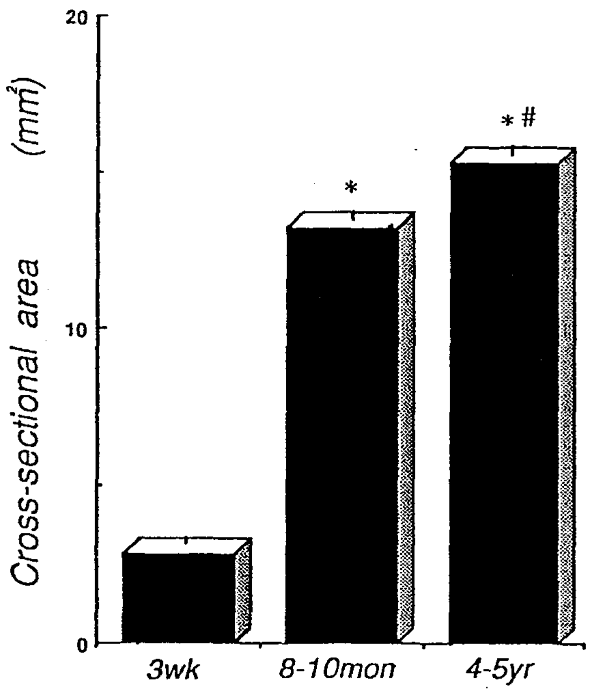

Fig. 3 Changes in the cross-sectional area of Achilles tendon during aging. Values are expressed as mean and standard error. * Significant difference from 3 wk-old rabbits ($p<.01$). # Significant difference for between 8-10 mon-old and 4-5 yr-old rabbits ($p<.01$).

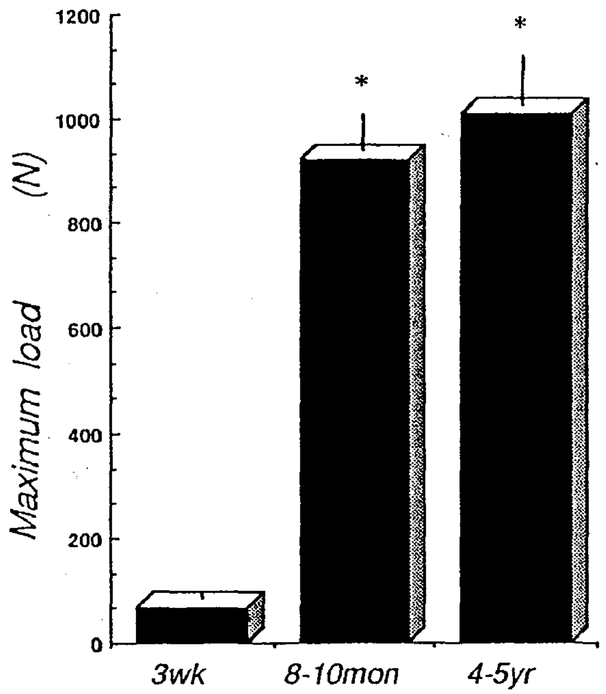

Fig. 4 Changes in the maximum load of Achilles tendon during aging. Values are expressed as mean and standard error. * Significant difference from 3 wk-old rabbits ($p<.01$).

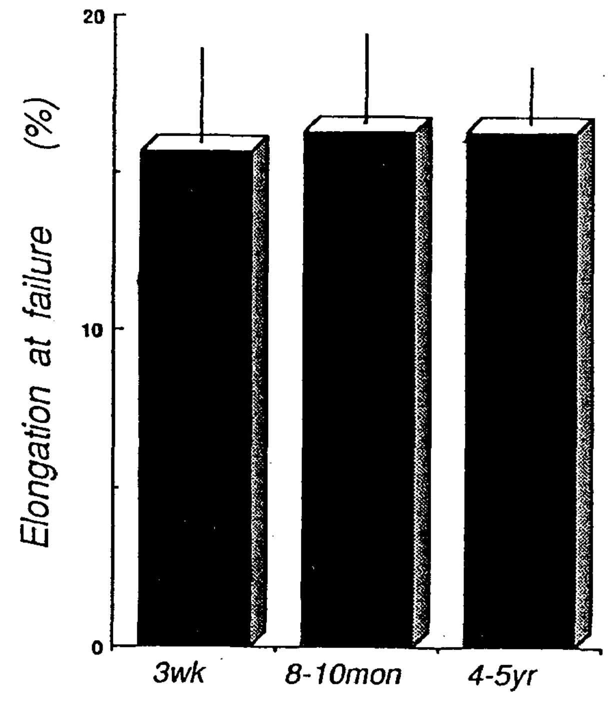

Fig. 5 Changes in the elongation at failure of Achilles tendon during aging. Values are expressed as mean and standerd error.

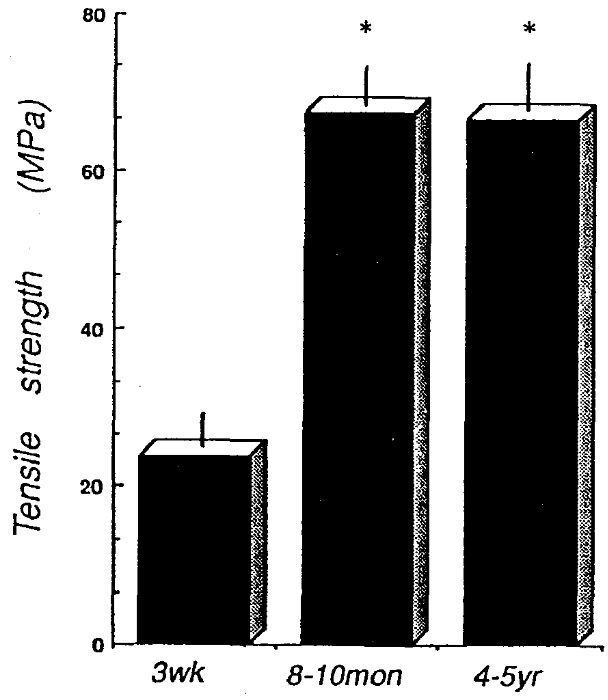

Fig. 6 Changes in the tensile strength of Achilles tendon during aging. Values are expressed as mean and standard error. * Significant difference from 3 wk-old rabbits ($p<.01$).

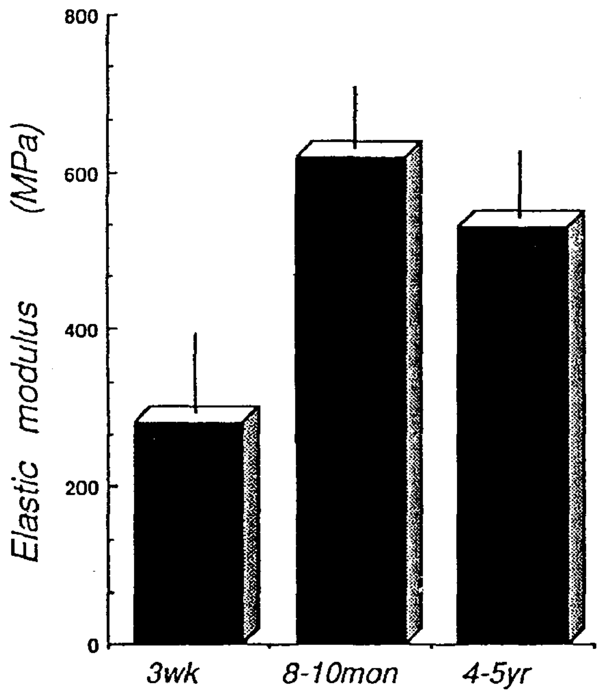

Fig. 7 Changes in the elastic modulus of Achilles tendon during aging. Values are expressed as mean and standard error.

old (530 MPa) tendons.

Discussion

The main purpose of this study was to study the mechanical properties of rabbit Achilles tendon from birth to senescence. In all the tests the break occurred in the central region of the tendon. Typical stress-strain curves obtained from tensile force tests on the tendon consist of a concave toe part with a rapidly increasing slope, then imperceptibly becoming linear with only a slightly increasing slope (Woo et al. 1980). However, in this study, the stress-strain curves are characterized a by sigmoid curve. That is to say, the stress-strain curves exhibited linear behavior with an initial portion characterized by high stiffness. After about a 3-7% strain, lower stiffness values were reached. A similar data for equine tendon has been proposed by (Reimersma and Schamhardt 1985). The reason that our results differ from these data may be due to the trimming of the tendon performed in this experiment.

Age-dependent alterations in the tensile strength of other kinds of mammalian tendon have been reported. For example, the tensile strength of human tendon increases from 30 MPa in infants to 100 MPa in adults (Elliot 1965). Viidik (1982) demonstrated the tensile strength of rat tail tendon to be 30 MPa at 1 month increasing to 100 MPa at 4 months. Similarly, increasing tensile strength during growth in canine leg tendons (Walker et al. 1976) and the digital tendon of miniature swine (Woo et al. 1982) has also been reported. Skeletally mature rabbits were used in this study. With growth, the tensile strength of mature tendon was much higher than that at birth; whereas the tensile strength of old tendon was not found to be clearly different from that of mature tendon. Changes in tensile strength reached a plateau (unchanging) form maturity to old age.

Several investigations have reported a nonuniform strain on tendon. Woo et al. (1981, 1982) reported an average failure strain of 9% for digital tendon in adult swine. Herrick et al. (1987), who loaded the whole leg in vitro, stated a 12% strain for the digital tendon of the forelimb of a horse. In this experiment on Achilles tendon, age-related alterations in the average elongation at failure were equivalent to 15.7% at immaturity, 16.3% at maturity and 16.3% at old age. Compared to the other studies, we found Achilles tendon to be highly extensile during growth and aging.

The elastic stiffness of tendon can be deduced from the dependence of the elastic modulus (i.e. the slope of the stress-strain curve). Walker et al. (1976) found an increased stiffness with age. Also, Viidik (1982) mentioned an increase in the elastic modulus of rat tail tendon through growth. In our data, the trend for the average elastic modulus of mature tendon to be higher than that of immature and old tendon seems to correlate markedly with the biological age of the animals.

The cross-sectional area and maximum load increased from birth to senescence. These changes may be influenced by physiological age, increase in body weight, or ground reaction force with growth and aging, rather than by the general increase (in growth) and decrease (in senescence) of metabolic activities.

I think that individual variations in the morphological and biochemical factors, alignment of the collagen fibrils, tissue distortion and anatomical locomotions contribute to the differences in the mechanical properties of tendon. During growth, tendon has a much higher tendon size, maximum load, tensile strength and elastic modulus than at immaturity. From maturity to senescence the mechanical parameters of Achilles tendon almost showed a plateau, but stiffness was lower. These results suggest that rabbit Achilles tendon becomes much stronger and stiffer through growth, and less stiff with senescence.

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References

Barfred, T. Experimental rupture of the Achilles tendon. Acta Orthop. Scand. 42: 406-428, 1971.

Elliot, D. H. Structure and function of mammalian tendon. Biol. Rev. 40;

392-421, 1965.

Haut, R. C. and R. W. Little. A constitutive equation for collagen fibers. J. Biomech. 5; 423-430, 1972.

Herrick, W. C., H. B. Kingsbury, and D. Y. S. Lou. A study of the normal range of strain, strain rate and stiffness of tendon. J. Biomed Materials Res. 12; 877-894, 1978.

Riemersma, D. J., and H. C. Schmhardt. In vitro mechanical properties of equine tendons in relation to cross-sectional area and collagen content. Res. Vet. Sci. 39; 263-270, 1985.

Shadwich, R. E. Elastic energy storage in tendons: mechanical differences related to function and age. J. Appl. Physiol. 63; 1033-1040, 1990.

Viidik, A. Age-related changes in connective tissues. in: Lectures on Gerontology, edited by A. Viidik. London: Academic, 1982, p.173-211.

Vilarta, R., and B. C. Vidal. Anisotropic and biomechanical properties of tendons modified by exercise and denervation: Aggregation and macromolecular order in collagen bundles. Matrix 9: 55-61, 1989.

Walker, P., H. C. Amstutz, and M. Rubenfeld. Canine tendon studies II. Biomechanical evaluation of normal and regrown canine tendons. J. Biomed. Mater. Res. 10: 61-76, 1976.

Woo, S. L-Y., M. A. Gomez, Y. K. Woo, and W. H. Akeson. Mechanical properties of tendons and ligaments. II. The relationships of immobilization and exercise on tissue remodelling. Biorheology 19; 397-408, 1982.

Woo, S. L-Y., M. A. Ritter, T. M. Sanders, M. A. Gomez, S. C. Keul, S. R. Garfin, and W. H. Akeson. The biomechanical and biochemical properties of swine tendons-long term effects of exercise on the digital extensors. Connect. Tissue Res. 7: 177-183, 1980.

Yamamoto, N., K. Hayashi, H. Kuriyama, K. Ohno, K. Yasuda and K. Kaneda. Mechanical properties of the rabbit pateller tendon. J. Biomech. Eng. 114; 332-337, 1992.