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Physical activity: does long-term, high-intensity exercise in horses result in tendon degeneration?

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Birch HL, Wilson AM, Goodship AE. Physical activity: does long-term, high-intensity exercise in horses result in tendon degeneration? *J Appl Physiol* 105: 1927–1933, 2008. First published October 2, 2008; doi:10.1152/japplphysiol.00717.2007.—This study explores the hypothesis that high-intensity exercise induces degenerative changes in the injury-prone equine superficial digital flexor tendon (SDFT), but not in the rarely injured common digital extensor tendon (CDET). The horse represents a large-animal model that is applicable to human tendon and ligament physiology and pathology. Twelve age-matched female horses undertook galloping exercise three times a week with trotting exercise on alternative days (high-intensity group, $n = 6$) or only walking exercise (low-intensity group, $n = 6$) for 18 mo. The SDFT, suspensory ligament, deep digital flexor tendon, and CDET were harvested from the forelimb. Tissue from the mid-metacarpal region of the right limb tendons was analyzed for water, DNA, sulfated glycosaminoglycan and collagen content, collagen type III-to-I ratios, collagen cross-links, and tissue fluorescence. Left limb tendons were mechanically tested to failure. The analyses showed matrix composition to have considerable diversity between the functionally different structures. In addition, the specific structures responded differently to the imposed exercise. High-intensity training resulted in a significant decrease in the GAG content in the SDFT, but no change in collagen content, despite a decrease in collagen fibril diameters. There were no signs of degeneration or change in mechanical properties of the SDFT. The CDET had a lower water content following high-intensity training and a higher elastic modulus. Long-term, high-intensity training in skeletally mature individuals results in changes that suggest accelerated aging in the injury-prone SDFT and adaptation in the CDET.

ligament; physical training; extracellular matrix

MANY PEOPLE ARE RELATIVELY physically inactive due to technological advances in the work place and home; a type of lifestyle known to contribute to disease. People are increasingly encouraged to compensate for this lifestyle by undertaking exercise to improve their health. The value of exercise is now also recognized for improving the symptoms of joint disease and arthritis (12, 48), although excessive exercise is a known factor that can contribute to the disease process (31). Little is, however, known about the effects of exercise on the skeletal system in general and in particular on soft connective tissues such as tendons and ligaments.

Injuries to tendon and ligaments are relatively common. A study in 1997 reported that 30–50% of human sports injuries were tendon related (16), while other studies have shown that the incidence of Achilles tendon rupture is increasing (14, 30). Some structures, such as the Achilles tendon, are particularly prone to injury, while other tendons, such as the anterior tibialis, are rarely affected. Tendon injuries are not restricted to humans, but also occur frequently in the horse (10, 18, 36, 51). As in humans, some equine tendons and ligaments, such as the superficial digital flexor tendon (SDFT) and suspensory ligament (SL) in the distal part of the forelimb, are particularly susceptible to exercise-related injuries (10, 18, 36), while the anatomically opposing common digital extensor tendon (CDET) is rarely injured. This suggests that there may be a structure-specific response of tendon to exercise in both human and equine subjects.

Previous studies investigating the effects of exercise on tendon properties have shown conflicting results. Some studies have shown tendon hypertrophy in response to training (6, 54) and increased collagen content (54), while others have shown no change (32, 53) or a decrease in mechanical and structural properties (29, 45). These apparent contradictions may be due to the variety of tendon types studied or due to variations in species, animal ages, exercise history, training duration, and intensities used in the studies.

In tendons prone to injury, it is now generally accepted that degenerative changes to the matrix precede clinical injury in human (17, 40) and equine subjects. Previous studies in horses have identified a reddish discoloration in the central core of the SDFT, which was deemed to represent degeneration (50). This central core discoloration has been shown to be associated with increased levels of type III collagen, sulfated glycosaminoglycan (GAG), cellularity, and rate of matrix turnover (3). In human tendons, similar changes have been observed. Degenerate supraspinatus and subscapularis tendons have been found to have an increased proportion of type III collagen relative to type I (40) and higher levels of sulfated GAGs (39). In addition, degenerated supraspinatus tendons had higher levels of the collagen cross-links, hydroxylysylpyridinoline and lysylpyridinoline, and lower levels of pentosidine (2). Histopathological changes have also been reported in spontaneously ruptured human tendons, including loss of parallel order of collagen fibers, hypoxic damage, and mucoid degeneration (17). In human tendons, these degenerative changes were associated with increasing age, although aging in equine tendons results in matrix changes that do not equate to degeneration, as older horses tend to have lower sulfated GAG levels and fewer cells (4). Increasing age in the equine SDFT is also associated with a decrease in collagen fibril diameters (9, 44).

The findings to date suggest that it is particularly important to determine the effects of exercise in skeletally mature indi-

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viduals undertaking a well-defined exercise regime and to study the effects on matrix biology of tendons that are prone to degeneration and injury. This type of study, however, is very difficult to carry out in human subjects, as tissue is required for in vitro analysis. Although human tissue can be collected at postmortem, this material does not have detailed information on exercise history, which precludes the study of exercise-related changes to tendon. The horse represents an excellent "natural model" for exercise-induced degenerative tendon disease in humans. The advantage of using equine subjects is that controlled exercise studies on age-, sex-, and breed-matched individuals can be carried out, and tissue harvested for in vitro matrix analysis.

In this study, we investigate the effects of long-term, high-intensity exercise on the distal limb tendons in skeletally mature Thoroughbred horses. We explore the hypothesis that high-intensity exercise induces degenerative changes in the SDFT and SL, but not in the rarely injured CDET.

METHODS

Animals. Twelve age-matched female Thoroughbred horses that had previously received no physical training were used for the study. Horses were paired based on size, and one of the pair was randomly assigned to the high-intensity exercise group, and the other to a low-intensity exercise group. All horses were 18 mo old at the start of the study, and age did not differ significantly between exercise groups (Table 1). Horses were kept in loose boxes (3.66 × 3.05 m) throughout the study. The study was conducted with appropriate regulatory approvals.

Training regime. The horses in the high-intensity exercise group were trained on a high-speed equine treadmill for 18 mo at a level similar to that which would be experienced in race training. A typical week's work was as follows: Monday, 3 km at 12 m/s, 3% slope; Wednesday, two times, 1.5 km at 12 and 14 m/s, 4% slope, 5-min recovery; and Friday, three times, 1 km at 12, 13, and 15 m/s, 3% slope, 5-min recovery. This was combined with 40-min walking on a mechanical horse walker 6 days/wk and 20-min trotting on days when no treadmill exercise was given. Horses in the low-intensity exercise group undertook only walking, and this was for 40 min each day on a mechanical horse walker for 6 days of the week. The low-intensity trained group allows comparison of high-intensity exercise with a "normal" level of activity rather than immobilization, which is well known to result in deterioration of tendon and ligament properties (1).

Tissue collection. The SDFT, SL, CDET, and deep digital flexor tendon (DDFT) were harvested from the right and left forelimb of each horse immediately following death. One of the horses in the high-intensity exercise group was not able to complete the training due to ill health and was, therefore, precluded from the analysis. Tendons from the right limb were used for matrix analysis and histological examination. The gross appearance of the whole tendon and transverse cross section were examined for any signs of damage or discoloration. A 1.5-cm section was taken from the mid-metacarpal region of each tendon, snap frozen in liquid nitrogen, wrapped in cling film to prevent dehydration, and stored at −80°C before analysis. An adjacent 1-cm section from the SDFT was fixed in formalin and processed for routine hematoxylin and eosin staining for qualitative assessment of fiber alignment. In addition, the cross-sectional area (CSA) of each tendon was measured [results reported previously (5)], and a sample of tissue processed for determination of collagen fibril diameters using electron microscopy and the mass average fibril diameter were calculated [results reported previously (9, 34, 35)]. The left forelimb SDFT and CDET were dissected free from the limb, wrapped in cling film, and stored frozen at −20°C for mechanical testing.

Water content. Tissue was semithawed at room temperature, and outer loose connective tissue and epitenon were removed. The remaining tissue from the SDFT only was divided into central zone and peripheral zone tissue, as described previously (3). Tissue was weighed and freeze dried until a constant weight was reached. Water content is expressed as a percentage of the wet tissue weight.

DNA assay and tissue fluorescence. Before DNA and GAG measurement, the lyophilized tissue was solubilized by papain digestion, as described previously (3). DNA was assayed by the fluorometric method of Kim et al. (19) using the bisbenzimidazole dye, Hoechst 33258, to give an indication of tissue cellularity. Fluorescence was also measured in the absence of Hoechst dye, and readings for DNA in the presence of Hoechst dye were corrected to account for background tissue fluorescence. DNA concentrations were calculated by comparison to a standard curve prepared with calf thymus DNA diluted in dye solution to give a range of concentrations from 0 to 0.5 μg/ml. DNA content in tendon samples is expressed as micrograms DNA per milligram dry weight tissue and tissue fluorescence as arbitrary units per milligram of collagen.

GAG assay. Total sulfated GAG content was quantified in aliquots of the papain digest by the method of Farndale et al. (11) using dimethylmethylene blue dye. Concentrations were calculated by comparison with a standard curve prepared with purified bovine trachea chondroitin sulfate (0–10 μg in 3 ml dye). Results are expressed as micrograms chondroitin sulfate equivalent sulfated GAG per milligram dry weight tissue.

Collagen content. Collagen content was determined by measuring the amino acid hydroxyproline in an aliquot of the papain digest, as described previously (3). Hydroxyproline concentrations were calculated by comparison with a standard curve prepared with standards (0–10 μg hydroxyproline/ml) and collagen content calculated, assuming hydroxyproline to be present at 14%. Collagen content is expressed as a percentage of the dry weight of tendon tissue.

Collagen type. Lyophilized tissue samples (~5 mg) from the central zone of the SDFT were digested with CNBr by the method of Light and Bailey (26). The resulting peptides were dissolved in 200-μl sample buffer (125 mM Tris, 2% sodium dodecyl sulfate, 10% glycerol, 0.01% bromophenol blue) and heated for 30 min at 60°C to ensure dissociation of the polypeptide chains. CNBr peptides were separated by SDS-PAGE on a 12.5% gel by the method of Laemmli (23) and stained with Coomassie brilliant blue. Standards of purified types I and III collagen prepared from equine fetal skin and digested with CNBr as above were also separated by electrophoresis, along with the samples. The bands α1(I)CB8 and α1(III)CB5 were used to

Table 1. *Horse age, body weight, and tendon cross-sectional area at the end of the training period*

Exercise Group	*n*	Age, mo	Body Weight, kg	Cross-Sectional Area			
				SDFT, mm²	DDFT, mm²	SL, mm²	CDET, mm²
Low intensity	6	38.4±1.1	504±32	105±25	159±5	178±37	32±2
High intensity	5	39.0±1.2	452±21*	98±8	165±12	189±28	31±3

Values are means ± SD; *n*, no. of horses. SDFT, superficial digital flexor tendon; DDFT, deep digital flexor tendon; SL, suspensory ligament; CDET, common digital extensor tendon. *Significant difference relative to the low-intensity-trained group, $P \leq 0.05$.

quantify types I and III collagen, respectively. Quantification was carried out using a transilluminator and LabWorks (version 3.0.02.00) software (UVP, Cambridge, UK).

Collagen cross-link analysis. The method used for the preparation and measurement of collagen cross-links was that of Sims and Bailey (42). Approximately 15 mg of dry tissue were suspended in phosphate-buffered saline, reduced with potassium borohydride, and hydrolyzed. Cross-linked amino acids were separated from non-cross-linked amino acids by fractionation on a CF-1-cellulose column. Cross-linked compounds were separated on a LKB 4400 amino acid analyzer and identified by comparison with a standard cross-link preparation. Results are expressed as moles of cross-link per mole of collagen.

Mechanical properties. The left SDFT and CDET from each horse were thawed at room temperature and mounted in a servohydraulic materials testing machine using cryoclamps. Tendons were preloaded with 25 N (CDET) or 100 N (SDFT) before precondition using 20 cycles from the preload to 1.5 kN (CDET) or 4 kN (SDFT). Tendons were then loaded to failure at 200%/s (SDFT) or 50%/s (CDET). Force and deformation data were collected, and the ultimate force, ultimate stress, stiffness, and elastic modulus were calculated.

Statistical analysis. Statistical significance was evaluated using a general linear model in SPSS (version 13, Microsoft). Tendon type and exercise group were used as fixed factors for each variable measured. If tendons were found to be significantly different from each other for a variable, they were considered separately to assess the influence of the exercise group for that variable. Differences between central and peripheral zone tissue in the SDFT were assessed using zone and exercise group as fixed factors. The level of significance was taken as $P \leq 0.05$. Data are presented as means ± SD.

RESULTS

Gross morphology and histological examination. All tendons appeared macroscopically normal on examination during the harvesting procedure and showed no signs of central core discoloration. Hematoxylin and eosin staining of longitudinal sections of the SDFT showed parallel collagen fiber alignment and rows of elongated nuclei with no apparent differences between sections from high- and low-intensity-trained tendons (Fig. 1). The CSA did not differ significantly between high- and low-intensity exercised groups for any of the structures (Table 1), as reported previously (5).

Water content. Water content, which can have a significant influence on tissue stiffness, ranged from 56.3 to 67.6%, and all structures were significantly ($P < 0.001$) different from each other (Table 2). The water content did not differ between the central and peripheral zone tissue for the SDFT. Water content was not significantly different between low- and high-intensity-trained groups for the SDFT, DDFT, and SL. The CDET from the high-intensity-trained horses, however, had a significantly ($P = 0.007$) lower water content than the CDET from the low-intensity trained horses (Table 2).

DNA content. DNA content gives an indication of cellularity and did not differ between the central and peripheral zone tissue of the SDFT, but was significantly different between the structures ($P < 0.001$). The SL had the highest levels followed by the SDFT, then the DDFT, while the CDET had the lowest levels (Table 2). DNA content did not differ significantly between the low- and high-intensity exercised groups for any of the structures.

GAG content. GAGs influence tissue hydration and have also been implicated in the control of collagen fibril diameters. The high-intensity-trained group of horses had a significantly lower GAG content in the SDFT ($P = 0.003$), SL ($P = 0.021$), and CDET ($P = 0.026$) than the low-intensity-trained group (Table 2). This difference was greatest in the central zone of the SDFT (Fig. 2). The GAG content was significantly different between structures ($P < 0.001$). The CDET had a significantly lower GAG content than all of the other structures (Table 2). The SDFT had a significantly lower GAG content than the SL, but was not significantly different from the DDFT. The SL had a significantly higher GAG content than the CDET and SDFT, but was not significantly different from the DDFT. There was no significant difference between the central and peripheral zone tissue of the SDFT.

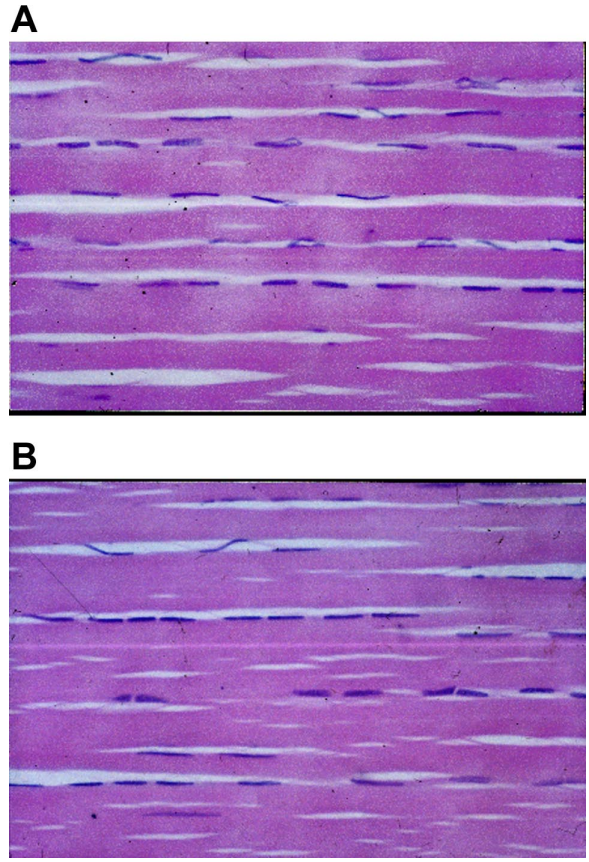

Fig. 1. Hematoxylin and eosin-stained longitudinal section of the superficial digital flexor tendon (×823) from a high-intensity-trained horse (*A*) and low-intensity-trained horse (*B*).

Collagen content. The collagen component provides high-tensile strength, and content varied between 70.7 and 75.2% of the dry weight of tendon tissue, and this was significantly ($P \leq 0.018$) higher than the collagen content of the SL (Table 2). Collagen content did not differ significantly between the central and peripheral zone tissue of the SDFT. The SL had a significantly ($P = 0.012$) higher collagen content in the high-intensity exercised group compared with the low-intensity exercised group of horses (Table 2).

Collagen cross-links. The ability of collagen to resist high-tensile forces depends on the formation of strong covalent cross-links between collagen molecules. The predominant mature cross-link detected in the SDFT, DDFT, and SL samples was hydroxylysylpyridinoline. The levels did not differ significantly between the high- and low-intensity-trained horses for

Table 2. *Matrix composition of the SDFT, DDFT, SL, and CDET following low- and high-intensity training*

	SDFT	DDFT	SL	CDET
Water content, %				
High intensity	64.3±0.8	61.8±1.2	67.6±1.5	56.3±0.8*
Low intensity	64.1±0.9	61.4±1.3	67.4±1.1	57.7±0.5
CI	−1.0 to +1.5	−1.3 to +2.2	−1.6 to +2.0	−2.2 to −0.5
DNA, μg/mg				
High intensity	1.49±0.13	0.73±0.16	2.32±0.29	0.39±0.09
Low intensity	1.53±0.19	0.85±0.12	2.23±0.31	0.54±0.22
CI	−0.26 to +0.19	−0.31 to +0.07	−0.33 to +0.50	−0.39 to +0.09
GAG, μg/mg				
High intensity	8.1±1.1*	9.6±3.5	12.1±1.2*	2.2±0.4*
Low intensity	9.9±1.3	11.3±2.6	14.2±1.3	2.7±0.3
CI	−3.4 to −0.18	−5.9 to +2.4	−3.8 to −0.4	−1.0 to −0.1
Collagen, mg/mg				
High intensity	0.72±0.05	0.75±0.05	0.68±0.07*	0.72±0.03
Low intensity	0.72±0.04	0.73±0.04	0.57±0.04	0.71±0.02
CI	−0.07 to +0.06	−0.04 to +0.08	+0.03 to +0.19	−0.02 to +0.04
Pyridinoline, mol/mol				
High intensity	0.48±0.07	0.35±0.06	0.45±0.05	0.04±0.01
Low intensity	0.47±0.05	0.36±0.04	0.48±0.04	0.03±0.02
CI	−0.08 to +0.08	−0.08 to +0.05	−0.10 to +0.04	−0.02 to +0.03
Tissue fluorescence, units/mg				
High intensity	152.7±9.9	149.0±7.8	160.2±7.9	116.6±16.2
Low intensity	156.8±15.7	160.7±13.0	162.0±19.0	135.3±24.2
CI	−22.6 to +14.3	−26.8 to +3.4	−22.5 to +18.9	−47.6 to +10.1

Values are means ± SD. CI, 95% confidence interval for difference between means. *Significant difference relative to the low-intensity-trained group, $P \leq 0.05$.

any of the structures (Table 2). There was no difference between the central and peripheral zone tissue of SDFT; however, the SDFT, DDFT, and CDET had significantly different levels ($P < 0.001$) from each other, with the SDFT having the highest levels followed by the DDFT, and the CDET having the lowest levels. Histidinohydroxylysinonorleucine, a major cross-link found in mature skin, was detected in all of the CDET samples (0.069 ± 0.005 mol/mol collagen) and some of the DDFT samples at trace levels, but did not differ significantly between high- and low-intensity-trained groups. A further peak of histidinohydroxymesodesmosine was detected in high amounts in the CDET samples (1.24 ± 0.15 mol/mol collagen) and at trace levels in the DDFT samples, but it did not differ significantly between high- and low-intensity-trained groups. The divalent immature aldimine cross-link dehydrohydroxylysinonorleucine was detected in the CDET samples (0.04 ± 0.01 mol/mol collagen), but none of the other structures.

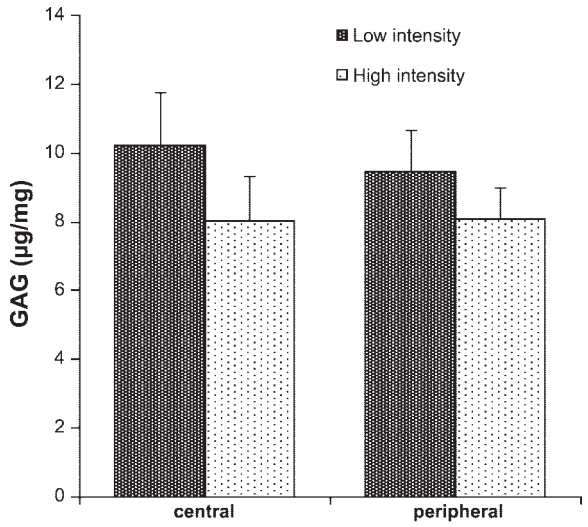

Fig. 2. Total sulfated glycosaminoglycan (GAG) content in the central and peripheral zone tissue of the superficial digital flexor tendon following high- and low-intensity training. Values are means ± SD.

Type III collagen. The ratio of type III collagen to type I collagen has been shown to increase in degenerated tendons (3). The central zone tissue of the SDFT contained 9.7 ± 2.2% type III (high-intensity group) and 7.5 ± 4.0% (low-intensity group), and this was not significantly different between the two exercise groups (95% confidence interval for difference between means = −2.3 to +6.8).

Tissue fluorescence. Tendon tissue fluorescence has been shown previously to correlate to the age of the horse (4) and shows a significant decrease in the core of degenerated SDFT relative to the peripheral zone tissue (3). The tissue fluorescence was not significantly different between central and peripheral zone tissue of the SDFT. The high-intensity-trained group had lower levels of tissue fluorescence in all of the structures than the low-intensity-trained group (Table 2), and this was significant ($P < 0.001$) when all structures were grouped together. The CDET had significantly ($P \leq 0.011$) lower levels of fluorescence than the SDFT, DDFT, and SL; however, the other structures were not significantly different from each other.

Mechanical properties. The force and stress withstood by the tendons before gross failure were not significantly different between the high-intensity and low-intensity-trained groups for the SDFT or CDET (Table 3). The SDFT had a similar stiffness and elastic modulus in the linear region of the loading curve for both exercise groups. The elastic modulus of the CDET, however, was significantly ($P = 0.004$) higher following high-intensity training (Table 3).

Table 3. *Mechanical properties of the SDFT and CDET following low- and high-intensity training*

	SDFT	CDET
Ultimate force, N		
High intensity	13,335±2,923	5,307±789
Low intensity	13,520±4,188	5,420±1,474
CI	−5,739 to +5,369	−1,782 to +1,555
Ultimate stress, MPa		
High intensity	123±24	203±34
Low intensity	128±33	187±43
CI	−50 to +39	−37 to +70
Stiffness index, kN/strain		
High intensity	135±20	39.7±1.6
Low intensity	136±17	37.6±4.9
CI	−28 to +27	−3.1 to +7.3
Elastic modulus, MPa		
High intensity	1,245±121	1514±55*
Low intensity	1,310±95	1,303±110
CI	−228 to +99	+88 to +333

Values are means ± SD. *Significant difference relative to the low-intensity-trained group, $P \leq 0.05$.

DISCUSSION

The results of this study do not support our hypothesis that high-intensity exercise results in tendon degeneration in the injury-prone SDFT. We were unable to show any of the matrix changes, such as increased type III/I collagen ratios, increased sulfated GAG levels, high cellularity, and low-tissue fluorescence associated with macroscopically degenerated equine tendons, a condition we consider to be analogous to long-standing painless tendinopathy in humans (27, 37). It may be that a more intense training program would have resulted in overt tendon damage; however, the level of activity in this study was similar to that experienced by horses in race training where tendinopathies are common. Furthermore, if our high-intensity-trained group of horses had been compared with a group of horses confined to box rest, we may have seen significant differences, but this would not be of particular relevance to high-intensity exercise vs. moderate levels of activity.

Although the tendons studied showed remarkably few changes in response to the high-intensity training regime, tendons that have evolved for different functional roles varied in their response to the increased exercise. This may, in part, explain the variation in results obtained in other training studies, where a variety of tendons, such as the Achilles (13), anterior tibialis (32), flexor digitorum longus (32), digital extensor (54), and patella (22, 38) tendons, have been assessed. This difference in response is likely to relate to the different physiological function of individual tendons and also differences in their composition and rates of maturation. Indeed, the data from this study have demonstrated marked differences in the matrix composition, including collagen cross-links, sulfated GAG, and cellularity between the anatomically and functionally distinct structures. Such variation is likely to result in specific mechanical properties, which relate to the different role of these tendons and ligament during locomotion.

In response to high-intensity training, the positional low-strain and rarely injured tendon (CDET) showed a decrease in water content, while the proportion of collagen in the dry weight of tissue remained the same, signifying an overall increase in collagen. This change would be expected to increase the stiffness of the tendon tissue, a response that seems appropriate for a positional tendon, such as the CDET, which is required to be relatively inextensible for efficient function. This finding is supported by the mechanical data showing a significantly higher elastic modulus, thus demonstrating a stiffer material in the high-intensity trained CDETs, even though fibril diameters and interfibrillar spacing were not significantly different, as reported previously (9).

In contrast to the positional tendon, in response to high-intensity training, the high-strain SDFT did not show a decrease in water content or an increase in collagen content. When considering the function of the tendon, this is not surprising, given that the force the SDFT experiences is due, to a large extent, the gravitational and inertial forces of locomotion rather than muscle contraction (52), and this would not be expected to increase with high-intensity training. An increase in collagen content or an increase in the CSA, which would both increase the stiffness of the structure, would reduce the efficiency of the SDFT. Indeed, the mechanical data demonstrate no changes in material stiffness or ultimate properties in the SDFT following high-intensity training. Furthermore, our laboratory has previously reported no difference in the CSA of the SDFT from the high- and low-intensity-trained horses (5).

Interestingly, the SL, which is also a high-strain, energy-storing structure, showed a significantly higher collagen content in the high-intensity-trained group of horses. This apparent contradiction is likely to result from a difference in the maturation time of the different structures studied. The SL is a vestige of the interosseus muscle and at birth has a considerable muscle component. As the ligament matures, the muscular tissue is replaced by collagenous tissue. The results of the present study suggest that this maturation process is accelerated by the imposition of high-intensity exercise or alternatively may be slowed down in the low-intensity-trained group by withholding high-speed exercise. In the high-intensity-trained group of horses, the collagen content of the SL was not significantly different to that of the SDFT.

In the energy-storing structures following long-term, high-intensity exercise, the levels of sulfated GAG were significantly lower compared with low-intensity-trained horses. Sulfated GAG chains are a component of proteoglycan molecules, which, in the tensional region of tendon, are represented predominantly by the family of small leucine-rich proteoglycans, namely decorin, fibromodulin, biglycan (49), and lumican (15). These molecules bind to collagen fibrils and play a role in fibrillogenesis and regulation of collagen fibril diameters (7, 8, 15, 47). Correspondingly, our laboratory has previously reported that collagen fibril diameters were significantly smaller in the core of the SDFT from high-intensity-trained horses than those in the low-intensity-trained horses (35), although the area covered by collagen was not significantly different between the two groups (high-intensity group: 66.2%, low-intensity group: 71.7%). However, reduction in collagen fibril diameters did not occur in the SL or the positional tendon following high-intensity training, despite a lower sulfated GAG content (9, 34). Other noncollagenous proteins have been implicated in the process of collagen fibril formation, including the glycoprotein, cartilage oligomeric matrix protein. The level of cartilage oligomeric matrix protein was also found to be

lower in the central zone tissue of the SDFT in the high-intensity-trained horses, as reported previously (43).

The analyses of the SDFT extracellular matrix suggested that accelerated collagen formation was not taking place. For example, we were unable to detect any immature cross-links, and the levels of tissue fluorescence, which our laboratory has previously found to be a good indicator of matrix age (3, 4), did not change. Our results, therefore, suggest that small-diameter collagen fibrils result from breakdown of larger fibrils. Small-diameter collagen fibrils are associated with tissues, with a less stiff matrix, and this has been suggested to be due to an increase in interfibrillar interactions relative to cross-links within the fibrils (33). This change in the matrix of the SDFT may be an adaptive response to increase the elasticity of the tendon or may represent microdamage, although we were not able to detect either with mechanical testing, whichever way; the mechanism for this is unclear but may involve loss of the proteoglycan molecule. The measurement of sulfated GAG content does not differentiate between loss of the whole proteoglycan molecule from the matrix, removal or partial removal of the GAG chain from the protein core, or synthesis of new proteoglycan molecules with shorter GAG chains. Interestingly, smaller fibril diameters and reduced levels of sulfated GAG have been reported in old tendons, suggesting reduction occurs as part of the natural aging process (39, 46).

Studies into the effects of exercise on human tendons are restricted to measurements that can be made nondestructively in vivo. Although this precludes matrix composition and tissue morphology analysis, measurement of gross tendon CSA and stiffness have been made using imaging techniques. Several studies comparing athletes and nonathletes found that the CSA of the energy-storing Achilles tendon was larger in the athletes, suggesting that there might be an adaptive hypertrophy in response to training (28, 41, 55). However, a subsequent study, which measured Achilles tendon CSA and stiffness before and after 9 mo of training, found no change (13). In contrast, strength training of the quadriceps muscle group in young and old human subjects was found to increase the stiffness and elastic modulus of the patella tendon (22, 38), a positional tendon having a similar function to the equine CDET. Studies in other species also suggest a tendon-specific response to an imposed training regime. Following 12-mo running exercise of miniature swine, the digital extensor tendons underwent significant hypertrophy, while the flexor tendons were not significantly larger than those of the sedentary animals (53, 54).

Exercise studies in humans have not been able to assess collagen and proteoglycan content and organization within tendon. Measurements have, however, been made on peritendinous tissue around the human Achilles tendon and suggest an increase in blood flow (24), collagen turnover (25), and change in protease activity (21), with exercise which may represent an adaptive response (20).

In conclusion, the results of this study show that specific tendons respond differently to an imposed training regime. Long-term, high-intensity exercise resulted in an adaptive change in the low-strain, rarely injured CDET, whereas changes observed in the high-strain, energy-storing SDFT suggest accelerated aging as a result of training, although macroscopic pathology was not evident. We were not able to show any differences in the mechanical properties of the SDFT, and, therefore, it is difficult to say whether these aging-associated changes represent a beneficial response or very early signs of microdamage. This study is not able to determine whether these changes occurred in the first few months of training or in the longer term; hence further work is needed to determine whether a rest period between episodes of high-intensity training would reverse the changes seen. In addition, the analyses in this study showed substantial differences between functionally distinct tendons. The precise relationship between composition, structure, and function is an important area with regard to tendon and ligament physiology.

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REFERENCES

1. **Amiel D, Woo SL, Harwood FL, Akeson WH.** The effect of immobilization on collagen turnover in connective tissue: a biochemical-biomechanical correlation. *Acta Orthop Scand* 53: 325–332, 1982.
2. **Bank RA, TeKoppele JM, Oostingh G, Hazleman BL, Riley GP.** Lysylhydroxylation and nonreducible crosslinking of human supraspinatus tendon collagen: changes with age and in chronic rotator cuff tendinitis. *Ann Rheum Dis* 58: 35–41, 1999.
3. **Birch HL, Bailey AJ, Goodship AE.** Macroscopic "degeneration" of equine superficial digital flexor tendon is accompanied by a change in extracellular matrix composition. *Equine Vet J* 30: 534–539, 1998.
4. **Birch HL, Bailey JV, Bailey AJ, Goodship AE.** Age-related changes to the molecular and cellular components of equine flexor tendons. *Equine Vet J* 31: 391–396, 1999.
5. **Birch HL, McLaughlin L, Smith RK, Goodship AE.** Treadmill exercise-induced tendon hypertrophy: assessment of tendons with different mechanical functions. *Equine Vet J Suppl* 30: 222–226, 1999.
6. **Buchanan CI, Marsh RL.** Effects of long-term exercise on the biomechanical properties of the Achilles tendon of guinea fowl. *J Appl Physiol* 90: 164–171, 2001.
7. **Chakravarti S.** Functions of lumican and fibromodulin: lessons from knockout mice. *Glycoconj J* 19: 287–293, 2002.
8. **Danielson KG, Baribault H, Holmes DF, Graham H, Kadler KE, Iozzo RV.** Targeted disruption of decorin leads to abnormal collagen fibril morphology and skin fragility. *J Cell Biol* 136: 729–743, 1997.
9. **Edwards LJ, Goodship AE, Birch HL, Patterson-Kane JC.** Effect of exercise on age-related changes in collagen fibril diameter distributions in the common digital extensor tendons of young horses. *Am J Vet Res* 66: 564–568, 2005.
10. **Ely ER, Verheyen KL, Wood JL.** Fractures and tendon injuries in National Hunt horses in training in the UK: a pilot study. *Equine Vet J* 36: 365–367, 2004.
11. **Farndale RW, Buttle DJ, Barrett AJ.** Improved quantitation and discrimination of sulphated glycosaminoglycans by use of dimethylmethylene blue. *Biochim Biophys Acta* 883: 173–177, 1986.
12. **Fransen M, McConnell S, Bell M.** Exercise for osteoarthritis of the hip or knee. *Cochrane Database Syst Rev* CD004286, 2003.
13. **Hansen P, Aagaard P, Kjaer M, Larsson B, Magnusson SP.** Effect of habitual running on human Achilles tendon load-deformation properties and cross-sectional area. *J Appl Physiol* 95: 2375–2380, 2003.
14. **Houshian S, Tscherning T, Riegels-Nielsen P.** The epidemiology of Achilles tendon rupture in a Danish county. *Injury* 29: 651–654, 1998.
15. **Jepsen KJ, Wu F, Peragallo JH, Paul J, Roberts L, Ezura Y, Oldberg A, Birk DE, Chakravarti S.** A syndrome of joint laxity and impaired tendon integrity in lumican- and fibromodulin-deficient mice. *J Biol Chem* 277: 35532–35540, 2002.
16. **Kannus P.** Tendons–a source of major concern in competitive and recreational athletes. *Scand J Med Sci Sports* 7: 53–54, 1997.
17. **Kannus P, Jozsa L.** Histopathological changes preceding spontaneous rupture of a tendon. A controlled study of 891 patients. *J Bone Joint Surg Am* 73: 1507–1525, 1991.
18. **Kasashima Y, Takahashi T, Smith RK, Goodship AE, Kuwano A, Ueno T, Hirano S.** Prevalence of superficial digital flexor tendonitis and suspensory desmitis in Japanese Thoroughbred flat racehorses in 1999. *Equine Vet J* 36: 346–350, 2004.

19. **Kim YJ, Sah RL, Doong JY, Grodzinsky AJ.** Fluorometric assay of DNA in cartilage explants using Hoechst 33258. *Anal Biochem* 174: 168–176, 1988.
20. **Kjaer M.** Role of extracellular matrix in adaptation of tendon and skeletal muscle to mechanical loading. *Physiol Rev* 84: 649–698, 2004.
21. **Koskinen SO, Heinemeier KM, Olesen JL, Langberg H, Kjaer M.** Physical exercise can influence local levels of matrix metalloproteinases and their inhibitors in tendon-related connective tissue. *J Appl Physiol* 96: 861–864, 2004.
22. **Kubo K, Kanehisa H, Ito M, Fukunaga T.** Effects of isometric training on the elasticity of human tendon structures in vivo. *J Appl Physiol* 91: 26–32, 2001.
23. **Laemmli UK.** Cleavage of structural proteins during the assembly of the head of bacteriophage T4. *Nature* 227: 680–685, 1970.
24. **Langberg H, Bulow J, Kjaer M.** Blood flow in the peritendinous space of the human Achilles tendon during exercise. *Acta Physiol Scand* 163: 149–153, 1998.
25. **Langberg H, Rosendal L, Kjaer M.** Training-induced changes in peritendinous type I collagen turnover determined by microdialysis in humans. *J Physiol* 534: 297–302, 2001.
26. **Light ND, Bailey AJ.** The chemistry of the collagen cross-links. Purification and characterization of cross-linked polymeric peptide material from mature collagen containing unknown amino acids. *Biochem J* 185: 373–381, 1980.
27. **Maffulli N, Khan KM, Puddu G.** Overuse tendon conditions: time to change a confusing terminology. *Arthroscopy* 14: 840–843, 1998.
28. **Magnusson SP, Kjaer M.** Region-specific differences in Achilles tendon cross-sectional area in runners and non-runners. *Eur J Appl Physiol* 90: 549–553, 2003.
29. **Michna H.** Morphometric analysis of loading-induced changes in collagen-fibril populations in young tendons. *Cell Tissue Res* 236: 465–470, 1984.
30. **Moller A, Astron M, Westlin N.** Increasing incidence of Achilles tendon rupture. *Acta Orthop Scand* 67: 479–481, 1996.
31. **Munneke M, de Jong Z, Zwinderman AH, Ronday HK, van Schaardenburg D, Dijkmans BA, Kroon HM, Vliet Vlieland TP, Hazes JM.** Effect of a high-intensity weight-bearing exercise program on radiologic damage progression of the large joints in subgroups of patients with rheumatoid arthritis. *Arthritis Rheum* 53: 410–417, 2005.
32. **Nielsen HM, Skalicky M, Viidik A.** Influence of physical exercise on aging rats. III. Life-long exercise modifies the aging changes of the mechanical properties of limb muscle tendons. *Mech Ageing Dev* 100: 243–260, 1998.
33. **Parry DA, Barnes GR, Craig AS.** A comparison of the size distribution of collagen fibrils in connective tissues as a function of age and a possible relation between fibril size distribution and mechanical properties. *Proc R Soc Lond B Biol Sci* 203: 305–321, 1978.
34. **Patterson-Kane JC, Firth EC, Parry DA, Wilson AM, Goodship AE.** Effects of training on collagen fibril populations in the suspensory ligament and deep digital flexor tendon of young thoroughbreds. *Am J Vet Res* 59: 64–68, 1998.
35. **Patterson-Kane JC, Wilson AM, Firth EC, Parry DA, Goodship AE.** Comparison of collagen fibril populations in the superficial digital flexor tendons of exercised and nonexercised thoroughbreds. *Equine Vet J* 29: 121–125, 1997.
36. **Pinchbeck GL, Clegg PD, Proudman CJ, Stirk A, Morgan KL, French NP.** Horse injuries and racing practices in National Hunt racehorses in the UK: the results of a prospective cohort study. *Vet J* 167: 45–52, 2004.
37. **Puddu G, Ippolito E, Postacchini F.** A classification of Achilles tendon disease. *Am J Sports Med* 4: 145–150, 1976.
38. **Reeves ND, Maganaris CN, Narici MV.** Effect of strength training on human patella tendon mechanical properties of older individuals. *J Physiol* 548: 971–981, 2003.
39. **Riley GP, Harrall RL, Constant CR, Chard MD, Cawston TE, Hazleman BL.** Glycosaminoglycans of human rotator cuff tendons: changes with age and in chronic rotator cuff tendinitis. *Ann Rheum Dis* 53: 367–376, 1994.
40. **Riley GP, Harrall RL, Constant CR, Chard MD, Cawston TE, Hazleman BL.** Tendon degeneration and chronic shoulder pain: changes in the collagen composition of the human rotator cuff tendons in rotator cuff tendinitis. *Ann Rheum Dis* 53: 359–366, 1994.
41. **Rosager S, Aagaard P, Dyhre-Poulsen P, Neergaard K, Kjaer M, Magnusson SP.** Load-displacement properties of the human triceps surae aponeurosis and tendon in runners and non-runners. *Scand J Med Sci Sports* 12: 90–98, 2002.
42. **Sims TJ, Bailey AJ.** Quantitative analysis of collagen and elastin cross-links using a single-column system. *J Chromatogr* 582: 49–55, 1992.
43. **Smith RK, Birch H, Patterson-Kane J, Firth EC, Williams L, Cherdchutham W, van Weeren WR, Goodship AE.** Should equine athletes commence training during skeletal development? Changes in tendon matrix associated with development, ageing, function and exercise. *Equine Vet J Suppl* 30: 201–209, 1999.
44. **Smith TJ.** *The Relationship Between Tendon Morphology and Function* (Dissertation). London: University College, 2006.
45. **Sommer HM.** The biomechanical and metabolic effects of a running regime on the Achilles tendon in the rat. *Int Orthop* 11: 71–75, 1987.
46. **Strocchi R, De Pasquale V, Guizzardi S, Govoni P, Facchini A, Raspanti M, Girolami M, Giannini S.** Human Achilles tendon: morphological and morphometric variations as a function of age. *Foot Ankle* 12: 100–104, 1991.
47. **Svensson L, Aszodi A, Reinholt FP, Fassler R, Heinegard D, Oldberg A.** Fibromodulin-null mice have abnormal collagen fibrils, tissue organization, and altered lumican deposition in tendon. *J Biol Chem* 274: 9636–9647, 1999.
48. **Thomas KS, Muir KR, Doherty M, Jones AC, O'Reilly SC, Bassey EJ.** Home based exercise programme for knee pain and knee osteoarthritis: randomised controlled trial. *BMJ* 325: 752, 2002.
49. **Vogel KG, Meyers AB.** Proteins in the tensile region of adult bovine deep flexor tendon. *Clin Orthop Relat Res* 367, Suppl: S344–S355, 1999.
50. **Webbon PM.** A post mortem study of equine digital flexor tendons. *Equine Vet J* 9: 61–67, 1977.
51. **Williams RB, Harkins LS, Hammond CJ, Wood JL.** Racehorse injuries, clinical problems and fatalities recorded on British racecourses from flat racing and National Hunt racing during 1996, 1997 and 1998. *Equine Vet J* 33: 478–486, 2001.
52. **Wilson AM, McGuigan MP, Su A, van Den Bogert AJ.** Horses damp the spring in their step. *Nature* 414: 895–899, 2001.
53. **Woo SL, Gomez MA, Amiel D, Ritter MA, Gelberman RH, Akeson WH.** The effects of exercise on the biomechanical and biochemical properties of swine digital flexor tendons. *J Biomech Eng* 103: 51–56, 1981.
54. **Woo SL, Ritter MA, Amiel D, Sanders TM, Gomez MA, Kuei SC, Garfin SR, Akeson WH.** The biomechanical and biochemical properties of swine tendons; long term effects of exercise on the digital extensors. *Connect Tissue Res* 7: 177–183, 1980.
55. **Ying M, Yeung E, Li B, Li W, Lui M, Tsoi CW.** Sonographic evaluation of the size of Achilles tendon: the effect of exercise and dominance of the ankle. *Ultrasound Med Biol* 29: 637–642, 2003.