Chapter 5
Tendon

Purpose:
1. To describe tendon structure.
2. To describe the mechanical properties of tendons.
3. To relate tendon structure to function.
4. To describe how tendons fail and how they are repaired.
5. To describe how tendons change with aging and adapt to exercise and disuse.

Tendon Anatomy

General Structure and Function
Tendons connect muscles to bones and transmit forces developed by muscles to bones to move and stabilize joints. Each muscle typically has two tendons, one proximal and one distal. The junction between the muscle and tendon is referred to as the myotendinous junction (MTJ) and the junction between the tendon and bone is called the osteotendinous junction (OTJ). The OTJ associated with the least moveable bone is referred to as the origin of the muscle-tendon-bone (MTB) complex. The OTJ associated with the more moveable bone is referred to as the insertion. For example the proximal OTJ of the biceps brachii muscle is the origin during an elbow curl movement, but it is the insertion during a chin-up movement. Tendons have the same structural organization as ligaments (see Chapter 4, Figure 1). Tendons vary considerably in size and shape. Some are wide and flat, others are cylindrical or fan shaped. Tendons must slide over bones and they often move through canals and sheaths that help direct their path and limit the friction they must overcome. Retinacula are fibrous sheaths that act as straps to hold tendons in a particular location. Bursae are fluid filled sacs located between tendon and bone and function to reduce friction and wear. Tendon sheaths surround some tendons and contain a fluid similar to synovial fluid. True tendon sheaths are found around some tendons in the hand and feet at locations where large frictional forces could be developed. Tendons that act in straight lines are surrounded by a connective sheath called paratenon.
Biochemical Constituents

The major constituents of tendons are Type I collagen (~80% of dry weight), water (65 to 70% of the wet weight), elastin (<3% of dry weight), and proteoglycans (~1%). This composition is similar to ligaments with a slight reduction in elastin and proteoglycans.

Blood Supply

Tendons surrounded by paratenon have a vascular network whereas those surrounded by a sheath are more avascular. Blood vessels enter tendons surrounded by paratenon at many locations and then branch to form a longitudinal system of capillaries. Tendons surrounded by a sheath receive nutrients by diffusion from the synovium and from blood vessels originating near the OTJs.

Neural Structures

Tendons contain a variety of neural elements, Ruffini corpuscles, Vater-Pacini corpuscles, Golgi tendon organs. Ruffini corpuscles function as pressure sensors. They are slow adapting and respond to static conditions of position and stretch. Vater-Pacini corpuscles are also pressure sensors, but they adapt quickly and can react to dynamic changes such as velocity and acceleration. Golgi tendon organs are located in the MTJ and adapt slowly. They function to sense stretch and force. Free nerve endings also exist and function as pain receptors. The extent of neural innervation varies between tendons. Tendons of finger flexors tend to have greater neural innervation compared to the Achilles tendon. Neural innervation tends to be greater near the MTJ and OTJ.

Biomechanics

Structural/Material Properties

Tendons have similar properties to ligaments. The ultimate tensile strength of animal tendons has been reported to vary between 45 and 125 MPa. For humans, the ultimate tensile stress ranges between 50 and 105 MPa, the elastic modulus ranges from 1.2 to 1.8 GPa, and the ultimate strain ranges from 9% to 35%. The elastic strain energy recovered during cyclic loading of tendon at physiological loading rates is greater than 90%. Tendons have different properties depending on their anatomic location. Swine digital flexor tendons have twice the tensile strength and stiffness compared to digital extensor tendons.

Effects of Aging

Age affects the mechanical properties of tendon. The crimp angle decreases with age leading to a decrease in the toe-region of the stress-strain curve. The number of tendon cells per unit volume decreases during development and aging (Figure 1). The cross-sectional area of tendon increases with age until adulthood (Figure 2) and decreases in later life. The increase in tendon cross-sectional area varies between tendons. In old age the collagen content may be slightly decreased along with a decrease in proteoglycans and glycoproteins. Water content declines and there is an increase in cross-linking of the tropocollagen molecules. Collagen fiber area and strength decrease. The collagen turnover rate declines in old age. Tendon becomes smaller, weaker, and more prone to overuse injuries.
Figure 1: Cell density decreases with age

Figure 2: Tendon cross-sectional area increases to adulthood and decreases in later life.
Exercise and Disuse

Tendon properties change in response to new physical demands (Elliot and Crawford, 1964; Woo et al., 1982; Józsa and Kannus, 1997). Results from mechanical and biochemical tests suggest that tendon tensile strength varies as a function of activity and is associated with the amount, orientation and architecture of collagen, and the interstitial matrix which binds collagen fasciculi together (O’Brien, 1992). Though the effects of strength training on human tendons have not been studied (Kannus et al., 1997), in-vitro studies of animal tendon suggest that a gradual increase in physical demands results in higher tensile strength, elastic stiffness and total weight (Józsa and Kannus, 1997). Vigorous exercise appears to reduce tendon properties initially, but may provide positive benefits in the long term depending on the tendon (Figure 3). Compared to muscle, the metabolic turnover of tendon is many times slower because of poor vascularity and circulation. Therefore it can be expected that during training muscles will adapt faster than tendons. Young tendons adapt to physical activity by increasing their size as well as changing their material properties. Adult tendons appear to adapt more by changing material properties with less change in cross-sectional area.

![Stress-Strain Curve](image)

**Figure 3:** Swine flexor and extensor tendons appear to respond differently to exercise. After three months of running exercise, both flexor and extensor tendons show increased compliance. After 12 months of exercise extensor tendons have increased stress for a given strain while flexor tendons show reduced stress relative to controls.

Ultrasonography and ankle joint testing procedures were utilized to test human muscle-tendon units in-vivo (personal data) and study the relative adaptation rates of muscles and tendons during eight weeks of strength training. Average stress-strain curves were computed for the entire group (Figure 4). The resulting curves showed a distinct linear region for effort levels above 40% of MVC. The slope of the linear region of each stress-strain curve was used to compute average stiffness values. Average stiffness values ranged between 2.87 GPa and 1.87
Stress-strain curves shifted to the left initially and then back to the right from week 6 to week 8. Alterations in the initial non-linear portion rather than alterations in tendon stiffness appear responsible for shifts in the stress-strain curves.

The group’s average maximum tendon strain did not exceed 0.055 mm/mm throughout the study, however, individual strains as high as 0.13 mm/mm were recorded (Table 2). Several in-vitro studies of various mammalian tendons suggest that strains below 0.06 mm/mm do not cause microdamage (Shadwick, 1990; Pollock and Shadwick, 1994). Our results obtained in-vivo were therefore comparable to literature data obtained in-vitro, but also showed that relatively large strains may occur within an individual. In fact, four of the eleven subjects had strains that were consistently greater than 0.06 mm/mm and two subjects had strains that were consistently less than 0.03 mm/mm. Six subjects in the study (group 1) had a similar adaptation trend, having an increase in $\varepsilon_{\text{max}}$ during the first one to two weeks of training followed by a return to pre-training strain values by week eight. The trend common to the remaining 5 subjects (group 2) was characterized by an initial decrease in $\varepsilon_{\text{max}}$ at week one, which was statistically significant in three subjects, followed by an oscillation in $\varepsilon_{\text{max}}$ that stabilized at values statistically similar to baseline in only two cases. Increases in $\varepsilon_{\text{max}}$ recorded in the first two weeks of the study for group 1, and decreases in $\varepsilon_{\text{max}}$ recorded in the first two weeks of the study for group 2, indicated that different adaptation mechanisms were taking place in the two groups.

Group 1 subjects may have experienced no change in tendon properties or some microdamage during the first few weeks, after which tendon remodeling brought $\varepsilon_{\text{max}}$ back to baseline levels. Group 2 subjects may have developed a protective neural mechanism to limit strain initially. Strain in the tendon could have been reduced by increased involvement of the gastrocnemius muscle. Alterations in the relative activation of the soleus and gastrocnemius muscles could cause a redistribution of the forces applied across the Achilles tendons width and length, resulting in lower strains in the portion of the Achilles tendon that was imaged with the ultrasound system. Additional information (e.g. gastrocnemius and soleus activation patterns and/or local deformations across the width of the tendon) is required to identify the exact mechanisms responsible for differences in the subject’s responses.

Several conclusions were drawn from this study. On average, tendons appear to have a preferred strain limit that is maintained as muscle strength increases. The magnitude of this limit or “set-point” varies between individuals. It is not known if these “set points” are genetic or can be modified with training, drugs, etc. There appear to be at least two different tendon strain responses to strength training. Some people have initial increases in local tendon strain while others have decreases. Those having an increased strain response may be at risk for tendon injury during the early phases of an intense strength-training program. Those having a decreased strain response may be less likely to suffer a tendon injury.

Our understanding of the affects of disuse on tendon properties is lacking. Presumably tendon would respond similarly to that of ligament. However, as a functional muscle-tendon unit the slower metabolic turnover of tendon suggests that the muscle would become weaker faster than would the tendon. Some studies suggest that during immobilization collagen fibrils become thinner and there is a reduction in the number of cross-links between collagen fibrils.
**Figure 4:** Average stress-strain curves showing the group’s response to the strength training program. Stress and strain values at effort levels corresponding to each subject’s 0%, 20%, 40%, 60%, 80%, and 100% MVC were combined to obtain the above graph. Each curve displays a linear region for effort levels above 40% of MVC. Stiffness values were computed using the linear portion of each curve shown. The stress-strain curve shifts to the left initially showing a maximum change at week 6 (W6). The stress-strain curve shifts back to the right at week 8 (W8), but it does not completely return to baseline (BL).

The integrity of a muscle-tendon-bone unit depends on the synchronous adaptation of the OTJ, the tendon, the MTJ, and the muscle. Very little is known about adaptation of the OTJ and MTJ. Eccentric muscle actions appear to increase the strength of the MTJ. Exercise increases the strength of the OTJ. The rate at which OTJs and MTJs change their properties is unclear.

**Trauma and Healing**

Tendon trauma may result from laceration, contusion, or tensile overload. Typically tendon is stronger than its muscle and its bony insertion, thus it is more common for the MTJ or OTJ to fail before the tendon during overload. Most mid-substance tears occur following some period of tendon degeneration. Damage to a tendon having a paratenon takes up to a year to heal. Inflammatory cells invade the site of damage within hours following the trauma. Within the first week fibroblasts fill the gap between tendon stumps. Capillaries grow into the gap. Collagen synthesis may begin as early as the third day. After two weeks the tendon stumps appear to be connected again. Collagen fibers near the tendon ends begin to align along the long axis of the tendon by the third to fourth week. Collagen organization and cross-linking continues thereafter. After 6 months there are minimal histologic differences between the repair and normal tissue, however, the repair continues to have inferior material properties for a year or more. The vascular supply is critical for the healing response of a tendon surrounded by a paratenon, however, there is very little vascular supply for a tendon surrounded by a sheath. It is
less clear how these tendons heal, but it appears that tendon cells can themselves invoke a healing response. Repair of these tendons is slower.

**Summary**

Tendon connects muscle to bone and functions to transmit muscular forces across joints to stabilize and/or move those joints. Tendon is a collagenous tissue with similar composition to that of ligament. Tendons in children adapt to increased physical activity by increasing their size and altering their material properties. Tendons in adults rely more on changing their material properties to accommodate increased physical demands. Tendon strength is related to the number and size of collagen fibrils. Collagen fibrils increase in size during development and in response to increased physical demands. Overuse injuries to muscle-tendon-bone units are common in sports and physical labor. Understanding the mechanisms of these injuries requires understanding the relative rates of muscle, tendon, OTJ, and MTJ adaptation. The responses of tendon, OTJ, and MTJ to altered loading conditions are poorly understood at this time.

**References**


Sample Problems

1. Explain the functional difference between ligaments and tendons.

2. Assume that during a 12 week strength training program the maximum voluntary force that a muscle can generate increases by 30%. Assume that during this same time frame the tendon cross-sectional area and material properties do not change. If the person maintains a training schedule that increments the weight lifted according to his/her maximum capability, then after 12 weeks the person is lifting a weight 30% greater than when he/she started. Assume Carina starts out doing one-arm bicep curls with a weight of 110 N (~25 lbs). After 12 weeks she is lifting 140 N. Assume a tendon constitutive equation of \( \sigma = A \cdot (e^{B \cdot \varepsilon} - 1) \), where \( A = 18 \text{ MPa} \) and \( B = 12 \). Calculate the strain induced in the bicep tendon during the first bicep curl at the onset of training and during the first bicep curl after 12 weeks of training. What is the percent increase in tendon strain from week 1 of training to week 12 of training. Assume the tendon cross-sectional area is \( 3.5 \times 10^{-5} \text{ m}^2 \) and a slack length of 8 cm. Assume the moment arm length of the tendon is 4 cm and the distance from the elbow axis of rotation to the hand (where the weight is held) is 35 cm.

3. The middle third of the Achilles tendon has a greater incidence of injury compared to the proximal or distal thirds of the tendon. Explain why you think this portion of the tendon is more susceptible to injury.

4. If a 60 kg mass person steps from a 1 m high box and lands with straight legs on the ground. Do you think all the energy of the fall can be absorbed by the two Achilles tendons without rupturing (assuming equal energy absorption by each tendon) as they are stretched during forced dorsi-flexion (movement upward) of the ankle? Assume a tendon slack length of 8 cm and a tendon cross-sectional area of \( 6.0 \times 10^{-5} \text{ m}^2 \). Show calculations to support your answer and state all assumptions. What do your results suggest to you about strategies that should be used when landing from a jump?

5. Knowing what you do about bone and tendon changes during maturation describe the site that you feel would be susceptible to injury in a the patellar bone-tendon unit of a 10 year old girl that participates in rigorous leg strength training.