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# The Anatomy of the Achilles Tendon

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## Introductory Comments

The Achilles tendon (tendo calcaneus) is the strongest and thickest tendon in the body and serves to attach the triceps surae (soleus and the two heads of gastrocnemius) to the calcaneus (Fig. 2.1). It is a highly characteristic feature of human anatomy and it has even been suggested that the tendon has helped to shape human evolution. The emergence of man is critically linked to his ability to run, and man's unique combination of moderate speed and exceptional endurance has been underestimated.[1] The Achilles tendon has been a key player in the natural selection process, and as in modern apes, an Achilles tendon was absent from *Australopithecus* (a genus ancestral to the genus *Homo*) and probably originated in *Homo* more than 3 million years ago.[1]

Several unique functional demands are placed upon the Achilles tendon that add to its vulnerability to injury:

1. The upright stance of the human dictates that the foot is at a right angle to the leg in the anatomical position and that the Achilles tendon approaches the back of the foot tangentially and generates heavy torque. The human thus has one of the largest angles between the long axis of the tibia and the calcaneus in any mammal.
2. The muscles contributing to the formation of the tendon have different functions and different physiological properties. The soleus plantar flexes the ankle joint and contains a high proportion of type I (slow-twitch) fibers, which facilitates its role as a postural muscle, preventing the body from falling forward when standing.[2] However, the gastrocnemius also flexes the knee joint, and contains a greater number of type IIB fibers (fast twitch). These promote the vigorous propulsive movements that occur in sprinting and jumping.
3. As the Achilles tendon attaches to the calcaneus, it acts on the subtalar as well as the knee and ankle joints. Because the axis of the subtalar joint typically passes upward and medially from the posterolateral corner of the calcaneus,[3] the triceps surae also supinates the foot.[4] Thus stress concentration between the medial and lateral sides of the Achilles tendon enthesis can be nonuniform.
4. The rotation of the limb bud that occurs during development implies that the adult Achilles tendon is twisted upon itself, so that the fibers derived from the gastrocnemius are attached to the lateral part of the calcaneal insertion site and those derived from soleus are attached medially.[5,6] Thus, when the tendon is under load, it is subject to a "wringing" action. Because the gastrocnemius crosses the knee joint and a flexed knee can rotate, the part of the Achilles tendon that is derived from the tendon of gastrocnemius can be variably twisted relative to the tendon of soleus (i.e., one tendon can exert a sawing action on the other).[4] This complex rotatory action is further compounded by the shape of the talus. This shape accounts for the fact that there is a subtle change in the position of the axis of the ankle joint relative to the Achilles tendon during dorsi- and plantar flexion. Slight passive rotation occurs.[7]

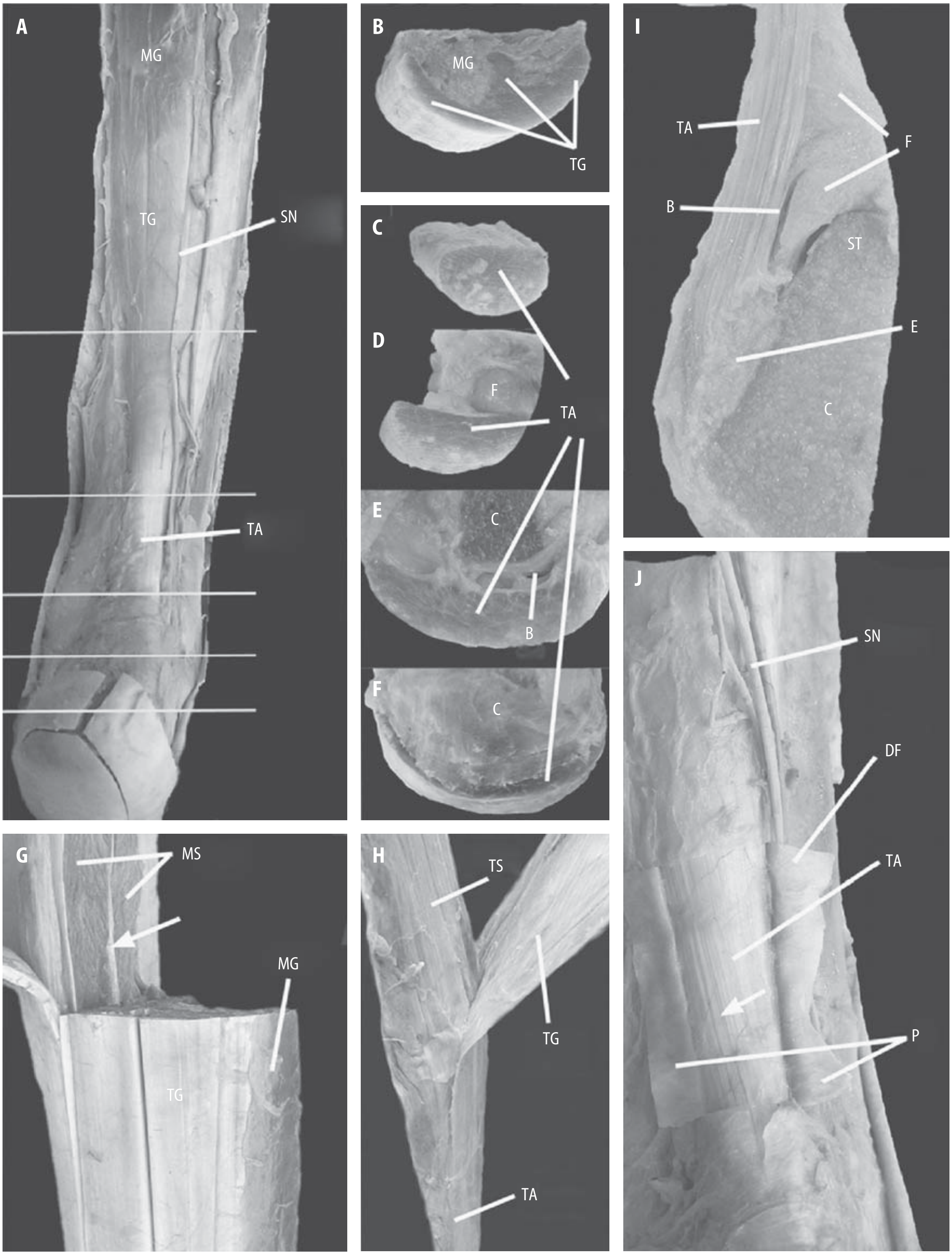
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**FIGURE 2.1.** Gross anatomy of the Achilles tendon. (**A**) A posterior view of the right Achilles tendon indicating with horizontal lines the levels at which the transverse sections featured in **B–F** are taken. Note the close relationship of the Achilles (TA) and gastrocnemius (TG) tendons to the sural nerve (SN). MG, muscle belly of gastrocnemius. (**B–F**) Transverse sections of the Achilles tendon to show the change in shape of the tendon from proximal to distal. Figures **B–F** inclusive correspond (from above down) to the 5 horizontal lines shown in figure **A**. Note that the gastrocnemius tendon is very broad and flat (**B**), that the Achilles tendon in the region vulnerable to ruptures is oval (**C**), and that the tendon flares out again (**D–F**) as it approaches the calcaneus (C). Sections taken at levels **D–E** pass through the pre-Achilles fat pad (F) and the retrocalcaneal bursa (B) into which the fat pad protrudes. At the enthesis itself (**F**), the extremely flattened Achilles tendon has a marked anterior curvature. (**G**) Here, both gastrocnemius and soleus have been partly removed so as to demonstrate the intramuscular tendon of soleus (arrow). MS, muscle belly of soleus. (**H**) The union of the tendons of soleus (TS) and gastrocnemius that form the Achilles tendon at mid-calf level. (**I**) A sagittal section through the calcaneus to show the Achilles tendon enthesis (E) and the prominent pre-Achilles fat pad (F). The tip of the fat pad is quite distinctive from the rest and protrudes into the retrocalcaneal bursa (B) between the Achilles tendon and the superior tuberosity of the calcaneus (ST). (**J**) A posterior view of the Achilles tendon to show its associated paratenon (P). A rectangular window has been cut into the paratenon exposing the underlying Achilles tendon in which a slight obliquity of the tendon fascicles can be noted (arrow).

5. The Achilles tendon transmits forces that are approximately seven times the body weight during running.[8] This represents an enormous increase on the forces that act during standing (which are roughly half the body weight).[8]

## Gross Anatomy

The formation of the Achilles tendon from the gastrocnemius and soleus muscles has been described in detail by Cummins et al.[6] The medial and lateral heads of gastrocnemius arise from the femoral condyles and their contribution to the Achilles tendon commences as a wide aponeurosis at the lower ends of these muscular bellies (Fig. 2.1A). In 2.9–5.5% of people, there is a third head of gastrocnemius, most commonly associated with the medial head.[9] Occasionally plantaris can effectively form a third head (i.e., when it joins gastrocnemius at the point of convergence of its medial and lateral heads).[9] The lateral head of gastrocnemius can sometimes be reduced to a fibrous cord.[9]

The soleus arises entirely below the knee, largely from the tibia and fibula, and its tendinous contribution to the Achilles is thicker but shorter.[6] Occasionally, the tibial "head" of soleus can be absent or an accessory soleus muscle present between the soleus tendon and flexor hallucis longus.[9] An accessory soleus can contribute to the formation of the Achilles tendon, attach independently on the calcaneus, or fuse with the medial collateral ligament of the ankle joint.[9] Typically, a broad sheet of connective tissue begins on the posterior surface of the soleus muscle belly, at a position more proximal than the start of the aponeurosis of gastrocnemius (Fig. 2.1H). Consequently, where the soleus and gastrocnemius muscle bellies are in contact with each other (i.e., are subject to mutual pressure), the two bellies are separated by dense fibrous connective tissue on the surface of the muscles (Fig. 2.1H) and by a thin film of loose connective tissue between them. There is a similar arrangement in the quadriceps femoris, where the anterior surface of vastus intermedius is aponeurotic and overlain by the rectus femoris, but separated from it by areolar connective tissue. Such a tissue probably promotes independent movement.

The sheet of connective tissue on the posterior surface of soleus is attached to the gastrocnemius aponeurosis by fascia at a variable point near the middle of the calf (Fig. 2.1H). The combined aponeurosis continues to run distally over the posterior surface of the soleus, receiving further tendinous contributions from the muscle as it descends. In addition, there is a narrow intramuscular tendon within the soleus (promoting a bipennate arrangement of muscle fibers) that merges with the principal tendon distally (Fig. 2.1G).[10] Typically, full incorporation of the soleus and gastrocnemius tendons into the Achilles tendon is evident 8–10 cm above the calcaneal attachment site, but occasionally the tendon of soleus can remain separate from that of gastrocnemius as far as the insertion itself.[11] Sometimes, the two heads of gastrocnemius remain separate, and the tendons that arise from them attach independently (both from each other and from the tendon of soleus) on the calcaneus.[9] Such anatomical variations can give a false impression of a pathologically thickened Achilles tendon. When viewed from behind, a typical soleus muscle belly is covered proximally by the gastrocnemius, but distally it protrudes on either side of the tendon of the gastrocnemius, making this a convenient site for biopsy or electromyography.[10]

As the tendon fibers derived from gastrocnemius descend, they converge so that the Achilles tendon narrows. However, the fibers also rotate around those of soleus, so that they ultimately come to be attached to the calcaneus laterally, whereas those of soleus (which also rotate) attach more medially.[6] The degree of rotation is variable, so that in addition to contributing to the lateral part of the calcaneal attachment site in all individuals, the gastrocnemius tendon contributes to its posterior part in some people and to its anterior part in others.[6] This rotation becomes more obvious in the terminal 5–6 cm of the tendon (Fig. 2.1J). Where the twisting of the tendon is marked, it is easier to trace the individual contributions of the soleus and gastrocnemius tendons to the Achilles tendon where rotation is slight.[4] The spiraling of the tendon fascicles results in less fiber buckling when the tendon is lax and less deformation when the tendon is under tension. This reduces both fiber distortion and interfiber friction.[12]

A variable proportion of the superficial fibers of the Achilles tendon do not attach to the calcaneus at all, but pass under the heel to become continuous with the fibers of the plantar fascia. Such soft tissue continuity is particularly marked in younger individuals[13] and is in line with a general principle that relatively few tendons attach to bone in isolation; most fuse with adjacent structures or attach at more than a single site, so as to dissipate stress concentration.[14] Myers[15] has greatly expanded on the related concept of myofascial continuities via an endless fascial "web" in the body.

The shape of the Achilles tendon varies considerably from proximal to distal (Fig. 2.1B–F). As with many tendons elsewhere in the body, the Achilles tendon flares out as it nears its bony attachment site. This contributes to the marked anterior-posterior flattening, and slight anterior concavity of the tendon, evident at the level of its enthesis (Fig. 2.1F). These features are also seen at imaging.[11] Typically, the distal part of the tendon does not exceed 7 mm in thickness and anything greater than that is suggestive of pathology.[16] At the insertion site itself, where the tendon is extremely flattened, it is approximately 3 cm wide and 2–3 mm thick.[17]

The Achilles tendon lacks a true synovial tendon sheath but has a false sheath or "paratenon" (Fig. 2.2A) that forms an elastic sleeve permitting the tendon to glide relative to adjacent structures.[18] The paratenon essentially consists of several closely packed, membranous sheets of dense connective tissue that separate the tendon itself from the deep fascia of the leg. It is rich in blood vessels and nerves and, together with the epitenon, which adheres to the surface of the tendon itself, is sometimes referred to as the peritenon. It can stretch 2–3 cm as the tendon moves.[19]

## Relationships

The deep fascia of the leg is immediately superficial to the sheath of the Achilles tendon (Fig. 2.1J), fuses with the tendon sheath near the calcaneus, and serves as an unheralded retinaculum for the tendon. It thus contributes to the slight anterior curvature of the tendon[20,21] and prevents the tendon from bowstringing in a plantar flexed foot. We thus suggest that it plays an important role in minimizing insertional angle changes that occur at the enthesis during foot movements. This in turn reduces wear and tear.

The sural nerve lies in close contact with the Achilles tendon sheath (Fig. 2.1A, J) and commonly crosses its lateral border approximately 10 cm above the tendon enthesis.[22] The vestigial muscle belly of plantaris arises adjacent to the lateral head of gastrocnemius and its long tendon runs along the medial side of the Achilles tendon to end in a variable fashion. Usually, it attaches to the calcaneus on the medial side of the Achilles tendon (47% of cases according to Cummins

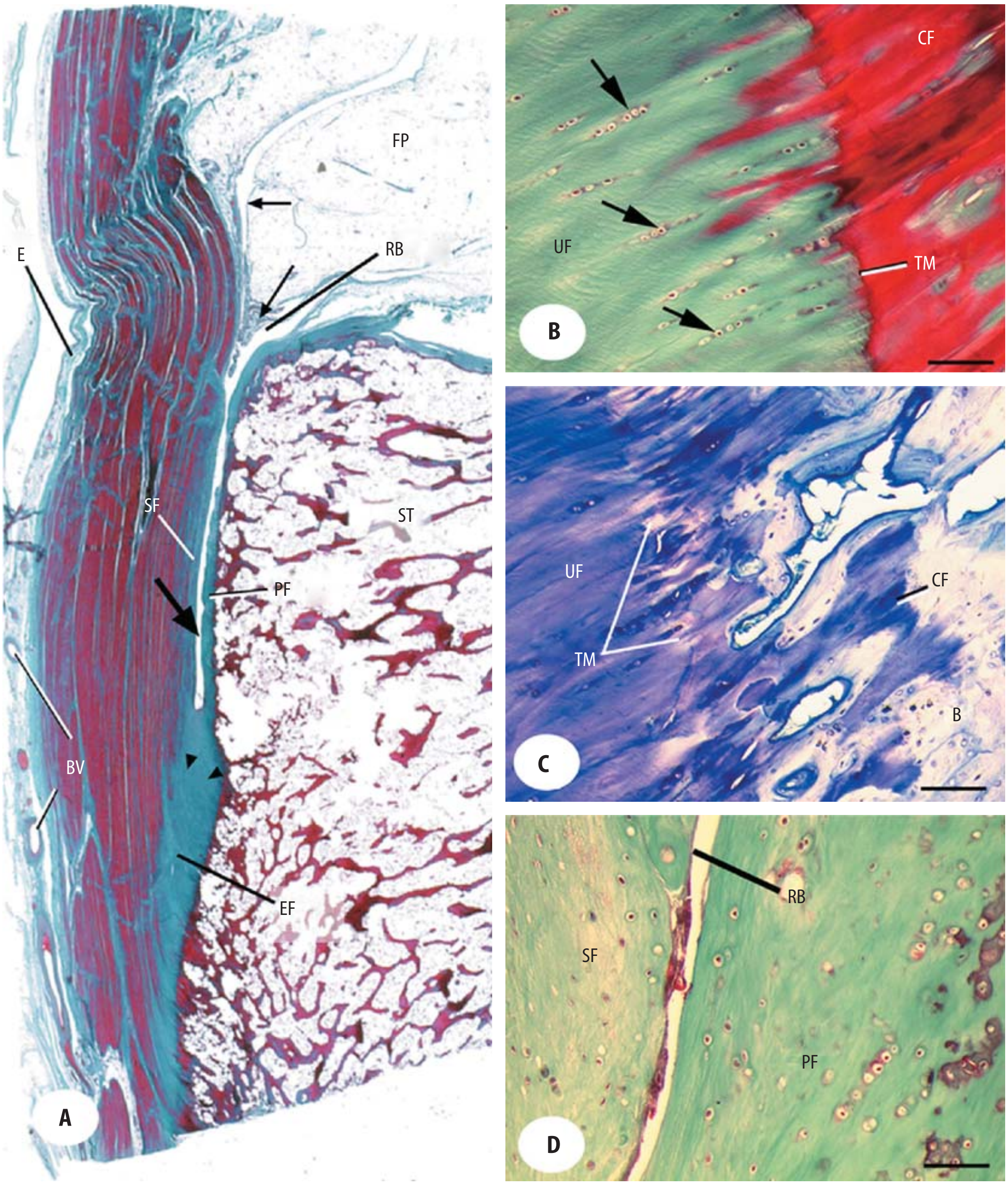


**FIGURE 2.2.** Microscopic anatomy of the Achilles tendon enthesis organ. (**A**) Low-power view of a sagittal section of the enthesis organ. The enthesis itself is characterized by a prominent enthesis fibrocartilage (EF), which is thickest in the deepest part of the attachment site (arrowheads). Immediately proximal to the osteotendinous junction, the deep surface of the tendon is related to the superior tuberosity (ST) of the calcaneus, but is separated from it by the retrocalcaneal bursa (RB). Protruding into the bursa is the pre-Achilles fat pad (FP), which is covered with a synovial membrane (arrows). The most distal part of the bursa is lined directly by sesamoid (SF) and periosteal fibrocartilages (PF). The former lies in the deep surface of the Achilles tendon, immediately adjacent to the enthesis, and the latter covers the superior tuberosity in a dorsiflexed foot. These fibrocartilages are shown in further detail in figure **D**. Note the epitenon (E) on the posterior surface of the tendon with several blood vessels (BV) visible within it and the paucity of a subchondral bone plate at the enthesis. (**B**) A high-power view of the enthesis fibrocartilage in the region either side of the tidemark (TM). Note the longitudinal rows of fibrocartilage cells (arrows) in the zone of uncalcified fibrocartilage (UF) and the zone of calcified fibrocartilage (CF) that lies immediately deep to the tidemark. (**C**) A high-power view of the enthesis fibrocartilage in the region either side of the tidemark, showing the complex interdigitations of the zone of calcified fibrocartilage with the underlying bone (B). (**D**) A high-power view of the fibrocartilaginous lining of the distal part of the retrocalcaneal bursa showing sesamoid fibrocartilage in the deep surface of the tendon and a periosteal fibrocartilage covering the bone. Note that neither fibrocartilage is covered with synovium. Scale bars: a = 2 mm; b–d = 100 μm. Figure **C** is of a specimen stained with toluidine blue; all the other sections are stained with Masson's trichrome.

et al.),[6] but in 36.5% of the 200 specimens with a plantaris tendon examined by these authors, the tendon inserts slightly anterior to the medial aspect of the Achilles. Intriguingly, in such individuals, the enthesis of the plantaris tendon serves to support the anteromedial part of the retrocalcaneal bursa. In the third variation of the plantaris insertion reported in 12.5% of cases by Cummins et al.,[6] the tendon fans out distally to invest the posterior and medial aspects of the Achilles tendon. Finally, in 4% of individuals, the plantaris tendon fuses with the Achilles tendon proximal to the calcaneal attachment site of the latter.[6]

Near its calcaneal insertion site, the Achilles tendon is flanked by two bursae.[23] There is a superficial bursa between the skin and the tendon that promotes skin movement and a deep (retrocalcaneal) bursa between the tendon and the superior calcaneal tuberosity that promotes tendon movement (Fig. 2.1I). Protruding into the retrocalcaneal bursa is a wedge-shaped, fatty, synovial-covered fold that represents the distal tip of Kager's fat pad, a mass of adipose tissue between the flexor hallucis longus muscle and the Achilles tendon (Fig. 2.1I). Intriguingly, the relative size of this fat pad differs between the foot of the newborn child and the adult,[24] though the significance of this is unclear. Latex molds of the bursa show that it is disc-shaped and has two extensions ("legs") directed proximally (see Fig. 4 in ref. 24). It is molded over the posterosuperior surface of the calcaneus, like a cap with an anterior concavity.[24] A healthy bursa has a smooth outline and 1–1.5 ml of contrast medium can be injected into it.[24] However, leakage of contrast material over time into the superficial bursa suggests that the bursae communicate with each other.[24] At magnetic resonance imaging (MRI), the retrocalcaneal bursa normally contains fluid, which gives a high-signal-intensity.[25] The bursa is filled with a clear, viscous fluid,[26] and in healthy individuals, the tip of Kager's fat pad moves in and out of the bursa in plantar and dorsiflexion respectively (M. Benjamin, P. Theobald, L. Nokes, and N. Pugh.[26A] This may influence the insertional angle of the Achilles tendon in different foot positions.[27] Although the retrocalcaneal bursa is enlarged in symptomatic patients, paradoxically, less contrast material can be injected into it.[23]

## Blood Supply

The Achilles tendon receives part of its blood supply from vessels running in the paratenon that are largely derived from the posterior tibial artery.[12,28,29] The vessels enter the tendon via a structure that is comparable to a mesotenon.[4] The mid-region of the tendon is relatively poorly vascularized and this may contribute to the vulnerability of the tendon to rupture, 2–6 cm above the calcaneus. The proximal part of the tendon receives an additional supply from the muscle bellies that continues into the tendon via the endotenon, though this contribution is not believed to be significant.[12,30–32] The distal region of the tendon also receives vessels from an arterial periosteal plexus on the posterior aspect of the calcaneus.[33] This supply starts at the margin of the insertion and extends up the endotenon for approximately 2 cm proximally.[12,30,32,34] A healthy fibrocartilaginous enthesis is avascular so that vessels do not normally pass directly from bone to tendon at the osteotendinous junction.[35,36]

## Innervation

There is no single comprehensive study of the innervation of the Achilles tendon from its myotendinous junction to its enthesis. Nevertheless, the sensory nerve supply of the tendon and its sheath is of nociceptive and proprioceptive significance. The integrity of the nerve supply to the tendon may also play a key role in promoting its repair, as peripheral denervation in rats reduces the load to failure of healing, transected Achilles tendons by 50% within two weeks.[37]

The Achilles tendon is supplied by sensory nerves from the contributing muscles and via twigs from neighboring cutaneous nerves, notably the sural nerve.[38] The paratenon is more richly innervated than the tendon itself, and it contains Pacinian corpuscles,[39] presumably important in proprioception. Both Golgi tendon organs and muscle spindles have been demonstrated in association with the Achilles tendon of the cat.[40] The former lie in the muscle itself, close to the myotendinous junction, but the latter are located more distally in the tendon.

There is an opioid system in the rat Achilles tendon that may contribute to a peripheral inhibition of pain.[41] Some of the sensory nerves (probably C fibers) immunolabel for the delta opioid receptor (DOR). Labeling is largely restricted to the endotenon and epitenon, where it typically occurs in association with blood vessels, and to the paratenon, where a vascular association is less obvious. The DOR labeling co-localizes with that for enkephalins, suggesting that the latter act as receptors. Enkephalins acting on DOR inhibit the nociceptive action and the pro-inflammatory response of sensory neuropeptides.[41] There is normally a fine balance between the expression of opioids in muscle-tendon units and the expression of sensory neuropeptides that could change with tendon pathology.[41]

It is difficult to reconcile what we know of the innervation of the Achilles tendon with the pain associated with tendinopathy.[42] Tendon pain may be linked to vascular changes. A common feature of tendinopathy is the proliferation of blood vessels either in the tendon itself or its sheath,[43–45] and injured tendons may show an ischaemic response.[42]

## Structure of the Tendon Midsubstance

As with all tendons, the Achilles tendon is dominated by type I collagen, which accounts for its considerable tensile strength,[46] in the order of 50–100 N/mm.[46,47] However, this may well be an underestimate because of the general difficulty of clamping tendons, which by their very nature consist of large numbers of partly independent fibers.[48] Type I collagen is organized into heterotypic fibrils in association with types III and V collagens[46] and these minor collagens play a role in regulating fibril diameter.[49] Western blot analyses of Achilles tendons from elderly individuals show that the β and γ forms of type I collagen are conspicuous—probably reflecting the increased formation of crosslinks with age.[46]

Type I collagen fibrils are grouped successively into fibers, fiber bundles, and fascicles, so that a tendon is analogous to a multistranded cable.[49] Individual fibrils do not run the length of a tendon and thus stress must be transferred between them.[49] This is a function of the amorphous matrix in which the fibrils are embedded and it has been suggested that type VI collagen (a non-fibrillar collagen) and decorin (a leucine-rich repeat proteoglycan) are important. Both these molecules, along with fibromodulin, biglycan, lumican, and versican, are present in the Achilles tendon[46] and have a relatively high turnover.[50]

In general, fibrils within tendons run a wavy course (i.e., are "crimped") with an axial periodicity of approximately 100 μm.[49] Such "pre-buckling" is thought to contribute to their flexibility, along with the partial independence of fibrils and fascicles that derives from the low compressive stiffness of the extracellular matrix.[49] Of key importance here is the endotenon that separates adjacent fascicles and is continuous with the epitenon on the surface of the tendon. The endotenon forms vascularized and innervated layers of loose connective tissue that promote independent movement between fascicles.

The cells in the midsubstance of the Achilles tendon are fibroblasts that are arranged in longitudinal rows and have a highly complex shape. In the midsubstance of tendons, there are a number of broad, flat cell processes that extend laterally from the cell bodies and partition the collagen fibers into bundles.[51] There are also more elongated and thinner cell processes that extend longitudinally within a tendon. In both cases, where processes of adjacent tendon cells meet, the cells communicate by means of gap junctions.[51] Communication is established between cells both within and between rows. Consequently, there is a three-dimensional network of interlinking cell processes in the Achilles tendon that is as impressive as the better-known network of osteocytic cell processes permeating the extracellular matrix (ECM) of bone. Gap junctional communication (involving connexins 32 and 43) could form the basis for a co-coordinated response of tendon cells to mechanical load.[51] Connexin 32 junctions occur predominantly between cells within a row (and thus along the lines of principal tensile loading), while gap junctions characterized by connexin 43 link cells between rows as well.[51] Waggett et al.[52] have thus suggested that the two different gap junctions have distinctive roles in ECM synthesis when tendon cells are subject to mechanical loading. They have shown that connexin 43 gap junctional communication inhibits collagen synthesis, whereas that involving connexin 32 is stimulatory.

## The Enthesis and the Enthesis Organ

The Achilles tendon attaches to a rectangular area in the middle third of the posterior surface of the calcaneus—with a greater surface area of the tendon attached medially than laterally.[53] The average height of the insertion (i.e., the distance between the superior and inferior limits of the tendon attachment) is 19.8 mm, and the average width is 23.8 mm superiorly and 31.2 mm inferiorly.[54] Thus, the tendon flares out considerably at its enthesis, dissipating the region of stress concentration. Although it is unlikely that the increased surface area of the tendon at this site is associated with a greater number of collagen fibers, the nature of the packing tissue has not been firmly established. In other tendons, fat accumulation near the osteotendinous junction is an important contributory factor.[55]

As with other tendons in the body, the direction in which the Achilles tendon approaches its insertion site is kept relatively constant in different positions of the foot and leg. When the foot is dorsiflexed, the superior tuberosity of the calcaneus (Fig. 2.2A) acts as a guiding pulley, but, during plantar flexion, simple inspection suggests that the deep crural fascia must be primarily responsible for controlling the insertional angle.[4] In pronation and supination movements of the calcaneus, comparable guiding control mechanisms for maintaining constancy of bone–tendon position are less obvious. Although continuity of the crural fascia with the periosteum on the medial and lateral aspects of the calcaneus is likely to be a factor, the fibrocartilaginous nature of the enthesis is probably also important. The "enthesis fibrocartilage" (Fig. 2.2A–C) balances the differing elastic moduli of the tendon and bone and reduces stress concentration at the insertion site.[56] Effectively, it stiffens the tendon at the hard–soft tissue interface and plays a role analogous to that of a grommet where a lead joins an electrical plug.[57] It ensures that any bending of the collagen fibers of the tendon is not all concentrated at the hard–soft tissue interface, but is gradually dissipated into the tendon itself, reducing the risk of wear and tear.

However, the task of reducing stress concentration at the Achilles enthesis does not all relate to mechanisms at the tendon–bone junction. In a dorsiflexed foot, the adjacent anterior surface of the tendon presses against the superior tuberosity of the calcaneus (Fig. 2.2A) and this reduces stress concentration at the enthesis itself. What never seems to be acknowledged in accounts of the surgical treatment of Haglund's deformity is the increase in stress concentration at the enthesis that inevitably follows any removal of bone from the superior tuberosity. The extent to which the stress concentration is increased depends on the prominence of the tuberosity. Such considerations may be particularly important when contemplating surgery on elite athletes in whom the Achilles tendon may periodically be heavily loaded.

The intermittent contact between the tendon and the superior tuberosity is associated with structural specializations at both surfaces because of the mutual compression of the tissues. Thus, the calcaneus is covered by a thick fibrocartilaginous periosteum and the deep surface of the tendon is lined by a "sesamoid fibrocartilage" (Fig. 2.2A, C, D).[58] The latter term was coined because this fibrocartilage lies within the substance of the tendon itself (i.e., it is comparable to a sesamoid bone). The free movement of the opposing surfaces is promoted by the retrocalcaneal bursa into which a tongue-like, downward extension of Kager's fat pad extends in a plantar flexed foot. The enthesis itself, the periosteal and sesamoid fibrocartilages, bursa and fat pad collectively constitute an "enthesis organ" (Fig. 2.2A).[14,36] This is a collection of tissues that all contribute to the common function of reducing stress concentration and the risk of failure at the osteotendinous junction.

At the distal tip of the retrocalcaneal bursa there is no synovial lining, for the walls of the bursa are formed directly by the sesamoid and periosteal fibrocartilages.[36,58] While it may surprise some readers to learn that part of the bursa is not lined by synovium, it is logical when one remembers that the bursa has much in common with a synovial joint.[36,59] The sesamoid and periosteal fibrocartilages serve effectively as articular cartilages and are thus subject to compression (in a dorsiflexed foot). Consequently, like classical articular cartilage, they cannot be covered with a vascular synovial membrane; this is therefore restricted to the more proximal parts of the bursa

(Fig. 2.2A). Degenerative changes paralleling those seen in osteoarthritic articular cartilage (in particular fissuring and chondrocyte clustering) are common in elderly people.[58] Detachment of tissue fragments into the bursa is also frequently seen. The inflammatory changes characteristic of retrocalcaneal bursitis may be a secondary consequence of what is primarily an issue of fibrocartilage degeneration.[58]

Four zones of tissue have been described at the enthesis itself: dense fibrous connective tissue, uncalcified fibrocartilage, calcified fibrocartilage, and bone.[36,58] Between the zones of calcified and uncalcified fibrocartilage is a tidemark, which marks the outer limit of calcification (Fig. 2.2B). In a healthy tendon, the tidemark is remarkably straight, for it serves as the mechanical boundary between hard and soft tissues. However, it is *not* the tissue boundary (i.e., the *exact* location of the tendon–bone junction). This boundary is the highly irregular interface between the zone of calcified enthesis fibrocartilage and the subchondral bone (Fig. 2.2C). The complex interdigitation of the two tissues in three dimensions is pivotal in securing the tendon to the bone, for little anchorage is provided by the direct continuation of collagen fibers from tendon to bone.[60] Thus, the mechanical and tissue boundaries of the tendon are spatially distinct. Conflicting functional demands means that they cannot coincide exactly. The mechanical boundary must be straight in a healthy enthesis so that the tendon is not damaged by jagged edges of bone as the tendon moves. However, the tissue boundary must be highly irregular to promote firm anchorage of tendon to bone. The mechanical paradox is solved in the adult tendon at least, by the presence of a thin coating of calcified fibrocartilage on the bone surface (Fig. 2.2C). This can be visualized as analogous to a layer of cement applied over rough cast brickwork. The presence of this layer accounts for the smooth marking left by the Achilles tendon on a dried bone. The soft tissues fall away from the bone at the level of the tidemark after maceration.[61]

As with other fibrocartilaginous entheses, Sharpey's fibers are not a prominent feature of the Achilles tendon insertion. This reflects both the development of the enthesis and the paucity of compact bone in the subchondral plate (Fig. 2.1A). In the rat Achilles tendon, the enthesis fibrocartilage develops by metaplasia of fibroblasts in the dense fibrous connective tissue of the tendon near its bony interface.[62] Thus the fibrocartilage cells are arranged in longitudinal rows (Fig. 2.2B) simply because the fibroblasts from which they develop also have this arrangement. The fibrocartilage probably develops in response to mechanical stimuli shortly after birth. The tissue acts as a "mini–growth plate" for the bone.[62] As tendon fibroblasts turn into fibrocartilage cells on one side of the enthesis (i.e., the border between the zones of dense fibrous connective tissue and uncalcified fibrocartilage), bone replaces fibrocartilage at the other, by a process analogous to endochondral ossification in the growth plate of a long bone.[62]

Enthesis fibrocartilage is not equally obvious over the entire osteotendinous junction. It is more conspicuous superiorly (i.e., in the deep part of the tendon; Fig. 2.2A) than inferiorly—where the enthesis is more fibrous. Curiously, bony spurs typically develop in the postero-inferior part. The wedge shape of the enthesis fibrocartilage may enable it to act as a soft-tissue pulley by virtue of its viscoelasticity.[60] This complements the action of the more obvious bony pulley that is formed by the superior tuberosity. However, such a soft-tissue pulley can compensate only slightly for the marked decrease in the moment arm of the Achilles tendon that inevitably occurs when the foot is dorsiflexed. Quigley and Chaffin[63] have calculated that the distance from the Achilles tendon to the axis of rotation of the ankle joint (i.e., the moment arm) decreases by 40% at 35° of dorsiflexion. This means that greater muscular effort is needed to rise onto the toes, and thus greater load is transferred from muscle to tendon and from tendon to bone.

Finally, little attention has been paid to the bone beneath the Achilles tendon enthesis. As stated above, there is a striking absence of any substantial layer of cortical bone (Fig. 2.2A). However, there is a highly ordered array of trabeculae orientated along the long axis of the Achilles tendon, linking the tendon enthesis to that of the plantar fascia.[60] The trabecular pattern suggests that there is a line-of-force transmission within the bone, linking these two soft tissues. In younger individuals, in particular, there can also be soft tissue continuity between the Achilles tendon and the plantar fascia.[13] The situation is thus analogous to that in the patellar tendon where again there are parallel trabeculae in the anterior region of the patella, and tendon fibers that pass over the anterior surface to establish direct continuity between the patellar and quadriceps tendons (M. Benjamin).[64] In both cases, this presents a classic example of the "myofascial" continuity concept[15] that emphasizes the endless web formed by connective tissue throughout the body.

***Acknowledgments.*** The work of Dr. D. Suzuki was supported by grants from the ITOH scholarship foundation and Sapporo Medical University, Japan.

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