Understanding the Anatomy and Biomechanics of Ankle Tendons

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KEYWORDS

• Tendon biomechanics • Tendon anatomy • Ankle tendons

KEY POINTS

- The composition and structure of tendons is complex. Molecular and biomechanical features unique to tendons allow for both strength and flexibility.
- Tendons have an ordered and hierarchical structure and comprise densely packed parallel yet staggered collagen fibrils, which results in high tensile strength.
- The tendon insertion may be either fibrous or fibrocartilaginous. The 4 zones of the latter include tendon, uncalcified fibrocartilage, calcified fibrocartilage, and bone.
- The particular anatomy of the Achilles, posterior tibial, anterior tibial, and peroneal tendons facilitates the unique function of each tendon.

INTRODUCTION

The tendons of the foot and ankle are complex and unique structures. In healthy individuals, they transmit large loads across several joints thousands of times each day. They also enable such diverse functions as standing, squatting, and running. The insertion of a tendon, which withstands several times body weight, rarely fails and might even be considered a controlled malignancy in which one tissue rigidly invades another.

This article reviews the intricate anatomy and biomechanics of the major tendon groups that cross the ankle and hindfoot, including the Achilles, anterior tibial, posterior tibial, and peroneal tendons.

TENDON COMPOSITION AND STRUCTURE

Tendons are a dense connective tissue designed to connect muscle to bone. In so doing, they transmit muscular forces across a joint and thereby produce motion.

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The dry weight of tendons comprises primarily type I collagen.[1] Type I collagen has superior tensile strength and, gram for gram, is reported to be stronger than steel.[2] Other proteins present in tendon include type III collagen, elastin, and fibronectin. As its name implies, elastin imparts elasticity to the tendon so that it can recoil after stretching. Meanwhile, fibronectin is a cell attachment molecule that is found on the periphery of tendons and likely facilitates gliding and lubrication.[3] Proteoglycans such as decorin and aggrecan are also present in tendon and play important roles in attracting water, lubrication, and the interconnection of tendon fibrils.[4]

At the supramolecular level, tendons have an orderly and hierarchal structure, which imparts substantial tensile strength and allows them to withstand the large forces generated by skeletal muscle contraction (**Fig. 1**). Densely packed parallel yet staggered collagen fibrils together form primary and secondary collagen fibers and bundles.[5] The tendon bundles are oriented parallel to the long axis of the tendon, which increases tensile strength. In the relaxed state, collagen bundles also have a wavelike or undulating pattern called *crimp* (**Fig. 2**). As Herchenhan and colleagues[6] note, unbuckling of the crimped collagen bundles during tenocyte contraction acts as shock absorber on initial loading and facilitates elastic recoil. Franchi and colleagues[7] also showed the presence of smaller fibrillar crimps that may act as a shock absorber during eccentric contraction.

As noted, the insertion of a tendon, or enthesis, is an impressive anatomic structure with remarkable pull-out strength. An enthesis may be either fibrous or fibrocartilaginous. Fibrous entheses are typically broad and have metaphyseal or diaphyseal insertions. These include the posterior tibial, peroneal, and tibialis anterior tendons. Meanwhile, fibrocartilaginous entheses typically occur at an epiphysis or apophysis, such as the Achilles at the calcaneal tuberosity. These entheses are characterized by a transition of tissue composition through 4 zones: tendon, uncalcified fibrocartilage, calcified fibrocartilage, and bone (**Fig. 3**). These zones allow for a more gradual transition from flexible to stiff tissue quality and also serve to dissipate stress as the tendon bends around its bony attachment point.

Fibrocartilaginous entheses may be more susceptible to overuse injury.[8] Although the midsubstance of a tendon is subject primarily to tensile loads, the tendon insertion is exposed to both compressive and tensile forces. Considering the Achilles, the anterior portion of the tendon insertion is exposed to high compressive loads as it courses over the calcaneal tuberosity. As described by Docking and colleagues,[9] tendons

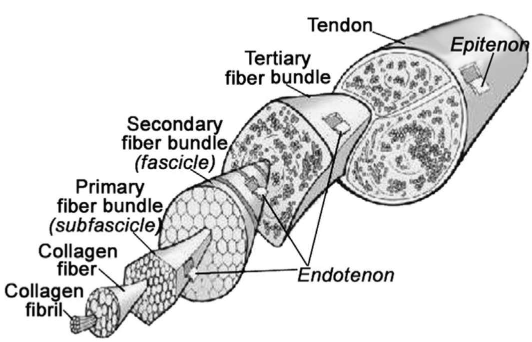

Fig. 1. The hierarchical structure of tendons. (*From* Sharma P, Maffulli N. Tendon injury and tendinopathy: healing and repair. J Bone Joint Surg Am 2005;87(1):187–202; with permission.)

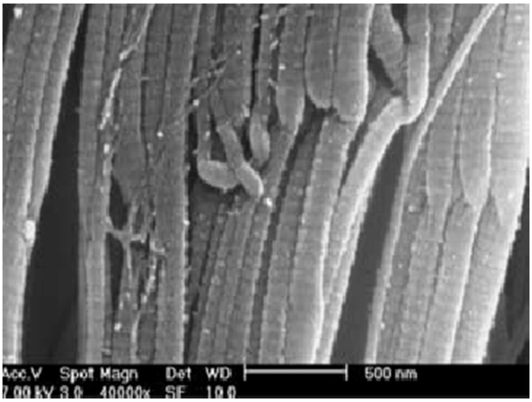

Fig. 2. Electron micrograph shows Achilles tendon crimp. (*From* Franchi M, Fini M, Quaranta M, et al. Crimp morphology in relaxed and stretched rat Achilles tendon. J Anat 2007;210(1):1–7; with permission.)

show adaptive responses when subjected to compression, including the development of fibrocartilage. With excessive or sudden increases in load, a patient may develop tendinopathy, characterized by cell proliferation and the production of disorganized collagen and extracellular matrix.[10]

Like other soft tissues in the body, tendons have both viscous and elastic properties and are therefore considered viscoelastic. With this, they exhibit time-dependent strain. The stress strain curve of tendons has been extensively investigated and has 3 major regions (Fig. 4). With initial load, the collagen fibrils uncrimp. This uncramping is referred to as the *toe* region of the stress strain curve and is representative of the stress created by normal, physiologic muscle contraction. Subsequently, the collagen fibers themselves are stretched and slide past one another. Without the buffer of the crimp, the collagen fibers are stiffer, and the stress strain curve becomes linear. In this linear region, the tendon exhibits elastic deformation. With increasing load, structural damage and fibril failure occur, which is the yield and failure region, and is characterized by plastic deformation with decreased stiffness and strain. The transition point between the linear and failure regions is referred to as the *elastic limit* or the *yield point*.

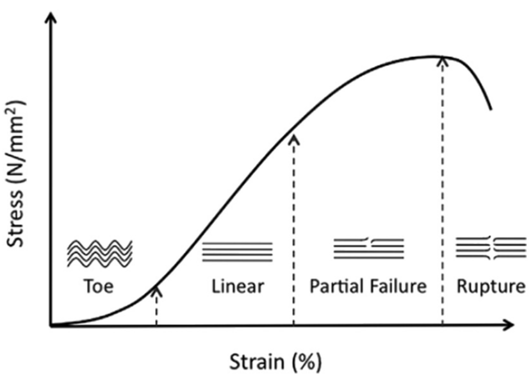

Fig. 3. Histology of a fibrocartilaginous enthesis. (*From* Apostolakos J, Durant TJ, Dwyer CR, et al. The enthesis: a review of the tendon-to-bone insertion. Muscles Ligaments Tendons J 2014;4(3):333–42; with permission.)

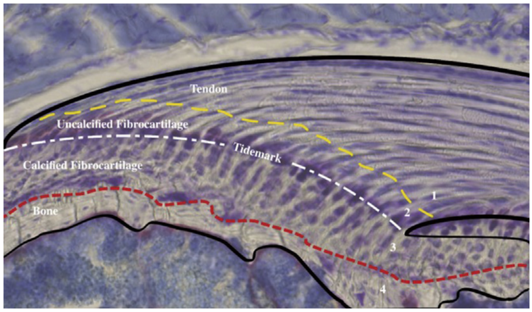

Fig. 4. Stress strain curve for normal tendon. (*From* Sharma P, Maffulli N. Tendon injury and tendinopathy: healing and repair. J Bone Joint Surg Am 2005;87(1):187–202; with permission.)

ACHILLES TENDON

In Greek mythology, Achilles was the son of Thetis, a sea nymph and the goddess of water. After his birth, Thetis dipped Achilles in the river Styx to bestow immortality. When doing so, she held him by the heel and as such this region of his body did not come in contact with the protective waters of the Styx. Later in life, Achilles would become a hero of the Trojan wars. Ultimately, however, he was killed when shot in the heel by a poison arrow. This is the origin of the phrase “Achilles heel” and the name of one of the strongest and largest tendons of the body.

The Achilles tendon connects the terminal fibers of the triceps surae, which comprises gastrocnemius and soleus muscles, to the posterior tuberosity of the calcaneus. When present, the plantaris muscle and tendon also coalesce with the Achilles. As they descend, the fibers of the Achilles internally rotate, which decreases buckling when the tendon is slack and deformation when it is loaded. It may also reduce fiber distortion and interfiber friction.[11]

Simply stating that the triceps surae and Achilles tendon are the main plantarflexors of the ankle joint is an oversimplification of the complex biomechanics of this motor unit. The soleus and gastrocnemius muscles have unique characteristics and different roles. The gastrocnemius crosses both the knee and ankle and has a higher proportion of fast twitch fibers. This configuration allows for the rapid propulsion necessary for running and jumping. On the other hand, the soleus does not cross the knee joint and has a higher proportion of slow twitch fibers when compared with the gastrocnemius. It thus serves as a postural muscle, firing when a person is standing still.

The triceps surae and Achilles can also have an eversion or inversion or moment arm, as seen with a valgus or varus hindfoot, respectively. This may result in an undesired deforming force, and is an important consideration when contemplating realignment procedures. On the other hand, such coronal moment arms may be protective. In the neutral hindfoot, the Achilles can have an inversion moment arm in eversion and an eversion one in inversion.[12] In other words, the Achilles may play a role in resisting the extremes of hindfoot motion.

ANTERIOR TIBIAL TENDON

The tibialis anterior muscle serves as the antagonist to the triceps surae and is the primary dorsiflexor of the ankle joint. Concentric contraction during the swing phase of gait allows the foot to clear the ground while eccentric contraction during early stance phase allows for controlled return of the foot to the ground.

The tibialis anterior muscle originates from the proximal two-thirds of the lateral tibia. Distally, the tibialis anterior tendon travels deep to the superior and inferior extensor retinaculum. These structures prevent bowstringing and extensor lag. The tendon inserts primarily on the first metatarsal base and medial cuneiform, medial to the sagittal midline. As such, coronal plane balance necessitates a motor unit with a corresponding dorsiflexion moment that is lateral to the midline, and this is provided by the extensor digitorum longs and peroneus tertius.

This anatomic interplay is important when it comes to treating a recurrent clubfoot or equinovarus deformity. Specifically, the vector of the unbalanced anterior tibial tendon can cause supination of the foot. In these situations the tendon must often be lateralized. Hui and colleagues[13] found that when transferring the whole tendon, it should be anchored in line with the third metatarsal. Meanwhile, when performing a split anterior tibial tendon transfer, inserting the lateral limb along the fourth metatarsal axis was most effective.

POSTERIOR TIBIAL TENDON

Although the Achilles and anterior tibial tendons allow for forward propulsion through ankle dorsiflexion and plantarflexion in the sagittal plane, coronal plane motion and stability is also necessary for ambulation on uneven terrain. This is made possible by the joints of the hindfoot, which, in turn, are stabilized by the posterior tibial and peroneal tendons.

The tibialis posterior muscle originates from the posterior tibia, fibula, and interosseus membrane. It lies in the deep posterior compartment of the leg, adjacent to the interosseus membrane and deep to the posterior tibial nerve and vessels. Distally, the posterior tibial tendon runs behind the medial malleolus and is stabilized here by the flexor retinaculum. The tendon has a broad insertion in the midfoot. The primary insertion is the navicular tuberosity. However, secondary slips also attach to the cuneiforms, cuboid, sustentaculum tali, and second through fourth metatarsal bases.

The primary function of the posterior tibial tendon is to invert the hindfoot just after heel strike during the stance phase of the gait cycle. Because the tendon travels posterior to the medial malleolus, it also plantarflexes the ankle. With inversion, the hindfoot locks and becomes a rigid lever for push-off; this happens as a result of the dynamic alignment of the axes of the subtalar and transverse tarsal joints. Specifically, these axes are parallel at heel strike. With this, the hindfoot is more flexible and serves as a shock absorber. As the foot progresses through stance, hindfoot inversion causes the axes to diverge, and the hindfoot becomes more rigid. Rather than absorbing the force of heel strike, the hindfoot now converts to a lever, making push-off and forward propulsion more efficient.

The posterior tibial tendon is also the dynamic stabilizer of the medial longitudinal arch. In this capacity, it supports and protects the calcaneonavicular or Spring ligament, which is the static stabilizer of the arch. The arches of the feet are important for several reasons, including structural support, shock absorption, and transmission of tendons and neurovascular structures.

With deficiency, dysfunction, or tearing of the posterior tibial tendon, increased load is placed on the medical longitudinal arch and talonavicular joint. Further, the eversion moment of the peroneal tendons is unopposed, which may ultimately lead to attenuation and failure of the Spring ligament, resulting in an adult acquired flatfoot deformity. Using a multisegment biomechanical model, Arangio and Salathe[14] have demonstrated that posterior tibial tendon dysfunction leads to increased load on the talonavicular joint, and that a 10-mm medial displacement calcaneal osteotomy can reduce this force back to normal values.[14]

PERONEAL TENDONS

The peroneal tendons run in a shared synovial sheath along the posterolateral ankle and hindfoot. Just distal to the fibula, they travel in separate fibro-osseous tunnels and are separated by the peroneal tubercle of the calcaneus. The primary function of the peroneals is to evert and stabilize the joints of the hindfoot. Otis and colleagues[15] found that the peroneus brevis is a more effective evertor than the peroneus longus. In addition, the peroneus longus is a strong plantarflexor of the first metatarsal.

Peroneus Brevis

The peroneus brevis muscle originates from the distal two-thirds of the lateral fibula. As it courses distally, the brevis tendon emerges as a broad and ribbon-shaped structure. At the level of the ankle, it sits immediately posterior to the fibula in the peroneal groove of this bone. Here it is stabilized by the superior peroneal retinaculum and is vulnerable to longitudinal tears that may result from instability, tendinosis, or both. Distally, the brevis tendon passes through a fibro-osseous tunnel in the hindfoot and then inserts on the base of the fifth metatarsal.

As noted, the primary role of the peroneus brevis is to evert the hindfoot. The peroneus brevis muscle contracts during mid to late stance. This stabilizes the hindfoot and also returns it to an everted and supple position in preparation for heel strike. Otis and colleagues[15] found in a cadaver model that the brevis is a more effective evertor than the longus.

The peroneals are also important dynamic stabilizers of the ankle joint. More specifically, they are integral to opposing inversion moments and protecting the tibiotalar joint from inversion injury. In this capacity, they serve to augment and protect the underlying lateral ligaments, which, along with the capsule, are the static stabilizers of the joint. To this end, Ashton-Miller and colleagues[16] found that evertor muscle strength compares favorably to taping, orthoses, and shoe height when it comes to protecting the inverted, weight-bearing ankle against further inversion.

Although mechanical lateral ligament instability may be caused by ligamentous laxity, functional ankle instability may in part be caused by peroneal tendon dysfunction. Méndez-Rebolledo and colleagues[17] recently found that the peroneals had longer reaction times and reduced postural control in basketball players with functional ankle instability. Similar findings were also reported by Donahue and colleagues.[18]

Peroneus Longus

The peroneus longus tendon has a rather circuitous route. It descends vertically with the peroneus brevis posterior to the fibula and then courses anteriorly along the lateral hindfoot. In the region of the calcaneocuboid joint, it again changes direction, coursing medially and obliquely toward the base of the first metatarsal. Here it enters a groove in the inferior aspect of the cuboid and is stabilized by the long plantar ligament. In approximately 25% of individuals an os peroneum bone is present, serving as a fulcrum and improving the tendon's efficiency.[19] After traveling across the foot, it inserts on the lateral aspect of the first metatarsal base and medial cuneiform.

Although the peroneus brevis everts the hindfoot, it also plantarflexes the first metatarsal. This process becomes especially relevant when treating a cavus foot or a forefoot-driven hindfoot varus. With these deformities, a peroneus longus to peroneus brevis transfer is an important consideration when formulating the surgical plan.

SUMMARY

The tendons that cross the ankle are complex and sophisticated structures that enable standing and forward propulsion and the ability to accommodate uneven ground. Understanding the biomechanics and local anatomy of these tendons is essential to the treatment of disorders of the foot and ankle, whether it be in formulating an appropriate physical therapy regimen or planning a reconstructive surgical procedure.

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