

Structure, Function, and Physiology of Tendons and Ligaments – A Review

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Summary

Tendons and ligaments are dense fibrous connective tissues that connect muscle-to-bone or bone-to-bone, respectively. Tendons and ligaments work cooperatively in anatomically similar locations to allow for and to stabilize musculoskeletal movement throughout the normal range of motion. Both tendon and ligament tissues transmit varied mechanical loads on-demand via a highly organized hierarchical collagen fiber structure. Tendons and ligaments are similar in material, composition, function, structure, mechanical behavior, healing profile, and healing capabilities. The delineation between the two tissues is not always clear, e.g. patellar tendon/ligament.

Tendons and ligaments can stretch or tear relatively easily, especially those located in the areas of highest use, the extremities. The most common tendon / ligament injuries occur in the shoulder (rotator cuff / acromioclavicular), ankle (Achilles / TFL), knee (patellar / ACL) and the hand (flexor / thumb metacarpophalangeal ligament). Orthopedic treatment to restore the normal mechanical function of ligaments and tendons remains challenging, typically requiring surgical intervention. Traumatic injuries or surgical intervention may initiate an exaggerated inflammatory response responsible for unwanted scarring. Peritendinous scarring and arthrofibrosis is a common complication of tendon, ligament, and joint repair procedures.

Differences between tendons and ligaments such as elastic fiber concentration or connection to bone vs muscle does not impact injury treatment modalities. Allograft and autograft tendons are often used for the reconstruction of a ruptured ACL, PCL or other knee ligament [1, 2] because these devices demonstrate the greatest outcomes related to restored ligament function [3]. Current therapies to prevent postoperative tendon and ligament tethering focus on the use of mechanical barriers and antiadhesive adjuvants [4-7].

INTRODUCTION

Tendons and ligaments are structurally and physiologically similar [8, 9]. Tendons and ligaments are dense fibrous connective tissues that connect muscle-to-bone or bone-to-bone, respectively (Fig 1). Tendons transmit axial load from muscles to bone while ligaments passively stabilize joints; tendons and ligaments are responsible for actions at rest and during the normal range of motion. Both tendons and ligaments are characterized by high tensile strength generated from thick, fibrous collagen bundles. Both tissues are also characterized by the presence of fibroblasts/fibrocytes (ligament) or tenoblasts/tenocytes (tendon) and an abundant extracellular matrix (ECM), mainly composed of collagen I [10], resulting in a dense, hypocellular structure. This structure is consistently and neatly aligned in longitudinal bundles along the direction of force. These bundles are grouped together, beginning in small units, and then combined with others to form larger and larger parallel fiber bundle groups, much like the structure of a cable on a bridge [11].

Tendon and ligament tissues transmit tensile loads, a pivotal mechanical role in joint stability. When tension is applied, tendon and ligaments deform or elongate, in a non-linear fashion, through the recruitment of crimped collagen fibers [12, 13].

Tendon and ligaments are lightly vascularized tissues, leading to a reduced healing capacity and capability; therefore management of injuries to these tissues is clinically challenging [14]. The most common tendon and ligament injuries occur in the extremities. Acute injuries to these tissues are treated by surgical repair and/or conservative approaches, including biophysical modalities. Unfortunately, healing tissues form fibrovascular

scars that possess inferior mechanical and biochemical properties as compared to native tendon and ligaments [15]. In addition, surgical interventions often result in permanent fibrinous scarring. Peritendinous scarring is a major complication of tendon repair surgeries [6, 16]. Similarly, arthrofibrosis after ACL reconstruction, total knee arthroplasty, or rotator cuff repair are common complications of ligament and joint repair procedures resulting in painful restriction of joint movement [5].

CLASSIFICATION AND DISTRIBUTION OF TENDONS

Tendons are soft tissue structures interposed between muscles and bones, responsible for transmitting force from the generating muscle to the terminating bone, making movement possible. Healthy tendons are brilliant white in color and fibro-elastic in texture. There are approximately 4,000 tendons in the human body, but the exact count depends on the person's size and muscle mass (Fig 2).

Tendons may vary considerably in shape and in the attachment to bone ranging from wide and flat tendons (rotator cuff, Achilles) to cylindrical (flexors, peroneal), fan-shaped (distal Biceps), and ribbon-shaped tendons (extensor). Muscles designed to create powerful, resistive forces, like the quadriceps and triceps brachii muscles, have short and broad tendons, while those that have to carry out subtle and delicate movements, like the finger flexors, have long and thin tendons. Cylindrical tendons respond equally to tensile loads with parallel collagen patterns while flat tendons can respond microanatomically in the form of

compression and shear forces as a result of longitudinal, oblique, and transverse collagen sequences [17].

Tendons may also be classified according to their anatomy as sheathed, synovial-coated (digital flexors) or as non-sheathed, paratenon-coated (Achilles).

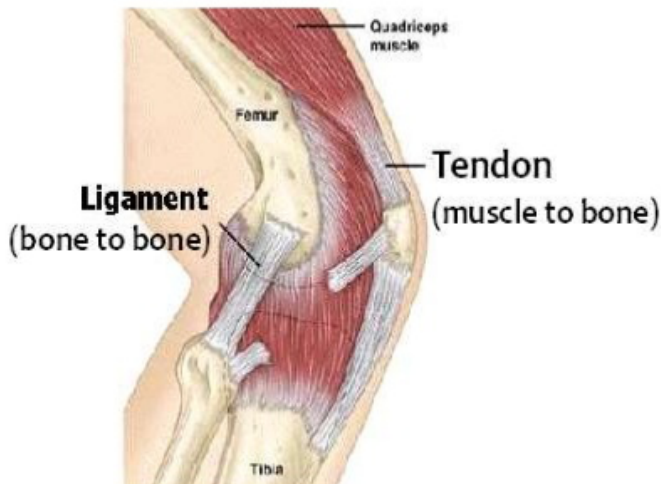


Fig 1. Tendons and ligaments are dense fibrous connective tissues that connect muscle-to-bone or bone-to-bone, respectively

CLASSIFICATION AND DISTRIBUTION OF LIGAMENTS

A set of collagen fibers joining two bones of an articulating pair is called a ligament. Thus, the articular bursal wall is a ligament, often referred to as either the fibrous capsule or the joint capsule. Ligaments are dull white when compared to tendons as a result of the presence of elastic and reticular fibers between the collagen fiber bundles [18]. Humans have approximately 900 ligaments (Fig 2).

There are two ligament types: *capsular and noncapsular*. *Capsular* ligaments are part of the articular capsule present as thickenings of the fibrous capsule that surrounds the synovial joints. Capsular ligaments act as mechanical reinforcements. The iliofemoral ligament of the hip joint is an example of a capsular ligament. Capsular ligaments are located on the outer surface of the capsule with one exception to this rule: ligaments of the shoulder joint (glenohumeral ligaments) are located on the inner surface of the capsule.

Noncapsular ligaments are free from the joint capsule but function alongside the capsular ligaments to provide joint stability. Noncapsular ligaments can be classified as internal or external. Internal noncapsular ligaments are located in the knee, wrist, and foot. The cruciate ligaments are examples of internal noncapsular ligaments and are paired ligaments in the form of a cross. Most articulations of the wrist carpal bones share a common joint cavity, and neighboring bones are connected sideways by short internal noncapsular ligaments. The same is true of the tarsal bones distal to the talus and calcaneus bones of the foot.

The *external noncapsular* ligaments are further subdivided: *proximate and remote*. The proximate external noncapsular ligaments pass over at least two joints and are near the capsules

of these joints; proximate external noncapsular ligaments are located on the outer side of the lower limb. Examples are the outer (fibular) ligament of the knee, and the middle part of the outer ligament of the ankle joint.

The *remote noncapsular* ligaments are so called because of the distance from the joint capsule. Examples of remote noncapsular ligaments include those that pass between the spine and laminae of neighboring vertebrae in the cervical, thoracic, and lumbar parts of the spinal column. Unlike most ligaments, remote noncapsular ligaments contain a high proportion of elastic fibers, making them yellow in appearance. These elastic fibers assist the spinal column in returning to its natural position after bending forward or sideways.

COMPOSITION

Structurally and physiologically, tendons and ligaments are very similar [8, 9]. Tendons and ligaments are viscoelastic materials composed of 55–70% water, and 30–45% extracellular matrix (ECM) predominantly comprising of aligned type I collagen fibers and small amounts of other collagens (65–80% dry weight) [19]. The tissues also contain proteoglycans [20] that assist to organize and lubricate collagen fiber bundles [19].

The main differences in composition between tendons and ligaments are the higher proteoglycan and water content and the lower collagen content in ligaments when compared to tendons [21]. Additionally, ligament structure is less uniform with collagen bundles generally showing a less ordered, interlaced, weaving pattern [22, 23]. The difference in the ECM composition and organization varies with each individual tendon and ligament according to the mechanical loading environment. Additionally, the delineation between the two tissues is not always clear. For instance, the patellar tendon is a continuation of the quadriceps tendon with the patella being as sesamoid bone (muscle to bone). However, many categorize this tissue as the patellar ligament that connects the patella to the tibial tuberosity (bone to bone).

STRUCTURE

Tendons and ligaments differ in function but are similar in structure. Both tendons and ligaments have a multi-unit hierarchical structure (Fig 3) [24]. Collagen molecules aggregate progressively from microfibrils to collagen fibrils. Several collagen fibrils form a collagen fiber, the basic unit of a tendon or ligament. Several collagen fibers form a primary fiber bundle (subfascicle), which group to form a secondary fiber bundle (fascicle). Fascicles are surrounded by a thin connective tissue sheath called endotenon (in tendons) or endoligament (in ligaments). These connective sheaths bind secondary fiber bundles together to form tertiary bundles. Tertiary bundles comprise tendon or ligament. The entire tendon is surrounded by a fine connective tissue sheath called epitenon whereas the ligament is surrounded by a fine connective tissue sheath called epiligament [25, 26]. The epitenon contains the tendon's vascular, lymphatic, and nerve supply. Similarly, the epiligament is vascular, contains sensory and proprioceptive nerves, and is rich

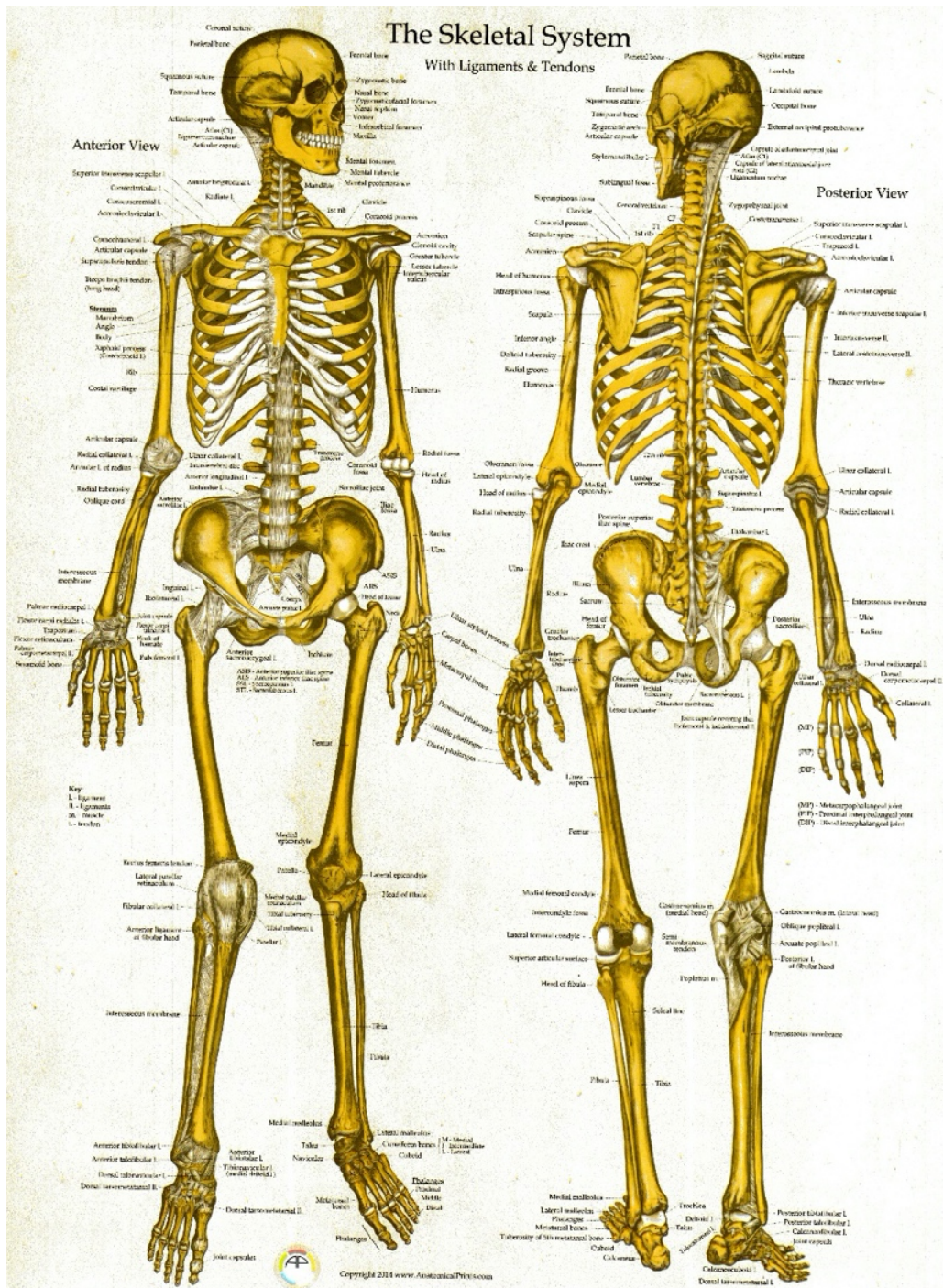


Fig 2. Tendons and ligaments in human body. (www. AnatomicalPrints.com)

in fibroblasts, fibrocytes and adipocytes [26, 27]. The epitendon and epiligament help in protecting and healing tendons and ligaments respectively.

Unlike ligaments, tendons glide. Tendons that pass through tight fibro-osseous tunnels or around corners, such as those at the fingers, wrist and ankle are surrounded by a tendon sheath. The sheath provides an access tunnel for tendon gliding at anatomic structures that might cause friction. The tendon sheath consists of an outer fibrotic layer and an inner synovial layer. The fibrotic

layer is protective and supportive while the synovial layer secretes synovial fluid (e.g., hyaluronic acid) to enable tendon gliding [28]. In regions where friction is not expected the synovial sheath is replaced with paratenon, a thin layer of loose fatty connective tissue (e.g., Achilles) [19].

The structure of tendons and ligaments makes them uniquely suited to their respective roles. The fibrils have a characteristic waviness referred to as crimp (Fig 3). Crimp plays a significant role in the mechanics of ligaments and tendons, enabling

maintenance of smooth joint movement and restraint of excessive displacement under high loads. As tension increases, collagen fibers progressively un-crimp, or elongate, until all fibers are nearly linear. Overstretched tendons and ligaments cause tears and injury [12, 13].

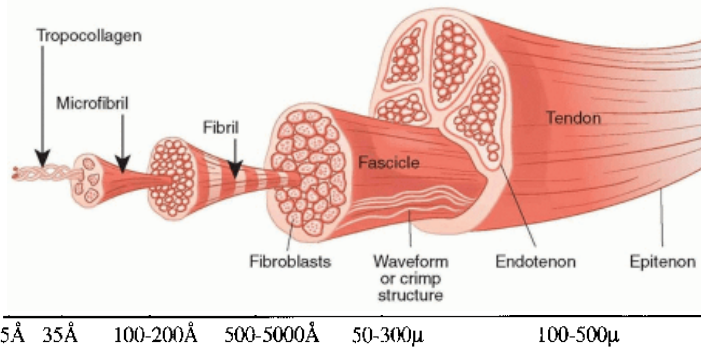


Fig 3. A schematic diagram of the structural hierarchy of ligament or a tendon. The first level is a collagen molecule, the sixth level is the ligament or tendon. In between, in ascending order, are the microfibrils, the submicrofibrils, the fibrils, and the fascicles. (Adapted from Kastelic et al., 1978)

INJURIES AND HEALING PROFILE

Ligaments and tendons can stretch or tear relatively easily, especially those located in the areas of highest use, the extremities. The most common tendon injuries involve the shoulder (rotator cuff), ankle (Achilles), and hand (flexor tendons). The most common ligament injuries involve the knee (anterior cruciate ligament (ACL)), ankle (anterior talo-fibular ligament (TFL)), foot (plantar fasciitis), and hand (thumb metacarpophalangeal ligament).

Acute injury to a tendon or ligament is followed by rapid initiation of the typical wound healing process wherein the defect is filled with fibrous tissue. This process is generally subdivided into three chronological stages: inflammation, proliferation, and remodeling [29-31]. While these stages overlap, each is characterized by distinct cytokine profiles and cellular processes.

The *inflammatory stage* of tendon or ligament healing begins immediately after acute injury, lasts about 24 h, and is characterized with inflammation, hematoma formation, and cell proliferation [31].

The *proliferative phase* lasts a few weeks and is characterized by expansion of the ECM including glycosaminoglycans, increased cellularity, and deposition of fibrovascular scar by fibroblasts [12, 15, 29, 32, 33]. Insulin-like growth factor-I (IGF-I) and transforming growth factor- β (TGF- β) expression remains high, continuing to attract fibroblasts to the site and to increase ECM production [34, 35]. The fibrous tissue formed contains a high proportion of Type III collagen.

Table 1. Key similarities and differences between tendons and ligaments

Similarities		
1	Material: Soft, collagenous tissue	
1	Composition: 55-70% water and are characterized by the presence of fibroblasts and fibrocytes and an abundant ECM composed primarily of Type I Collagen (65-85% dry weight) and proteoglycans	
3	Function: Provide mechanical strength by transmitting tensile load	
4	Structure: Multi-unit hierarchical structure with collagen fiber as the basic unit; fibers are bundled in a crimped pattern to provide tensile strength	
5	Mechanical Behavior: Nonlinear and viscoelastic	
6	Healing Profile: Inflammation, proliferation, and remodeling phases	
7	Healing Capabilities: Hypocellular and hypovascularized with low healing capabilities	
8	Challenges: Susceptible to post-operative scarring and tissue tethering of the upper and lower extremities	
Differences		
Tendon	Ligament	
1	Connects muscle to bone	Connects bone to bone
2	Transmit the mechanical force of muscle contraction to bones by gliding	Stabilize and guide joints during natural range of motion
3	Higher concentration of collagen fibrils and lower percentage of proteoglycan	Lower concentration of collagen fibrils and higher percentage of proteoglycans
4	Brilliant white	Dull white to yellow (higher percent of elastic fibers make them appear yellow)
5	Approximately 4000 tendons in human body	Approximately 900 ligaments in human body
6	Collagen fibers grouped in distinct parallel fascicles	Collagen fibers are architecturally oriented to effectively control and constrain joint motion
7	Less elastic	More elastic
8	Surrounded by a fine sheath to assist in gliding	No sheath as ligaments do not have a gliding function
Concluding Remarks		
Tendons and ligaments share similarities in material, composition, structure, function, mechanical behavior, healing profile, healing capabilities, and challenges of scarring in the upper and lower extremities. Differences between tendons and ligaments such as anatomical structures that they connect, composition of ECM, presence of sheath, and elasticity do not impact the treatment approach for tendon and ligament injuries.		

After about 6 weeks, the *remodeling phase* begins, wherein the fibrous repair tissue becomes less cellular, glycosaminoglycan concentrations decrease, and the proportion of Type I collagen increases. Over the next 10 weeks, the repaired tissue changes to scar-like tendon/ligament tissue. Eventually newly formed collagen fibers and tenocytes/fibrocytes align with the direction of applied stress to increase the repaired tissue tensile strength. The remodeling phase can last several months [3, 29]. The repaired tissue (scar) is inevitably inferior in strength when compared to the native tissue and is subsequently prone to further injury such as tears and re-rupture.

While vascularized tendons and ligaments have at least some capacity to heal, avascular tendons (rotator cuff) and ligaments (intra-articular) generally do not heal themselves. Ironically these tissues are located in areas of greatest use, movement, and therefore are highly susceptible to injury.

POSTOPERATIVE SCARRING

Scarring is a result of an exaggerated inflammatory response to an injury or surgical procedure. Specifically, this inflammatory response involves the over-production of fibroblastic cells and an increase in the deposition of extracellular matrix proteins, encouraging fibrotic cellular deposition. This scarring often causes tissues to tether that would otherwise be separate. Unnatural tissue tethering almost inevitably produces functional disability by causing pain and by limiting range of motion. Tendon healing within the synovial sheath (e.g. digital flexor tendons) is invariably associated with scar formation [6, 16, 31]. Arthrofibrosis of the knee is one of the most serious complications that can result from ligament procedures. Reported incidence of arthrofibrosis following ACL reconstruction ranges from 4% to 35% [36]. Arthrofibrosis is a fibrotic joint disorder which may occur in most joints [37], and is referred to by a number of names including frozen shoulder, adhesive capsulitis, joint contracture, stiff knee and stiff elbow.

Sterile arthrofibrosis is typically caused by chronic or repetitive injury or surgery that leads to a dysregulated immune reaction and fibrosis in and/or around a joint [38]. The process begins when stress signals stimulate immune cells. Positive feedback networks then dysregulate processes that normally terminate healing processes [39, 40]. In knee joints the suprapatellar pouch, anterior interval, intercondylar notch, medial and lateral gutters, posterior capsule, infrapatellar fat pad (IFP or Hoffa's fat pad) and articular surfaces, may all be affected [39], with symptoms typically involving loss of flexion and/or extension (**Fig 4**). The consequent pain and restricted knee mobility resulting from arthrofibrosis may lead to disabling events including severe quadriceps atrophy, loss of patellar mobility, patellar tendon adaptive shortening, patella infera, and articular cartilage deterioration [41].

THERAPY MODALITIES

Restoration of tendon and ligament function is challenging. Allograft and autograft tendons are often used for the reconstruction of a ruptured ACL, PCL or other knee ligament [1, 2] because these devices demonstrate the greatest outcomes related to restored ligament function [3]. Current therapies to

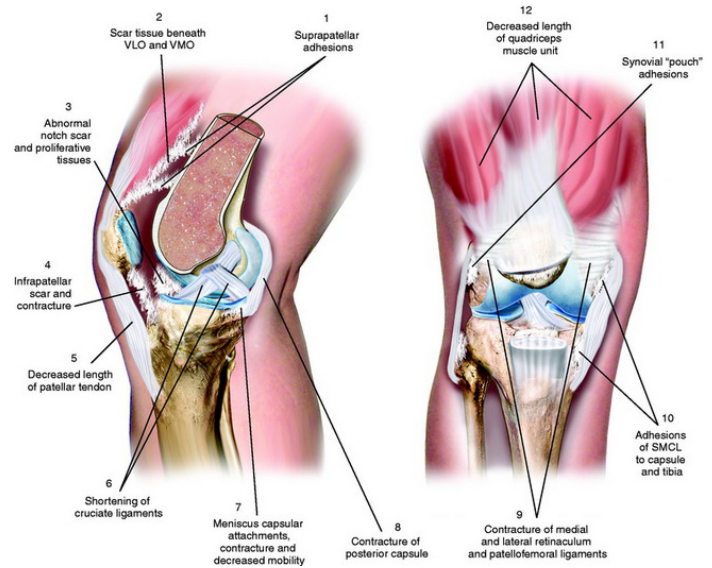


Fig 4. Multiple areas of soft tissue contracture, tissue tethering, and scar tissue formation with knee arthrofibrosis [39].

prevent postoperative tendon and ligament tethering focus on the use of mechanical barriers and antiadhesive adjuvants [4-7].

CONCLUSIONS

Ligaments and tendons are both individually, and cooperatively, responsible for allowing natural musculoskeletal range of motion and for joint stabilization. Ligaments and tendons work together in anatomically similar locations. Ligaments and tendons are generally hypocellular, hypovascular, viscoelastic materials primarily comprised of highly organized collagen fibers with varying concentrations of elastic fibers.

Ligaments and tendons can stretch or tear relatively easily, especially those located in the areas of highest use, the extremities. The two tissues have a similar healing profile including the proclivity to scar, resulting in unwanted tethering to surrounding tissues. Treatment of tendon and ligament injuries is a significant clinical challenge.

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