Biomechanics of Tendon and Ligaments
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Introduction

• Passive structures- tendons, ligaments, joint capsules.

• Ligament and joint capsule-prevention of excessive motion, enhance mechanical stability, guide the joint motion.

• Tendons- attach muscles to the bones and transmission of tensile loads.
Increases in athletics and trauma has lead to increases in soft tissue injuries.

- Tendons & ligaments govern joint motion and share load in Diarthrodial joints.

- Injury → changes in joint motion and wear → premature joint degeneration → increased morbidity

Fig. 2
Tendons

Ligaments

Dense connective tissues

• Similar in structural composition and mechanical behavior

- Longer & narrower
- Connect muscle to bone
- Collagen more longitudinally arranged

- Load-bearing structures
- Shorter & wider than that connect bones
- Less collagen & more ground substance
- Experiences more varied loading thus collagen arrangement more variable
<table>
<thead>
<tr>
<th>Component</th>
<th>Ligament</th>
<th>Tendon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cellular material= fibroblasts</td>
<td>20%</td>
<td>20%</td>
</tr>
<tr>
<td>Extracellular matrix</td>
<td>80%</td>
<td>80%</td>
</tr>
<tr>
<td>water</td>
<td>60-80%</td>
<td>60-80%</td>
</tr>
<tr>
<td>solids</td>
<td>20-40%</td>
<td>20-40%</td>
</tr>
<tr>
<td>Collagen</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Type 1</td>
<td>70-80%</td>
<td>Slightly higher</td>
</tr>
<tr>
<td>Type 3</td>
<td>90%</td>
<td>95-99%</td>
</tr>
<tr>
<td>Ground substance</td>
<td>20-30%</td>
<td>Slightly lesser</td>
</tr>
</tbody>
</table>
Anatomy

• Type I collagen is the predominant constituent of tendon and ligaments (86% fat-free dry weight)

• **structure:** each collagen molecule consist of 3 polypeptide α chains combined making a collagen molecule, each coiled in helix with approximately 100 amino acids.
  - **Type I:** two (peptide chain) α1..... and one α2 chains slight different, form right-handed triple helix held together by hydrogen and covalent bonds.
  - Length=280nm diameter=1.5nm
Procollagen

Secretion

Cleavage

Collagen monomer/propeptides

Cross-linkage

Fibril formation

Cell membrane

Procollagen III secretion

Collagen monomers

Circulation

Fibril formation

Collagen fibrils
a Assembly of three procollagen chains

b Assembly of triple helix

c Cleavage of propeptides

d Assembly into collagen fibrils

e Formation of covalent cross-links

Synthesis of a fibril-forming collagen
Anatomy

- 2/3 of collagen molecule consist of 3 amino acids, glycine, 33%, proline 15% & 15% hydroxyproline

  - every third amino acid in each chain is glycine, and repetitive sequence essential for triple helix.
  - Small size of glycine allows tight helical packing of collagen molecule, & enhances the stability of molecule by forming hydrogen bonds among three chains. Hydroxyproline and proline also form hydrogen bond.
  - The intra- and interchain bonding or cross-linking between specific groups on the chains is essential for the stability & strength of the molecule.
Microfibril quaternary structure

Collagen molecule

Tertiary structure

Secondary structure

Glycine Hydroxyproline

Proline
Factors effect the stability & strength

- In newly developed collagen the crosslinkage are few..
- the collagen are soluble in natural salt and in acid solution,
- cross linkage easily damaged with high heat, as well aging reduce number of cross links decrease stability and strength.
- overlapping and Organization of collagen molecules into a stable low-energy biologic unit →microfibril
- The arrangement of adjacent molecules aligns oppositely-charged acidic and basic Amino Acids makes a very stable construct that takes a lot of energy to separate its molecules
• Microfibril: 5 collagen molecules -- Subfibril---- Fibril-- collagen fiber(1-20um in diameter)---

• Fascicle:….Closely-packed, longitudinal, parallel bundles of fibrils bound together by proteoglycans and glycoproteins in association with water incorporated in a matrix. Fibroblasts are aligned in rows between these bundles and are elongated along an axis in the direction of ligament or tendon function

• Tendon: Fascicles held together by loose connective tissue, the endotenon.

  ❖ Endotenon: Allows longitudinal fascicle movement, and supports blood vessels, lymphatics and nerves

  ❖ Tendon itself surrounded by epitenon
• The arrangement of collagen in tendons and ligaments varies as in accordance with the function.
• Parallel arrangement in tendons.... Uniaxial or Unidirectional tensile loads.
• In ligaments not all in parallel direction and suited according to the function.
Muscle fibers

GTO capsule

Ib afferent

Loosely packed innervated collagen

Densely packed (bypassing) collagen

TENDON
- Tendons typically carry tensile forces.
- **Mesotenon joins epitenon & tension side of sheath.**
- Tendon act cartilage type ..........
- acts as a pulley & directs the path of the tendon.

- **Tendon in sheath:::**
  - Synovial fluid released from parietal & visceral synovial membranes facilitates sliding of tendons in sheath.
- **Tendons not enclosed w/in a sheath** move in a straight line and are surrounded by a loose areolar connective tissue called the paratenon (continuous w/ the tendon).
Elastin

- Mechanical properties.....
- present less in tendons and more ligaments.
- Ligamentum flavum: protection of spinal nerve roots, intrinsic stability to the spine, 2:1 ratio of Elastin to collagen.

Ground substance:

- PGs, Same structures as in AC.
- Forms gel like material and binds ligaments or tendons.
- Cement like properties provide structural stability.
Insertion into Bone

- At the tendo-osseus junction the collagen fibers of the endotenon continue into the bone as Sharpey’s Fibers
- Then becomes continuous with the periosteum
- Zone I: end of tendon
- Zone II: collagen fibers intermesh with Fibrocartilage
- Zone III: fibrocartilage then gradually becomes mineralized fibrocartilage
- Zone IV: merge into cortical bone
Mechanical Behaviour of Tendon and ligaments

• Both are Viscoelastic tissues
• Visco - a small amount of load results in quite a bit of deformation (relative)
• Elastic - refers to Elastic Region
• Importance of Viscoelastic qualities?
Biomechanical Behaviour

• can sustain high tensile loads
• flexible to allow changes in direction of muscle pull
  • When load is great enough to cause injury, damage is dependent on: rate and amount of load
Physiological loading of tendons and ligaments

- Stress relaxation
- Creep
- Curves for creep and stress relaxation
- Load Deformation curve variation (stress strain curve)
- Hysteresis
**Figure 9.1** Stress ($\sigma$)–strain ($\varepsilon$) curve for parallel-fibered collagenous tissue until failure (solid line); tan $\alpha$ is elastic stiffness. The beginning and end of the linear segment are marked with bars. The dashed curve is for unloading, if the cycle is reversed at the point ($\sigma_R$, $\varepsilon_R$).
FIGURE 4.6 Stress–strain curve. When stressed, initially the wavy collagen fibers straighten (toe region). With additional stress, recoverable deformation occurs in the elastic range. Once the elastic limit is reached, sequential failure of the collagen fibers and tissue occurs in the plastic range, resulting in release of heat (hysteresis) and new length when the stress is released. The length from the stress point \(X\) results in a new length when released \(X'\); the heat released is represented by the area under the curve between these two points (hysteresis loop). \(Y\) to \(Y'\) represents additional length from additional stress with more heat released.) Necking is the region in which there is considerable weakening of the tissue and less force is needed for deformation. Total failure quickly follows even under smaller loads.
Load-elongation curve for a human ligamentum flavum (60 to 70% elastic fibers) tested in tension to failure. At 70% elongation the ligament exhibited a great increase in stiffness with additional loading and failed abruptly without further deformation. (Adapted from Nachemson and Evans, 1968.)
The curve produced during tensile testing of a human anterior cruciate ligament in vitro (Noyes, 1977) (see Fig. 3–8) has been converted to a load-displacement curve and divided into three regions correlating with clinical findings: (1) the load imposed on the anterior cruciate ligament during the anterior drawer test; (2) that placed on the ligament during physiologic activity; and (3) that imposed on the ligament from partial injury to complete rupture. It should be noted that the divisions shown here represent a generalization. Microfailure is shown to begin toward the end of the physiologic loading region, but it may take place well before this point in any given ligament.
Creep

• When a load is applied for an extended period of time, the tissue elongates, resulting in permanent deformation.

• It is related to the viscoelasticity of the tissue and is therefore time-dependent.

• Low-magnitude loads, usually in the elastic range and applied for long periods, increase the deformation of connective tissue and allow gradual rearrangement of collagen fiber bonds (remodeling) and redistribution of water to surrounding tissues.

• Complete recovery from creep may occur over time, but not as rapidly as a single strain. Patient reaction dictates the time a specific load is tolerated.

stress relaxation

• When a force (load) is applied to stretch a tissue and the length of the tissue is kept constant,

• after the initial creep there is a decrease in the force required to maintain that length, and the tension in the tissue decreases.
FIGURE 4.7 Tissue response to prolonged stretch forces as a result of viscoelastic properties. (A) Effects of creep. A constant load, applied over time, results in increased tissue length until equilibrium is reached. (B) Effects of stress-relaxation. A load applied with the tissue kept at a constant length results in decreased internal tension in the tissue until equilibrium is reached.
Viscoelastic Behavior in Tendons and Ligaments

The viscoelasticity (rate dependency, or time dependency) of ligaments and tendons can be demonstrated by two standard tests: the load-relaxation test and the creep test. **A.** Load relaxation is demonstrated when the loading of a specimen is halted safely below the linear region of the load-deformation curve and the specimen is maintained at a constant length over an extended period (i.e., the amount of elongation is constant). The load decreases rapidly at first (i.e., during the first 6 to 8 hours of loading) and then gradually more slowly, but the phenomenon may continue at a low rate for months. **B.** The creep response takes place when loading of a specimen is halted safely below the linear region of the load-deformation curve and the amount of load remains constant over an extended period. The deformation increases relatively quickly at first (within the first 6 to 8 hours of loading) but then progressively more slowly, continuing at a low rate for months.
Figure 1. Knee alignment can be categorized as genu valgum (knock-knee), normal or genu varum (bow legged).
Tendon Vascularisation

• Limited vascularisation...healing process & metabolic activity

• Tendons blood supply from vessels in perimysium, periosteal insertion, surrounding tissues vessels in paratenon and mesotenon

• **Tendons with in paratenon sheath**(vascular tendon) Vessels enter from periphery and anastamose w/ longitudinal system of capillaries

• **Tendons w/o sheath**(covered by tendon sheath as avascular tendon):

  • Blood from Mesotenons vincula, & osseus insertions......avascularity in tendons adopt

• Dual pathway for nutrition: vascular and synovial, i.e. diffusion

• Diffusion Clinically important...-- tendon healing
Ligamentous Vascularisation

• hypovascular compared to surrounding structures
• Uniform microvascularity originating from insertion sites
  ❖ Flow is limited but essential to maintenance of cell population, matrix synthesis & repair.
• Variety of specialized nerve endings & mechanoreceptors (proprioception & nociception--- joint function.)
Crimping

- Fibrils appear in sinusoidal pattern under microscopy
- influences biomechanical behavior of tendons and ligaments
- **Tensile resistance occurs once crimp pattern is straightened (toe region)**

Crimp pattern

- Load-deformation non-linear
Ligament Failure and Tendon Injury Mechanism

• **Grade I injury:**
  - Negligible clinical symptoms
  - Some pain is felt, but no joint instability can be detected clinically
  - Micro failure of the collagen fibers may have occurred.
**Grade II injury:**

- severe pain and some joint instability can be detected clinically.
- Progressive failure of the collagen fibers has taken place resulting in partial ligament rupture.
- The strength and stiffness of the ligament may have decreased by 50% or more, mainly because the amount of undamaged tissue has been reduced.
- The joint instability produced by the partial rupture or a ligament is often masked by muscle activity.
- The clinical test for joint stability is usually performed with the patient under anesthesia.
Grade III

- Severe pain trauma time
- Less pain after trauma time, the joint is found to be completely unstable.
- Most collagen fibers have ruptured, but a few still be intact, giving the ligament the appearance of continuity even though it is unable to support any loads.
- Ligament or joint capsule rupture produces abnormally high stresses on the articular cartilage.
- Early osteoarthritis in humans and in animals.
Two additional factors become important in tendons because of their attachment to muscles:

1. The amount of force produced by contraction of the muscle to which the tendon is attached ... A tendon is subjected to increasing stress as its muscle contracts.

2. Cross-sectional area of the tendon in relation to that of its muscle.

- Tensile strength or health of tendon is more than muscles.
- Muscle ruptures are more common than are ruptures through a tendon. (Muscle size and tendon size correlation.)
- Quadriceps
- Plantaris?
Factors That Affect the Biomechanical Properties of Tendons and Ligaments

- Maturation and aging
- Pregnancy and the postpartum period
- Mobilization and immobilization
- Diabetes mellitus
- Steroids
- Nonsteroidal anti-inflammatory drugs
- Hemodialysis
- Grafts
Maturation and aging

- Aging results in a decline in the mechanical properties of tendons and ligaments, i.e. their strength, stiffness, and ability to withstand deformation.

- During maturation (up to 20 years of age), the number and quality of cross-links increases resulting in increased tensile strength of the tendon and ligament.

- **Pregnancy and the Postpartum period:**
  - Increased laxity of the tendons and ligaments in the pubic area during later stages of pregnancy and the postpartum period.
  - Decreased strength in the early postpartum period but was later restored.
Mobilization and immobilization

• Like bone, ligament and tendon appear to remodel in response to the mechanical demands placed on them; they become stronger and stiffer when subjected to increased stress and weaker and less stiff when the stress is reduced.

• Physical training has been found to increase the tensile strength of tendons and of the Ligament-bone interface.

• Immobilization has been found to decrease the tensile strength of ligaments.

• Stress-strain characteristics after remobilization return to normal but that the energy-absorbing capabilities or the bone-ligament complex improved but did not return to normal
Diabetes Mellitus

• The term diabetes refers to disorders characterized by excessive urine excretion. Diabetes mellitus is a metabolic disorder in which the ability to oxidize carbohydrates is more or less completely lost.

• This is usually caused by pancreas insufficiency and a disturbance of the normal insulin mechanism, resulting in hyperglycemia, glycosuria, and polyuria.

• Diabetes mellitus is known to cause musculoskeletal disorders.

• Diabetics compared with non-diabetics show higher rates of tendon contracture (29 VS. 9%), tenosynovitis (59 vs. 7%), joint stillness (40 vs. 9%), and capsulitis (16 Vs. 1%).

• Diabetes also causes osteoporosis.

• Difference in mode of failure.
Steroids

• Corticosteroids, when applied immediately after injury, may cause significant impairment of the biomechanical and histological properties in ligaments.

• Corticosteroids also are known to inhibit collagen synthesis

• Single Application Vs Long Term usage.

• NSAIDS

• NSAIDs (which include aspirin, acetaminophen, and indomethacin) are frequently used in the treatment of various painful conditions of the musculoskeletal system.

• widely used in the treatment of soft tissue injuries such as inflammatory disorders and partial ruptures of tendons and ligaments

• SHORT TERM USE VS LONG TERM USE
Hemodialysis

- Tendinuous failure resulting from chronic renal failure does occur, with tendon rupture reaching 36% among individuals receiving hemodialysis.

- Hyperlaxity of tendons and ligaments was found in 74%, patellar tendon elongation in 49%, and articular hypermobility in 51% of individuals receiving long-term hemodialysis.

- Dialysis-related amyloidosis may cause the deposition of amyloid in the synovium of tendons.
Grafts

• Grafts derived from different individuals of the same species are called allografts.

• Grafts derived from the same individual are called autografts.

• Heterografts

• Bone-patellar, tendon-bone, and Achilles tendon are usually used as allograft tissue.

• Central tissue of the patellar tendon is commonly used as autografts tissue.

• Allografts and autografts are useful in ligament reconstruction but material properties do not return completely to normal levels.
THAKS