Mechanics of Tendon, and Ligament

Ozkaya and Nordin
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The roles of ligaments and tendons

<table>
<thead>
<tr>
<th>Ligaments:</th>
<th>Tendons:</th>
</tr>
</thead>
<tbody>
<tr>
<td>• connect bones together</td>
<td>• attach muscle to bone</td>
</tr>
<tr>
<td>• augment joint stability</td>
<td>• transmit muscle force to bone</td>
</tr>
<tr>
<td>• guide joint motion (direction and magnitude)</td>
<td>• absorb and release energy</td>
</tr>
</tbody>
</table>

Outline

• review of tendon and ligament anatomy
• nonlinear stiffness
• hysteresis
• deformation and energy absorption during running
• creep and stress relaxation
• ligament injury

Collagen molecules are the building blocks of tendons and ligaments

• 70-80% of the dry weight of tendon or ligament is Type 1 collagen
• a type I collagen molecule is a right-handed triple helix of 3 polypeptide α chains
• tensile strength of the tendon or ligament is derived from strong (a) intramolecular covalent bonds and (b) intermolecular hydrogen bonds (between α chains)
**Tendon and ligament organization**

- Collagen molecules combine to form microfibrils, subfibrils, and fibrils.
- Water makes up 60-80% of the wet weight of tendon or ligament, entrapped between proteoglycan molecules having fixed negative charges.
- Fibroblasts bodies are drawn out in the primary direction of loading.

**Collagen molecules are oriented to match functional demands**

- Tendons contain totally parallel arrangements of collagen fibrils, which provides high unidirectional strength.
- Ligaments contain nearly parallel arrangements of collagen fibrils, which makes them able to withstand loads in different directions.

**Attachment of tendon and ligament to bone**

- Bone has a modulus of elasticity 10-fold greater than tendon or ligament.
- Direct bonding between these materials would be difficult, due to discontinuities in stress and strain at the interface.
- Nature solves the problem by having a sequential spacial arrangement of tendon (or ligament), fibrocartilage, and mineralized fibrocartilage (Sharpey’s) fibers that insert directly into the bone, perpendicular to the surface.

**Tendons and ligaments have nonlinear stiffness**

- Like most soft tissues, the stiffness of tendon or ligament increases with increasing load (non-Hookean behaviour).
- Therefore, work cannot be calculated from final force and deflection.
- This behaviour has been explained by the fiber recruitment model: with increasing deformation, an increasing number of initially slack fibers become taut and bear load.
Tendon/ligament: material and structural properties

- The Young’s modulus of tendons and ligaments (beyond the “toe region”) ranges between 400 and 1500 MPa.
- The ultimate tensile strength of tendons and ligaments ranges between 50 and 100 MPa.
- The stiffness and force bearing capacity of tendons and ligaments depends on their length and cross-sectional area.

Tendons and ligaments exhibit viscoelastic (rate-dependant) behaviour

Like most polymers, these tissues exhibit the following “viscoelastic” characteristics:

- creep
- stress relaxation
- hysteresis (energy dissipation)
- increased stiffness with increased rate of loading

NOTE: viscoelasticity and nonlinear stiffness are different phenomenon!

Techniques to quantify hysteresis: rebound resilience and percent energy dissipation

rebound resilience = \( \frac{W_c}{W_a} \)

percent energy dissipation = \( \frac{W_c}{W_a} \left( \frac{W_a - W_b}{W_a} \right) \)

NOTE: tendons are good springs; they return about 93% of the work done in stretching them.
How much do tendons stretch during daily activities?

Example problem. During running, peak foot contact forces average about 2.7 times BW, or 1900 N for a 70 kg individual. If the Achilles tendon has a cross-sectional area of 89 mm$^2$, a length of 250 mm, and a Young’s modulus of 800 MPa, how much will it deform? Approximately how much energy will it absorb and return during each stride (of the total of 115 J lost and regained every second)?

The foot also acts as a spring during running
- The arch of the foot compresses approx. 1 cm during running, under a 6400 N tibial compressive force.
- In doing so, it absorbs about 32 J of energy, and returns about 80% of this during unloading.
- This springiness, along with that of the Achilles tendon and quadriceps tendon, reduces the metabolic energy demands, and the required magnitude and speed of shortening, in the muscle.

Tendons and ligaments have rate-depandanlt (or viscoelastic) properties

Creep: A step increase in load (or stress) causes a deformation (or strain) that increases in magnitude with time.

Stress relaxation: A step increase in deformation (or strain) causes an increase in load (or stress), that reduces in magnitude with time.

Creep response consists of instantaneous and slow elastic strains, and viscous flow
A step increase in stress causes a a viscoelastic material to experience:
- an instantaneous elastic strain (which disappears after the load is removed);
- a slow elastic strain (which declines to zero after the load is removed); and
- a viscous flow (which remains after the load is removed).
**Knee ligaments**

*Anterior cruciate ligament (ACL)*
- Tibial attachment anterior and medial
- Femoral attachment posterior and lateral
- Prevents anterior sliding of tibia on femur
- ACL tear gives “anterior drawer” sign

*Posterior cruciate ligament (PCL)*
- Tibial attachment posterior and lateral
- Femoral attachment anterior and medial
- Prevents posterior sliding of tibia on femur
- PCL tear gives “posterior drawer” sign

*Collateral ligaments*
- Tibial collateral of the knee resists knee hyperextension, and lateral rotation of tibia relative to femur
- Medial collateral of the knee resists knee hyperextension, and medial rotation of tibia relative to femur
- During knee flexion, the ACL, MCL, and LCL slacken, allowing tibia to rotate ~8 deg about AP axis, and 24 deg about long axis
- Isolated ACL tears are often due to forces that hyperextend knee, and rotate tibia medially with respect to femur.

**Patellar tendon rupture**

In 1977, biomechanicians were recording the force and motion of a world-class lifter (body mass = 84 kg, or 186 lb) as he attempted a clean-and-jerk movement with a 175 kg (386 lb) weight. Remarkably, the patellar tendon was torn completely at its insertion on the tibia. The estimated tensile force in the tendon at rupture was 14.5 kN, or 17.5 times the lifter’s body weight.

**Knee ligaments (cont)**

*Terrible triad: ACL, MCL, med. meniscus*
- Medial meniscus less mobile
- Medial meniscus attached to MCL
- MCL tear can damage medial meniscus
- Often due to lateral impact to knee

**Review questions**

- What are the primary roles of ligaments and tendons?
- What types of molecular bonds contribute to the tensile strength of collagen fibrils?
- How are tendons attached to bone?
- What is the fiber recruitment model?
- What is the Young’s modulus and ultimate tensile strength of tendon and ligament? How do these compare to bone?
- How much energy is absorbed and returned in the Achilles tendon, and in the spring of the foot, during a stride of running?
- How does the ratio of tendon to muscle energy absorption scale with the ratio of tendon to muscle length?
- What three components of deformation (or strain) contribute to the creep response?
- How do the collateral and cruciate ligaments contribute to knee joint stability?
- What type of loads are most often involved in ACL injuries?