Biomechanics of Joints, Ligaments and Tendons.

Course Text: Hamill & Knutzen (some in chapter 2 and 3, but ligament and tendon mechanics is not well covered in the text) Nordin & Frankel (Ch 2 & 3) or Hall (Ch. 5)

Hippocrates (460-377 B.C.)

“All parts of the body which have a function, if used in moderation and exercises in labours to which each are accustomed, thereby become healthy and well-developed: but if unused and left idle, they become liable to disease, defective in growth, and age quickly. This is especially the case with joints and ligaments, if one doe not use them.”


Joints

- Review architecture of cartilaginous joints (specifically the vertebrae). We will look at these again.
- Review architecture of synovial joints.
- This will help with understanding the structures we are discussing. The anatomy of the synovial joint will not be specifically examined.

Articular Cartilage

- The joints of a mechanical device must be properly lubricated. Articular cartilage, a dense white connective tissue coats (1-7 mm thick) the ends of bones articulating at synovial joints. It serves two purposes:
  1: Spreads the load. Cartilage can reduce the maximum contact stress by 50% or more.
  2: Reduces friction during movement.
Articular cartilage has a combination of elastic and viscoelastic properties. As load is applied, deformation increases with time, first in an elastic fashion, then with a slow creep. With the removal of the load there is an elastic recoil and a slow recovery to the baseline.

**Articular Fibrocartilage**
- The function of fibrocartilage includes:
  - Absorption and distribution of loads
  - Improvement of the fit of articulating surfaces.
  - Increase in joint stability.
  - Protection of the periphery of the articulation.
  - Lubrication.

**Knee Menisci**
Stress distribution in a normal knee and in a knee with the menisci removed. With the menisci removed the contact area is limited to the centre of the tibial plateau hence increasing the stress. In the average male the knees support 88% of the body weight.
Articular Connective Tissue

- Tendons and ligaments are much less extensible than muscle and do not have the ability to contract.
- Made primarily of collagen fibres (with some elastin fibres) they will return to their normal lengths when unloaded.
- However, there is an elastic limit (bone lecture) after which the tendon or ligament will not return to resting length (region of plasticity - 2nd degree strain). This will take time for the body to repair.
- If the ligament completely fails (3rd degree strain) this can only be restored by surgery.

Ligament Composition

Fibre Arrangement

Figure 3.2 The microscopic appearance of ligament 'crimp'. This is one of the keys to normal fibre recruitment (H&E, x 60).

Ligament Crimp

Unloaded Ligament

Loaded Ligament
**Collagen Fibres**

- Deformation Range: small 6 - 8%
- Strength: 50% of that of cortical bone tested in tension

**Young’s Modulus**

Young’s Modulus is the ratio of:

tensile stress / tensile strain

<table>
<thead>
<tr>
<th>Material</th>
<th>Young’s Modulus</th>
<th>Tensile Strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tendon</td>
<td>$2 \times 10^9$</td>
<td>$1 \times 10^8$</td>
</tr>
<tr>
<td>Bone</td>
<td>$1.7 \times 10^{10}$</td>
<td>$1.8 \times 10^8$</td>
</tr>
<tr>
<td>Carbon Steel</td>
<td>$2 \times 10^{11}$</td>
<td>$3 \times 10^9$</td>
</tr>
<tr>
<td>Soft rubber</td>
<td>c.$10^6$</td>
<td></td>
</tr>
</tbody>
</table>

**Fibre Arrangement**

- Tendon
- Ligament
- Skin

**Elastic Fibres**

Elastin and microfibrils

- Deformation Range: large >100%
  - (150% Fawcett 1986)
- Strength: weak
**Joint Stability**

- Stability to resist dislocation and damage to the ligaments, tendons and muscles surrounding a joint.
- The shape of the articulating surfaces is important.
- Some joints are obviously not designed to be as stable as others as range of motion can be compromised in a very stable joint.

**Tendons & Ligaments**

- Tendons and ligaments are predominantly made up of collagen.
- Hence their stress / strain relationship will mirror that of collagen.
- The less-structured orientation of the collagen in the ligaments will provide additional elastic properties (directional) compared to tendons.

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![Load-Elongation Graph for Primate Ligament (Noyes 1977)](image)

![Load-Elongation curve for rabbit tendon tested to failure in tension](image)

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![Progressive failure of the anterior cruciate ligaments (cadaver knee tested in tension to failure at a physiologic strain rate, Noyes 1977)](image)
Curve from previous slide divided into three regions correlating with clinical findings.

Repetitive stress causes failure at lower load than that required to cause failure in a single application. As a ligament undergoes cyclic loading it relaxation behaviour results in continuously decreasing stress (protecting ligament from fatigue failure)...

Hysteresis during cyclic loading of a knee ligament.

Repetitive stress causes failure at lower load than that required to cause failure in a single application. As a ligament undergoes cyclic loading it relaxation behaviour results in continuously decreasing stress (protecting ligament from fatigue failure)...

Therefore, there is a time dependant increase in elongation when a viscoelastic material is subjected to a repetitive constant stress (cyclic creep).

Max. load to failure for primate anterior cruciate ligaments Noyes 1977
Quantity not Quality?

- Eighteen weeks of remobilization were necessary to reverse the detrimental effects of a six-week immobilization on the structural properties of ligaments (Laros et al., 1971).
- Structural properties nearly normal but mechanical properties of healed ligaments almost always remain inferior when compared to normal tissue.
- This is possible as the tissue accumulates mass to compensate for inferior tissue quality.
- Some areas of healed MCL were up to 2.5 times larger than controls (Ohland et al., 1991)
This graph is a stress-strain curve for the femur-MCL-tibia complex. Therefore this graph shows fundamental tissue properties compared to the previous specimen load-deformation curve.

Biomechanics of the Knee

As the knee flexes more force is required to maintain balance and the compressive force increases due to tendon alignment (vector resolution).

Patellofemoral joint reaction force ($P$) is formed by the vector sum of the force vector of the quadriceps tendon ($F_Q$) and the force vector of the patellar tendon ($F_P$).
Calculate $F_c$ if the angle between $F_Q$ and $F_T$ is 90°, if the force in both tendons is 2,000 N.

Cosine Law

\[ R^2 = F_Q^2 + F_T^2 - 2(F_Q)(F_T)\cos\theta \]

\[ R^2 = 2000^2 + 2000^2 - 2(2000^2)\cos90° \]

\[ R^2 = 8,000,000 - (8,000,000)(0) \]

\[ R^2 = 8,000,000 \]

\[ R = \sqrt{8,000,000} = 2,828 \text{ N} \]

See the Problem Set Booklet for an example of vector resolution for the knee.

**Full Squat**

Crease at hip (a) is below knee. So thighs tend to just break below parallel.

**Seated Knee Extension**

Force on Tibial Tuberosity

Pelvis tends to rotate back furthering the relaxation of the hamstrings

If the hamstrings do not forcefully contract, the dominant quadriceps force acting on the knee will create considerable shear (red vector component).

**Patella Tendon Rupture.**

Force in patella tendon $\lambda$. 14.5 kN (17.5 x body weight)

Load weight 175 kg
**Knee Ligament Function**

Fig. 25. A human knee joint, showing the action of the cruciate ligaments. (From Barnett, Davies & MacConnall, 1941.)

**Anterior Cruciate Ligament Injury**

Fig. 6.24 Anterior cruciate ligament (ACL) injury caused by a twisting force to the knee joint. (From R. D. W. M. Whelan, 1976.)

**Figure 6.20** Ratio of patellar tendon force ($F_p$) to quadriceps tendon force ($F_q$) as a function of flexion angle.

Adapted from Hayes, Stone, & Shviv 1984.

**Figure 6.21** Patellofemoral contact areas as a function of change in degree of knee flexion. As the knee is flexed from full extension ($0^\circ$) through $90^\circ$, the contact area migrates from the inferior patellar surface to the superior region. At $135^\circ$ of flexion, the contact area is on both the superolateral surface and the medial odd facet.

From "Biomechanics of the patellofemoral joint" by D.S. Hungerford & M. Barry, 1979, *Clinical Orthopaedics and Related Research*, 144 (Fig. 2, p. 1). Copyright 1979 by Lippincott-Raven. Adapted by permission.
Posterior Cruciate Ligament Injury

Joint Flexibility - Range of Motion

- Properties of soft connective tissues (collagen and elastin) are crucial.
- Extensibility of muscles
- Elasticity of the articular capsules & fluidity of discs
- Extensibility of the longitudinal ligaments
- Anatomical architecture of the articulations
- Resistance of the surrounding tissues.
- Collagen shortens in the absence of tension but shows plasticity. Everyday movement keeps ROM acceptable, but specialized stretching routines also help.