UNIT 3 - TENDONS & LIGAMENTS

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SUMMARY

SAQ ANSWERS

END OF UNIT EXERCISE
UNIT 3 - TENDONS & LIGAMENTS

OBJECTIVES

On completing your study of this unit you should be able to:

1. Discuss the functional requirements of tendons and ligaments.
2. Describe the material composition and structural organisation of tendons and ligaments.
3. Explain the effect of elastin content on the tensile behaviour of ligaments.
4. Describe the outer structure of tendons and ligaments.
5. Describe the structure of bone insertion sites.
6. Name the three regions of the characteristic tensile stress-strain curve of tendon and ligament tissue.
7. Explain the characteristic shape of a tensile stress-strain curve of tendon and ligament tissue.
8. Write down the typical ranges of values for the ultimate tensile strength, ultimate tensile strain and Young's modulus.
9. Describe the viscoelastic behaviour of tendons and ligaments.
10. Define the term “strain rate sensitivity”.
11. Discuss the normal operating conditions of tendons and ligaments and the injury mechanisms that occur if they are exceeded.
12. Define the term “avulsion”.
13. Discuss the importance of strain-rate sensitivity on the type of failure.
14. List the changes that occur to the structural and mechanical properties of tendons and ligaments with increased mechanical stress.
15. List the changes that occur to the structural and mechanical properties of tendons and ligaments with decreased mechanical stress.
16. Explain how the changes to ligaments after a period of immobility lead to increased joint stiffness.
17. Discuss the rate of recovery of ligament tissue and ligament-bone insertion sites after a period of immobility.
18. Describe the influence of age-related changes on the structural and mechanical properties of tendons and ligaments.
UNIT 3 - TENDONS & LIGAMENTS

1. INTRODUCTION

Tendons and ligaments are soft connective tissues. Generally, tendons connect muscles to bones, and ligaments connect bones to bones. For example, in the knee joint the patellar tendon (also known as the quadriceps tendon) connects the quadriceps muscles to the patella, and the patellar ligament, which is an extension of the patellar tendon, connects the patella to the tibia (Figure 1).

Functionally, tendons transmit tensile loads from muscle to bone. Tendons also allow muscles to be positioned away from their point of action so that bulky muscle bodies do not obstruct movements. For example, many of the muscles that act to move the digits of the hand are located in the forearm. Functionally, ligaments play a significant role in stabilising joints, guiding joint motion and preventing excessive motion. Despite their different functions, both tendons and ligaments must be capable of withstand high tensile forces and for this reason they both have similar tissue structures and composition (see Section 2). For example, during walking, the forces in the patellar tendon and ligament can be as high as 2500 N which is equivalent to nearly four times body weight.

Tendons and ligaments and their bone insertion sites are particularly prone to injuries caused by large tensile loads. Many of these injuries occur during sporting activities. Tendons, and muscles, may be ruptured by a sudden violent contraction. The commonest tendon rupture is that of the Achilles tendon which is often caused by a sudden forward lunge. Treatment requires the two ends to be held together and a long period of immobilisation followed by physical therapy all of which can take as long as four months. Similarly, ligaments may be injured when joints are physically wrenched, resulting in a sprain (a partial tear), a partial rupture (a partial tear but with loss of joint stability) or complete rupture (Figure 2). These injuries also require extended periods of treatment before the original condition is restored and recurrence is common. Injuries to bone insertion sites are also common and require long periods of treatment. The most common example is tennis elbow in which a tear occurs in the insertion of the common extensor tendon on the lateral condyle of the humerus. The prevention and optimum treatment of all of these injuries requires an understanding of the mechanical function and properties of tendons and ligaments, and particularly their capacity for remodelling and self-repair.

![Diagram of knee joint showing patellar tendon and ligament](image-url)
2. COMPOSITION AND STRUCTURE

Tendons and ligaments are dense fibrous connective tissues known as parallel-fibred collagenous tissues. They are composed of cells, called fibroblasts, which are embedded in an extracellular matrix. The sparsely distributed fibroblasts occupy around 20% of the total tissue volume but account for only around 5% of the wet weight. They are elongated along the direction of the collagen fibres (see Section 1.1 below). The extracellular matrix is composed of water and solids, which account for around 70% and 30% of the wet weight of the matrix respectively. The solid part of the extracellular matrix is composed largely of collagen. The exact proportion of collagen varies, being generally greater in tendons than in ligaments, but is at least 75% of the dry weight. The remainder of the solid part of the matrix is made up of ground substance and a small amount of elastin (see Sections 2.2 and 2.3).

2.1 Collagen

The long, thin collagen molecules are bonded into long chains by cross-links to form strong, fine collagen fibrils. The fibrils themselves are organised into collagen fibres. These fibres range from 1 to 20 μm in diameter and can be several centimetres long (Figure 3). The fibres are bound together into bundles, called fascicles. The fibroblasts are aligned in rows between the fascicles and elongated along the direction of the collagen fibres (Figure 4). The fascicles are grouped together to form the gross tendon or ligament.

SAQ 1
(a) Do tendons connect muscles to bone, or bone to bone?
(b) What type of forces must tendons and ligaments withstand?
The arrangement of the collagen fibres reflects the loading conditions. For this reason the arrangement differs slightly in tendons and ligaments. In tendons, the collagen fibres are arranged completely in parallel (Figure 4A) as they need to withstand large loads in one direction only. In ligaments, the collagen fibres are not arranged completely in parallel (Figure 4B) and in some ligaments, such as the cruciate ligaments in the knee, the fibres are branched and interwoven. This is because, although ligaments need to withstand large loads mainly in one direction, they also need to withstand smaller loads in other directions. When unloaded the collagen fibres in both tendons and ligaments are “crimped” (Figure 3). This arrangement allows tendons and ligaments to be initially stretched without much resistance (see Section 3.1).

**2.2 Ground Substance**

The ground substance accounts for only 1% of the dry weight of tendon and ligament tissue. Nevertheless, it is important to their functioning. It acts as a cement-like filling between the long, thin collagen molecules that form the collagen fibrils and so helps to stabilise the collagenous “skeleton” of tendons and ligaments. It also provides the lubrication and spacing that enables the collagen fibrils to slide. Furthermore, it contains proteoglycan molecules which bind most the extracellular water.

**2.3 Elastin**

Elastin is a protein that forms thin strands of highly elastic fibres which can be likened to rubber. Although it is scarcely present in most tendons and extremity ligaments, in some ligaments the proportion of elastin fibres is substantial. For example, the ligament that binds the neural arches of adjacent vertebrae together, ligamentum flavum, contains around twice as many elastin fibres as collagen fibres (Figure 5). In neutral position the ligament is under slight tension so that it contracts during extension of the spine and extends during flexion. It is the elastin content that allows the ligament to act in this manner, like an elastic band, providing stability whilst still allowing a wide range of motion.
2.4 Outer Structure

Tendons and ligament have a similar outer structure but there are important differences arising from their different functions. Both are surrounded by a loose (areolar) connective tissue which binds together the bundles of collagen fibres. In tendons, the surrounding connective tissue is more structured than in ligaments and has its own specific name, paratenon. The paratenon forms a protective sheath that enhances gliding. In some tendons the sheath runs the whole length of the tendon whilst in others it only covers the tendon where it wraps around a joint. In some tendons a parietal synovial layer, called the epitelenon, is found beneath the paratenon. The epitelenon contains synovial cells that produce synovial fluid which facilitates the gliding of the collagen fibre bundles. The extra lubrication provided by the epitelenon is only required in tendons subjected to particularly high friction forces, such as those in the hand and wrist. Other tendons are surrounded by the paratenon only.

2.5 Insertion into Bone

The insertion sites of tendons and ligaments into bone are similar in structure. Near to the insertion point, the collagen fibres become intermeshed with fibrocartilage which gradually changes to mineralised fibrocartilage and merges into cortical bone. This change alters the mechanical properties of the tissue; with the tissue becoming gradually stiffer as it inserts into the stiffer bone tissue.

3. BASIC MECHANICAL BEHAVIOUR

Tendons and ligaments are required to withstand large tensile forces. In addition, they must be flexible enough to wrap around anatomical structures and allow joints to move freely. In fulfilling these requirements their tensile and viscoelastic behaviours are of particular interest. In vivo, the actual mechanical behaviour and properties of a particular tendon or ligament will depend on its composition and structure, which will be optimised to the tendon’s or ligament’s own particular loading requirements. In this section, we will examine the basic mechanical behaviour of tendon and ligament tissue in general, whilst in the following section, the behaviour of tendons and ligaments in vivo will be examined.

3.1 Tensile Behaviour

Tendons and ligaments are predominately loaded in a tensile manner and so their tensile mechanical properties are particularly important.

When specimens of tendon or ligament are strained under a constant strain rate, the tensile stress-strain behaviour is non-linear as shown in Figure 6. The characteristic shape is produced by the increase in the number of collagen fibrils resisting the strain as the slack fibrils are straightened and stretched, reducing the crimp pattern. As some collagen fibrils are stressed beyond their ultimate strength they break, increasing the

SAQ 2
(a) What are tendon and ligament cells called?
(b) What percentage of dry weight does collagen account for?
(c) How does the arrangement of collagen fibres differ between tendons and ligaments?
(d) What functions does the ground substance perform?

SAQ 3
(a) What is the loose connective tissue which binds together the bundles of collagen fibres in a tendon called?
(b) What type of cartilage is present at bone insertion sites?
stress on the remaining intact fibrils eventually leading to complete failure. The curve can be divided into three regions:

- toe region
- linear region
- failure region

In the first region, the toe region, the curve is concave with an increasing slope. This is produced by gradual recruitment of collagen fibres as they become straightened and begin to resist the tensile load.

In the second region, the linear region, all the collagen fibres are resisting the tensile load and so the slope is more or less constant as is the case with any homogenous material (for example a steel wire).

In the third region, the failure region, individual collagen fibres rupture as their ultimate tensile strain is exceeded. The fibres that fail first will be those that were less crimped, whilst those that fail last will be those that were the initially crimped and so were recruited last.

Values for the basic tensile properties of tendons and ligaments vary widely according to the particular composition and structure of the specimens measured and the testing protocols used. Ranges of values for ultimate tensile strength and strain and Young’s modulus are given in Table 1. Of these values the ultimate tensile strain is most notably different between tendons and ligaments. This may be explained by the higher proportion of collagen and lower proportion of elastin in tendons and the more uniform arrangement of collagen fibres.

<table>
<thead>
<tr>
<th></th>
<th>Tendon</th>
<th>Ligament</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultimate tensile strength</td>
<td>up to 80 MPa</td>
<td>up to 100 MPa</td>
</tr>
<tr>
<td>Ultimate tensile strain</td>
<td>up to 10%</td>
<td>15 to 45%</td>
</tr>
<tr>
<td>Young’s modulus</td>
<td>50 to 450 MPa</td>
<td></td>
</tr>
</tbody>
</table>

Although the curve shown in Figure 6 and the values given in Table 1 are typical for most tendons and ligaments, some non-extremity ligaments have a high proportion of elastin, such as ligamentum flavum, which alters their tensile behaviour. Ligaments with a high proportion of elastin can be stretched much further, to a strain of more than 50%, before there is any appreciable rise in stiffness (Figure 7). However, beyond this the stiffness increases rapidly and the ligament fails abruptly with a strain of up to 70%.
3.2 Viscoelastic Behaviour

Both tendons and ligaments exhibit viscoelastic behaviour, undergoing creep when subjected to a constant stress and stress relaxation when subjected to a constant strain. The most important viscoelastic property, however, is strain rate sensitivity. This is the dependence of the stress-strain behaviour on the rate of increase of the applied strain. With increasing strain rate the tendon or ligament becomes progressively stiffer so that the slope of the stress-strain curve increases (Figure 8). The tendon and ligament also becomes stronger, with a higher ultimate strength and strain. This phenomenon is particularly important in ligaments and will be discussed further in the section on injury mechanisms (Section 4.3).

SAQ 4
(a) Name the three regions of a typical tensile stress-strain curve for tendons and ligaments.
(b) Do tendons or ligaments have the greatest tensile strain?
(c) What is strain rate sensitivity?
4. BEHAVIOUR IN VIVO

In the previous section we considered the basic mechanical behaviour of tendon and ligament tissue as materials, rather than as structures. However, clinically the most interesting mechanical behaviour of tendons and ligaments are those that are observed in vivo (with the tendon or ligament still in position).

4.1 Normal Physiological Loads

During everyday activities, tendons and ligaments are not subjected normally to loads that will cause failure. Instead, the normal physiological loads are thought generally to be below a third of the ultimate tensile strength and strain. This means that tendons and ligaments will generally operate in the toe region and lower part of the linear region of the stress-strain curve.

4.2 Injury Mechanisms

Clinically, injury mechanisms are very important. Since the mechanical behaviour of all the different tendons and ligaments in the body can not be covered here, as an illustrative example we will look at the anterior cruciate ligament (ACL) in detail.

The anterior cruciate ligament, so named to reflect its anterior insertion into the tibia, lies within the capsule of the knee joint, and functions as a major stabiliser of knee motion. When a specimen is tested in vivo, as shown in Figure 9, by the application of a tensile load it is found the anterior cruciate ligament may be elongated by around 7 mm before it fails completely.

A typical load-elongation curve produced using this test, with the joint displacement (the gap between the articular surfaces) along the horizontal axis and the applied tensile load along the vertical axis, is shown in Figure 10. In this case the amount of force required to break the ligament is around 1000 N (which is roughly equivalent to between one and a quarter and one and a half times body weight). The curve has the same characteristic regions as noted in the previous section, with a concave toe region (up to around 2 mm), a linear region (up to around 4.5 mm) and a failure region.

The amount of elongation produced using this type of tensile test can be equated to injuries of the ACL that are reported clinically. Up to an elongation of around 4 mm, the
ligament is still within the linear region and it remains undamaged. Beyond around 4 mm, collagen fibres are progressively ruptured resulting in progressively more pain and joint instability. Finally, at around 7 mm, the ACL ruptures completely. The inability of the ACL to heal once torn, and its important role as a joint stabiliser means that any ACL injuries can have serious long-term consequences for the whole knee joint.

**FIGURE 10. TENSILE FORCE-DISPLACEMENT CURVE FOR ANTERIOR CRUCIATE LIGAMENT.**

**4.3 Avulsion**

Clinically, tendons and ligaments do not only fail by tearing, but often fail at their bone insertion sites. This type of failure is termed avulsion. One of the factors that determine which type of failure occurs is the **strain rate**. As with tendon and ligament, the stiffness of bone increases with increasing strain - bone is strain rate sensitive. However, bone is more sensitive to strain rate than tendons or ligaments, so that its stiffness increases more proportionally. The consequence of this is that avulsion is more common at slow strain rates and tendon and ligament tearing is more common at higher strain rates. This relationship is illustrated in Figure 11 which shows how the percentage of injuries changes with strain rate. During slow strain rates, avulsion is common, whilst, as the strain rate increases, the bone becomes stronger than the tendon or ligament and so tearing becomes more common.

**FIGURE 11. DEPENDENCE OF TYPE OF FAILURE ON STRAIN RATE.**
5. REMODELLING

Tendons and ligaments, like bone, are capable of remodelling themselves in response to changes in the mechanical demand placed upon them. Generally, they become stronger and stiffer when subjected to increased stress, and weaker and less stiff when the stress is decreased.

The effect of increased stress, resulting from increased physical activity, on tendons and ligaments is to:

- increase the mass
- increase collagen fibre diameter
- increase cross-sectional area
- increase strength and stiffness
- strengthen their bone insertion sites.

These changes may be as much as 20%.

The effects of stress deprivation, resulting from bed rest or joint immobilisation, is particularly profound in ligaments. It:

- decreases the tensile strength and stiffness
- reduces the strength of the ligament-bone junction.

These reductions may be as much as 50% after several weeks of immobilisation. This is thought to be due to changes in the structural organisation of the collagen fibres and molecules, with increased randomisation of collagen fibre orientation and reduction in the number of cross-links between collagen molecules.

The biomechanical changes to a ligament after stress deprivation are often accompanied by contraction (shortening) of the ligament which noticeably increases joint stiffness. The observed joint stiffness does not contradict the reduction in stiffness of the ligament itself. This is because the contracture of the ligament means that for any given joint position the ligament will be under a greater strain and will be functioning on a stiffer portion of its stress-strain curve.

Consider the case whereby a ligament of length 20 mm contracts due to stress deprivation to 19 mm and undergoes a loss of 25% in its other mechanical properties. Thus it undergoes a 5% reduction in length. If, at a certain joint position, the ligament must elongate to 20.5 mm in length, then its strain at this point can be calculated using the following equation:

\[ \text{strain} = \frac{\text{change in length}}{\text{original length}} \]

Thus, for the ligament with a length of 20 mm, it must elongate by 0.5 mm to achieve a length of 20.5 mm:

\[ \varepsilon_{20} = \frac{0.5}{20} = 0.025 = 2.5\% \]

SAQ 5

(a) By referring to Table 1, estimate the maximum levels of normal physiological stress and strain.

(b) Approximately how far can the anterior cruciate ligament be elongated before rupturing completely?

(c) Is bone tissue more or less sensitive to strain rate than tendon or ligament tissue?
And for the contracted ligament with a length of 19 mm which must elongated by 1.5 mm:

\[ \varepsilon_{19} = \frac{0.5}{19} = 0.079 = 7.9\% \]

Thus, in this case, the contracted ligament has a strain more than three times that of the normal ligament so that it is operating on a much stiffer part of its stress-strain curve. This is illustrated below in Figure 12 which shows how the tangent to the stress-strain curve at the operating point is greater for the contracted ligament than for the normal ligament despite the general loss of stiffness.

The overall effects of exercise and immobility on ligaments are illustrated in Figure 13. The curves show how after a period of exercise comparatively small gains are achieved in the structural and mechanical properties whilst a short period of immobilisation produces a large rapid decrease. The decreases in the structural and mechanical properties of the ligament can be regained in approximately the same period of time over which they were originally lost. However, the ligament-bone insertion sites requires many times longer to recover.
6. AGE-RELATED CHANGES

With maturation and ageing, the structure and quantity of collagen changes. These changes have important implications for the mechanical properties of tendons and ligaments. During maturation, the number and strength of the cross-links between collagen molecules increases, increasing the diameter of the collagen fibrils and the tensile strength of the tendon and ligament. With ageing, the collagen content decreases, producing a corresponding decrease in the stiffness, strength and ultimate strain of the tendon and ligament. These changes can be as much as 20%.

Age is also thought to be a very important factor in determining the type of ligament failure. In the young the ligament-bone junction is comparatively weak resulting in a greater likelihood of avulsion. With maturity the strength of the ligament-bone junction increases more rapidly than that of the ligament tissue so that the strength of the ligament-bone junction exceeds the ligament tissue resulting in a greater likelihood of tearing.

SAQ 6
(a) Using Figure 12 estimate how many times greater the stress is in the contracted ligament compared to the normal ligament when both are elongated to 20.5 mm.
(b) After a period of immobilisation, does the ligament tissue or its insertion sites recover quickest?

SAQ 7
(a) How does the diameter of collagen fibres change with maturation?
(b) How does the collagen content of tendons and ligaments change with ageing?
SUMMARY

In this unit you have been introduced to the tissue mechanics of tendons and ligaments. You have discovered how they are uniquely adapted to carry large tensile loads whilst still allowing free movement of joints.

The structural and mechanical properties and behaviour of tendons and ligaments are very similar, nevertheless, there are important differences:

- Tendons generally have a higher collagen content and lower elastin content than ligaments so that they are generally stiffer.
- Ligaments may also carry non-tensile forces and so have a more branched and interwoven arrangement of collagen fibres.
- Some non-extremity ligaments have a much higher elastin content which allows them to strain to a much greater extent.

Other important points to note about tendons and ligaments are:

- Some non-extremity ligaments have a much higher elastin content which allows them to strain to a much greater extent.
- They remodel according to the mechanical demands placed upon them.
- The rate of recovery of the ligament-bone insertion site is many times longer than that of the ligament tissue.
- Strain-rate and age are important factors in determining the type of failure.
SAQ 1

(a) Tendons connect **muscles to bone**.
(b) Tendons and ligaments must withstand **very high tensile forces**.

SAQ 2

(a) Tendon and ligament cells are called **fibroblasts**.
(b) Collagen accounts for at least **75%** of the dry weight.
(c) Collagen fibres are arranged completely in parallel in tendons whilst in ligaments they are partially branched and interwoven.
(d) The ground substance functions to stabilise the collagenous structure and provides lubrication and spacing for the sliding of collagen fibrils.

SAQ 3

(a) In tendons, the loose connective tissue that binds together the bundles of collagen fibres is called **paratenon**.
(b) Fibrocartilage is present at bone insertion sites.

SAQ 4

(a) The three regions of a typical tensile stress-strain curve for tendons and ligaments are the **toe region**, **linear region**, and **failure region**.
(b) Ligaments have a greater ultimate tensile strain than tendons.
(c) Strain rate sensitivity is the sensitivity of mechanical properties to the rate of application of strain.

SAQ 5

(a) The maximum levels of normal physiological stress and strain will be up to around **27 MPa** and **3%** in tendons, and **33 MPa** and **5%** to **15%** in ligaments.
(b) The anterior cruciate can be elongated by approximately **7 mm** before rupturing completely.
(c) Bone tissue is **more** strain rate sensitive than tendon or ligament tissue.

SAQ 6

(a) The stress in the contracted ligament is **11** times greater than that in the normal ligament when both are elongated to **20.5 mm**. From diagram, **33 mm divided by 3 mm equals 11**.
(b) After a period of immobilisation, the ligament tissue recovers quicker than its insertion sites.

**SAQ 7**

(a) The diameter of collagen fibres increases with maturation.

(b) The collagen content of tendons and ligaments decreases with ageing.
END OF UNIT EXERCISE

1. Describe the structural hierarchy of tendons and ligaments using a diagram to illustrate your answer. [8 marks]

2. Construct a table of the dry and wet weight composition of tendons and ligaments. [12 marks]

3. Explain how the elastin content alters the mechanical behaviour of ligaments. [5 marks]

4. Sketch the characteristic tensile stress-strain curve of tendons and ligaments, labelling the three regions and describe the state of the collagen fibres in each region. [8 marks]

5. (a) Explain the difference between the failure of tendon or ligament tissue by tearing and avulsion.
(b) Explain how the type of failure is dependent on strain rate and sketch a diagram showing how the percentage of injuries of each type alters with strain rate.
(c) What other factor affects the type of failure? [12 marks]

6. (a) List five changes in the structural and mechanical properties of tendons and ligaments that occur as a result of increased mechanical stress, and state up to what percentage their values may change.
(b) List two changes in the structural and mechanical properties of ligaments that occur as a result of decreased mechanical stress, and state up to what percentage their values may change. [5 marks]

Total = 50