Biomechanics Exam 2010/2011

Students need to answer three of the four questions.
Note: students are allowed to browse lecture notes and books during the exam.

Question 1
Many people suffering from arthritis in one of the hip joints use a walking stick to reduce the load in the affected joint. Often they are not certain in which hand they should hold the stick to unload the affected joint.

a. (30) Draw two free body diagrams that allow you to calculate the load on the affected hip joint during one-legged stance, one with the stick on the same side as the standing leg and one with the stick at the opposite side of the standing leg.

b. (25) Formulate the equations that allow you to calculate the load on the hip joint in both cases.

c. (25) Calculate the joint force in both cases, assuming a force through the stick equal to 20% of the body weight. In which hand should the stick be held during walking to minimise the load on the affected joint?

d. (20) In which hand should the stick be held during two-legged stance to minimise the load on the affected joint? Explain your answer, but you do not need to re-calculate the joint force.

For the calculations, assume the person weighs 75 kg and is 1.75 m tall and the weight of the stick is negligible. Use the table below to find further weights and dimensions.

<table>
<thead>
<tr>
<th>Joint</th>
<th>From joint centre to</th>
<th>Typical distance (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hip</td>
<td>M. abductor</td>
<td>5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Segment</th>
<th>Weight (% total body mass)</th>
<th>Length (% total body length)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower extremity</td>
<td>15.7</td>
<td>46.5</td>
</tr>
</tbody>
</table>

Question 2
Articular joints need to operate with little friction, and therefore need lubrication. The exact lubrication mechanism has proved difficult to find. One idea is that hydrodynamic lubrication may be important.

a. (25) Explain what hydrodynamic lubrication is.

b. (30) Assuming a constant joint configuration, describe which factors govern the thickness of the fluid film and the coefficient of friction. Show this in a graph.

c. (20) Synovial fluid from arthritic joints is less viscous and less thixotropic (shear-thinning) than that from healthy joints. Using the graph you made in 2.b, explain the effects of these two changes on friction and film thickness.

d. (15) Two other lubrication mechanisms proposed for cartilage are ‘boosted lubrication’ and ‘weeping lubrication’. Discuss the principles of these mechanisms and how they seem to disagree.
e. (10) How could the two mechanisms in 2.d be reconciled with each other?

**Question 3**

In an experiment to investigate mechanical factors determining bone ingrowth into porous coatings, Qin et al. (1996) used an experimental situation shown in Fig. 4a, and found an ingrowth pattern as found in Fig. 4b.

a. (20). Assume the drill hole has no implant. For that case, make a drawing which shows (i) the original round shape of the drill hole and (ii) the deformed shape of the drill hole after the compressive load has been applied to the bone. Place the two shapes in the same drawing, with the centres overlapping, so it is clear how the load affects the shape.

b. (30) The implant is very stiff relative to the bone and you may assume it does not deform when the bone is loaded. Using your drawing in Question 3.a of the deformed shape, make a drawing that shows the expected pattern of stresses around the circumference of the pin upon loading. You don’t need to give magnitudes, but your drawing should show where stresses are large or small, and tensile, zero or compressive.

c. (30) Use the stress pattern to explain the bone ingrowth pattern shown in Fig. 4b.

d. (20) Theorise how osteocytes might be able to perceive the differences in local loading environments that you have drawn.

**Question 4**

a. (20) Hill’s equation is often used to study the force-velocity relation of skeletal muscle. Sketch a curve showing Hill’s equation, and explain characteristic points.

b. (20) In your sketch in 4.a, add a curve that shows the mechanical power produced by the muscle. Explain the shape of this mechanical power curve.

c. (20) Long-distance runners and sprinters will have different muscle characteristics. What differences do you expect in the relation between force and velocity?

d. (20) Hypothesize at which region on the force-velocity curve the muscle will predominantly act for the two types of runner.

e. (20) If you compare the force-length relationships of skeletal and heart muscle, in what important way do they differ? Explain the reason for this difference.
Model Answers Biomechanics Exam 2010/2011

Question 1

a. See graph

b. Sum of forces in x-direction: \( F_{jx} - F_m \sin \alpha = 0 \) 
   Sum of forces in y-direction: \( F_{jy} - F_m \cos \alpha + F_s - F_g = 0 \) 
   Sum of moments: \( F_m \cdot m - F_g \cdot g - F_s \cdot s_{\text{same}} = 0 \) 
   \( F_m \cdot m - F_g \cdot g + F_s \cdot s_{\text{opp}} = 0 \) (same hand, 3a) 
   (opposite hand, 3b)

c. (1) \( \rightarrow F_{jx} = F_m \sin \alpha \) 
   (2) \( \rightarrow F_{jy} = F_g + F_m \cos \alpha - F_s \) 
   (3a) \( \rightarrow F_m = (F_g \cdot g + F_s \cdot s_{\text{same}}) / m \) 
   (3b) \( \rightarrow F_m = (F_g \cdot g - F_s \cdot s_{\text{opp}}) / m \) 
   If on same side: 
   (1+3a) \( \rightarrow F_{jx} = 1/m \cdot (F_g \cdot g + F_s \cdot s_{\text{same}}) \cdot \sin \alpha \)
   (2+3a) \( \rightarrow F_{jy} = 1/m \cdot (F_g \cdot g + F_s \cdot s_{\text{same}}) \cdot \cos \alpha + F_g - F_s \)
   If on opposite side: 
   (1+3b) \( \rightarrow F_{jx} = 1/m \cdot (F_g \cdot g - F_s \cdot s_{\text{opp}}) \cdot \sin \alpha \)
   (2+3b) \( \rightarrow F_{jy} = 1/m \cdot (F_g \cdot g - F_s \cdot s_{\text{opp}}) \cdot \cos \alpha + F_g - F_s \)
   Although we could take the calculations a step further to work out \( F_s \), it is now easy to see that holding the cane in the hand opposite to the affected leg is the best strategy. The force from the stick reduces the joint moment arm caused by gravity, and thereby reduces the muscle and thus the joint load. If held in the hand on the same side, it increases the joint moment arm.

d. During two-legged stance, the stick should be held in the same hand because there is no joint moment arm generated by gravity. In principle, one could then even completely unload the affected joint by using the healthy joint and the cane to stand.
Question 2

a. Hydrodynamic lubrication is a mechanism of lubrication where opposing surfaces are fully separated by a fluid film. The separation relies on pressure inside the fluid. The pressure is generated by relative movement between the opposing surfaces which need to be slightly angled to form a wedge into which fluid is dragged. Forcing fluid into the wedge creates the pressure.

![Graph](image)

b. The thickness of the fluid film and the coefficient of friction are governed by the “viscovelocity factor”, which is the product of the viscosity of the lubricating fluid and the relative speed between the surfaces, divided by the applied normal load.

c. If the fluid is less viscous, you move to the left on the graph. The film thickness will reduce and the friction is likely to increase (graph). A fluid is shear thinning if its viscosity reduces with increasing shear rate. This has the effect that friction increases less at high joint velocity. If the fluid is less shear thinning, the viscosity reduces less at high shear rates. Friction is therefore likely to increase at high joint velocity. The effect of less shear thinning on film thickness is unlikely to be large, if any.

d. Boosted lubrication is a lubrication mechanism by which fluid, which resides between opposing joint surfaces, is pressed into the cartilage under the influence of load. Removing fluid from between the surfaces increases the concentration of lubricating proteins, thus locally increasing the viscosity of the joint fluid. Increasing viscosity improves lubrication (see 2.c). Weeping lubrication is a lubrication mechanism by which fluid is pressed from the cartilage into the space between the joint surfaces under the influence of load. The extra fluid is supposed to help lubrication by increasing the distance between the opposing surfaces. The two theories disagree on the effect of load on the direction of fluid flow in the cartilage: boosted lubrication requires load to force fluid into the cartilage and weeping lubrication requires load to force fluid out of the cartilage.

e. The two theories can be unified by taking into account the effect of gliding motion (drawing). Just before the area of contact, fluid is forced out of the cartilage by the pressure at the area of contact (weeping lubrication), and just behind the area of contact fluid is drawn back into the cartilage (boosted lubrication).
Question 3
3a See sketch below

3b See sketch below

Around a stiff implant, there will be higher compressive bone strains at the top and bottom, and probably lower tensile strains left and right.

3c It seems that bone ingrowth occurs predominantly in areas of higher normal strain. The exact amount of tensile and/or compressive strain seems less important.

3d Areas of high normal strain, compressive or tensile, are areas with a relatively small change in shape but a large change in volume. In such areas, generation of fluid flow through the bone due to mechanical loading is highly likely, and the osteocytes could be sensible to this flow. Moreover, osteocytes could directly sense the strain in the bone.
Question 4

The solid curve shows the relation between force and velocity. It is essentially a curve denoting constant power (force*velocity). However, the line shows a point (marked a) where the force is maximal at zero velocity and a point (marked b) where the velocity is maximal at zero force.

4b (see sketch at 4a, curve is dashed line) Power equals force * velocity. Although the force-velocity curve is essentially a constant power line, the power will be zero at the points where this curve touches the x-axis (max velocity, zero force) and the y-axis (max force, zero velocity). Therefore, the curve goes to zero at the ends and rises quickly to a maximum in the middle regions.

4c
Long-distance runners have “slow” muscles, whereas sprinters have “fast” muscles. “Fast” muscles have a higher maximum velocity than “slow” muscles, while giving an equal maximum force. Therefore, the curves for slow (LDR) and fast (S) muscles go through the same point at (zero velocity, maximum force). However, the curve for the fast muscle goes to a higher velocity at zero force than that for the slow muscles.
4d (regions shown in sketch at 4c)
The slow muscles of long-distance runners will operate in the middle region of the curve, hence where the power is maximal. The fast muscles of sprinters will act on the right side of the curve to obtain maximum velocity. However, because the muscle is relatively weak in that region, sprinters need to have large bulky muscles to obtain enough power.

4e
The force-length curve of skeletal muscle (SM) shows zero force at small length, a clear maximum at intermediate length, and a drop to zero at maximum length. Heart muscle (HM) shows a steadily increasing force at increasing length. This steady increase in force with increasing length is very important for the heart to make sure that it can always pump out the blood. If the force would drop with increasing length, the heart muscle might be unable to pump out the blood.