BIOLOGICAL FRAMEWORKS FOR ENGINEERS

Laboratory Experience #3 [Skeletal Muscle Biomechanics]

General Objectives:
- ✓ Examine the maximum voluntary contraction of the biceps throughout its physiologic range of muscle lengths and arm positions.
- ✓ Study inverse relationship between load and velocity in muscle.

Central Framework:
- ✓ Muscle strength is dictated by the length-tension and velocity-tension relationships at the sarcomere level and the biomechanics at musculoskeletal system level.

Background:

Skeletal muscle is a very organized tissue. The entire muscle is composed of individual muscle fibers, which are made up of smaller units called myofibrils. Actin and myosin filaments, the components responsible for muscle contraction, make up the myofibrils. Each myofibril is made up of ~1,500 myosin filaments and 3,000 actin filaments. The organization of actin and myosin filaments forms a banded pattern that can be seen under a microscope. Actin and myosin are polymerized proteins; their interaction produces muscle contraction through a ratcheting mechanism.

There are two main determinants of muscle strength. The first is the length-tension relationship that is based on the interaction of the microscopic actin and myosin fibers. The biomechanics of the musculoskeletal system is the second component. The length-tension curve of a muscle fiber demonstrates that each muscle fiber has an optimal length generating maximal force. However, this length does not correspond to the most advantageous position according to the biomechanics of our muscles, bones, and joints. The following experiment will examine how these two factors affect our movements and strength.

Maximum force is generated when the maximum number of cross bridges between actin and myosin are formed. The cross-bridge formation corresponds with the length-tension curve of a single muscle fiber in Fig. 1, where the peak represents the length at which the greatest tension is produced. This graph represents the muscle fiber only *ex vivo* (out of the body). The muscle within the body is limited by surrounding bone and connective tissue.

Figure 1. *Length-Tension curve of a muscle fiber. Note that maximum tension occurs at a length which corresponds to the greatest number of cross bridges formed between actin and myosin filaments.*
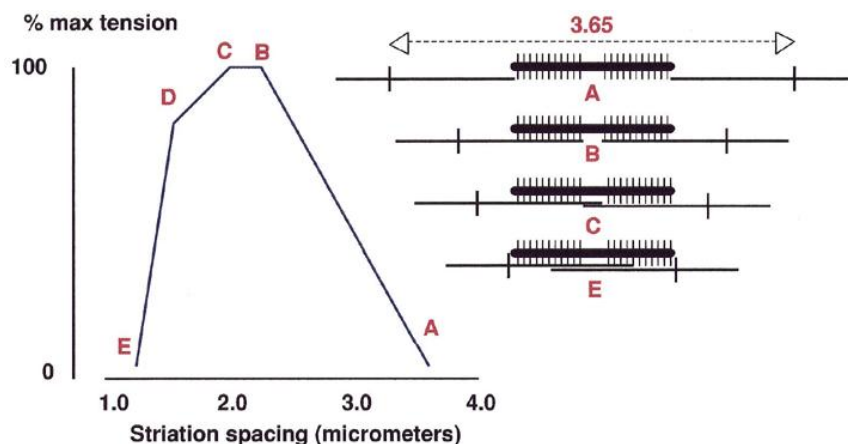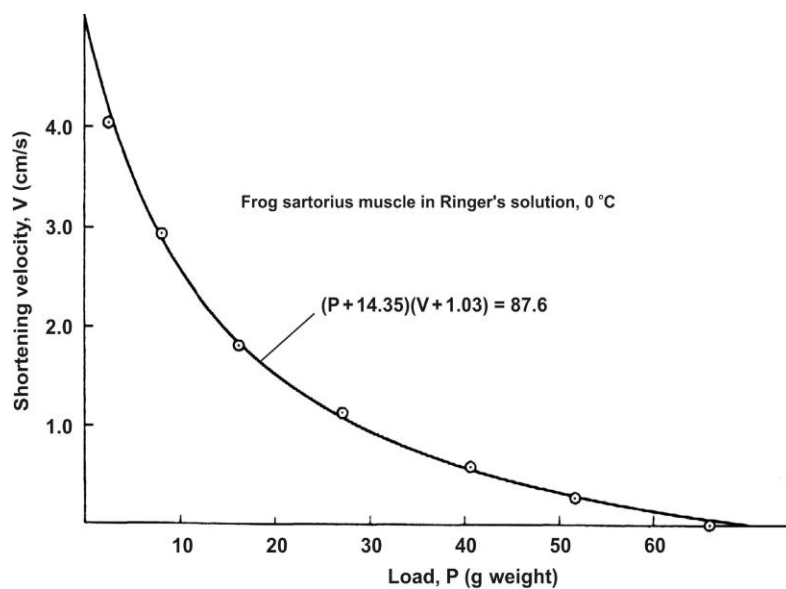
Suppose that we isolate a muscle and want to characterize its behavior. There are two basic types of tests that can be performed on it – isometric and isotonic. In an isometric test, the muscle is held at a constant length and the force generated by the muscle during contraction is recorded. In an isotonic test, a known tension is applied to the muscle and its length is recorded.

Suppose that a muscle is stimulated to contract while being held in an isometric state and then suddenly released to isotonic shortening. The velocity of the contraction V can be measured for different loads placed on the muscle, P. For some large load P_0, the muscle will be unable to move the load and the contraction force will be zero. On the other extreme, the muscle will contract faster for small loads and will have its maximum velocity when no load it applied. This leads to the load-velocity relationship in Fig. 2. A.V. Hill (1938) showed that this relationship could be described by the equation

$$(a + P)(b+ V) = b(P_0 + a)$$ (Eq.1)

where a, b, and P_0 are constants, with P_0 equal to the applied load when V is zero. This relation, known as Hill's equation, is found to describe nearly all muscle thus far examined, include cardiac and smooth muscle as well as skeletal muscle. It is a matter of common experience that muscles shorten more rapidly against light loads than they do against heavy ones – a person can snatch a barbell from the floor and lift it rapidly over his or her head, but does this action slower if the weight is added and finally there is one weight that she cannot move. This observation is partially explained by inertia of the weight, but the main cause is that active shortening of muscles produces less force than those that are contracted isometrically.

Frog sartorius muscle in Ringer's solution, 0 °C

$(P + 14.35)(V + 1.03) = 87.6$

Figure 2. *Force-Velocity relationship for muscle under different loading. Data are obtained from frog sartorius muscle and the solid line is a plot of Eq. 1 with load P expressed in grams and V in cm/s.*

Skeletal muscle is always attached to bone, and forces developed during musclar contraction are usually transmitted to the "outside world" via the bone. Basic Newtonian physics can be used to analyze the mechanics of a bone joint (along with simplifications). The biomechanics of the biceps brachii muscle can be found using a free body diagram for the forearm (Fig 3.) and computing the moments from the about the point of rotation of the elbow joint (Note: $\otimes$ = cross-product).

$$M \; = \; (P \otimes L) \; + \; (BF \otimes Lb)$$ (Eq.2)

The effective force in the biceps (BF) can be found by simplifying the moment equilibrium (Eq. 2). First, we assume that there is no internal friction at the elbow (M = 0). Second, we assume that as the arm is bent into flexion or extension, the bicep force BF at the insertion remains parallel to the upper arm.
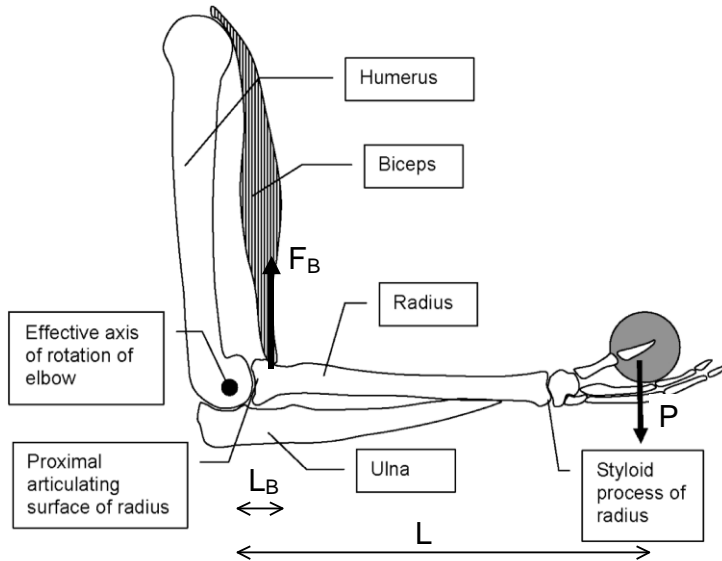
Figure 3. *Bones of the upper and lower arm as seen from the lateral side. A load P is supported by the biceps force (F_B). This figure demonstrates the joint mechanics of the elbow as it relates to the tendon insertion point (L_B) and the length of the forearm and hand (L). The attachment point of the biceps on the radius is approximately 2.54-cm in females and 3.60-cm in males from the elbow joint.*

It is easy to see from the moment of force equation that it is an advantage to have a muscle insertion farther from its associated joint. Muscle force may be considered a resultant force that can be decomposed into two constituent forces, rotary and joint compressive. The size of each component depends on the angle at which the force is applied. If the force is perpendicular to the segment being moved, the segment moves in a rotating direction. If the force is parallel to the segment being moved, the segment moves in a parallel or compressive direction. The basic idea is that as joint angles increase to the point where the muscle-tendon complex is pulling at 90° to its bony lever, there will be a constant change in the proportion or ratio of compressive to rotary forces. That is, the rotary force progressively increases, thus affording more torque (turning force) about the joint axis, whereas (joint) compressive forces decrease, thus decreasing the joints' inertia and tendency to remain stationary. This explains clinically why subjects or patients have difficulty initiating movements. However, once movement starts, further motion becomes easier. The reverse scenario is therefore also true. As the angle of insertion gets smaller the compressive forces increase whereas the rotary forces decrease. There are two extremes here, one practical and one theoretical. If the muscle-tendon complex is at 90° to the lever then there is only rotary force (i.e., no compression exists). The other case is theoretical. If the tendon's line of pull could become parallel with its lever (it cannot because this would mean that the tendon would have to fall inside the boundary of the neutral axis of the bone), then the force would be all compressive with no rotation.

There are both physiological and mechanical advantages involved in muscle contraction and maximum tension generated. The length-tension concept states that the maximum tension generated by the muscle occurs at its resting length when there is the greatest number of cross bridges between myosin and actin. However, there are optimal angles at which the maximum moment of force or torque can be generated throughout a joint range of motion. That is why

the summation of the biomechanics and muscle mechanics is necessary to understand the maximum muscle contraction and joint moment.

In this laboratory, we will have to make a number of assumptions in order to simplify the problem. For example, we are assuming that only one muscle is used to lift the upper arm, but in fact four muscles are working as a group to perform this case – the biceps, the brachialis, the brachioradialis, and the extensor carpi radialis longus (ECRL). Research has shown that the force exerted by muscles cooperating in a single task differs from muscle to muscle and it has been argued that the force distribution is such to minimize the effort. Here, we will stick with our simple assumption of a single muscle and treat the elbow as a basic hinge with reactions forces acting through the center of rotation.

Experimental Procedure:

This experiment will involve three separate phases of investigation on muscle biomechanics. The first phase will involve developing a free body diagram for the biceps strength experiment in an isometric state. Phase two is the measurement of the biceps strength at various angles of arm flexion. The final phase of this experiment examines the force-velocity relationship as the speed of bicep curl is retarded by the amount of load applied. Together, these experimental phases should provide a good picture of muscle mechanics and musculoskeletal biomechanics as separate phenomena.

PHASE I

Draw the free body diagram of the arm for the biceps strength test set up. You will test bicep strength from 135-degrees to 60-degrees of flexion (note: straight arm is 180-degrees). Sum the moments about the joint center of rotation in the elbow and develop an equation that will yield the force in the biceps muscle. LB is approximately 2.54-cm in females and 3.60-cm in males. We will be examining 5 different angles of arm flexion from 135, 120, 90, 75, and 60-degrees.

PHASE II

At the biceps muscle strength apparatus, each individual will perform a maximal contraction of their biceps lifting up on a load cell. Each subject will grip the cable attached to the load cell at the handle like a microphone. This cable will be adjusted to put the subject in different angles of arm flexion. The subject will be instructed to flex only their biceps and try and minimize corruption of the data by using other muscles, i.e legs, shoulders, etc. Each subject will be asked to pull on the cable with a steady maximum force for 3 seconds at each of the angles.
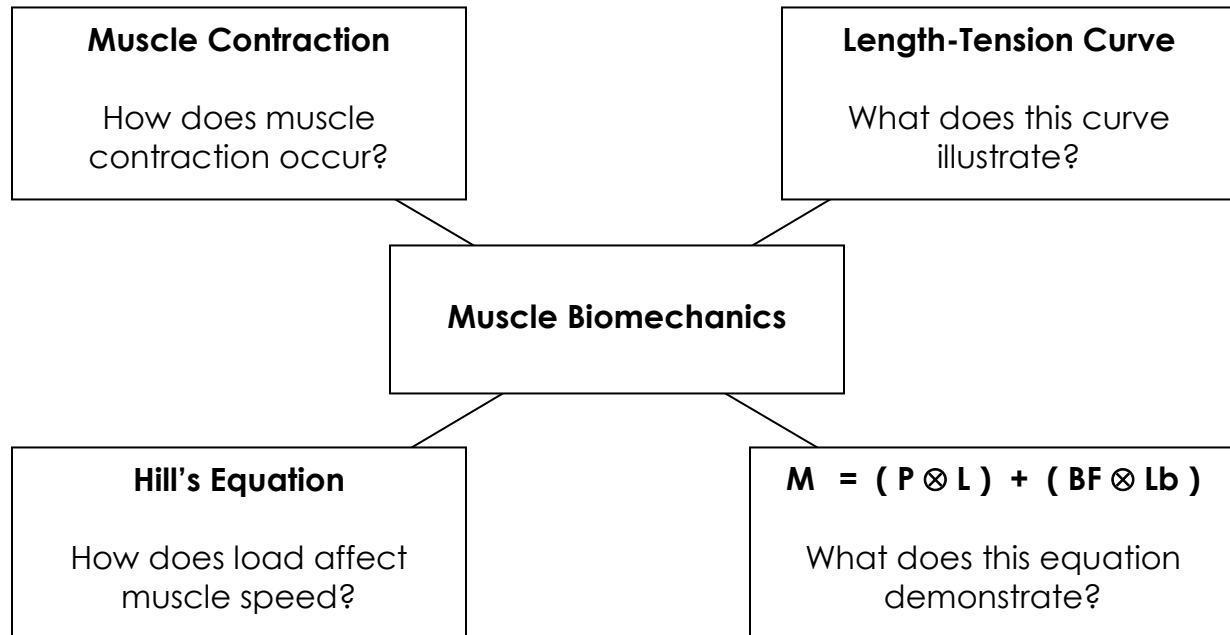
PHASE III

This third phase of experimentation will involve examining the speed of your muscles under different loads. The experiment will involve you standing in front of a digital video camera while lifting weights. One person will operate the computer that is recording from camera. On cue, the individual will be asked to curl the weight and hold it to their shoulder. You will use the video to time the effort to lift the weights.

SUMMATION QUESTIONS

Prepare a short report on the lab exercise and submit it in **one week**. Please do this part individually; do not collaborate.

✓ While answering the questions for this lab experiment, try and synthesize the relationships between the diagram blocks below.

Muscle Contraction	**Length-Tension Curve**
How does muscle contraction occur?	What does this curve illustrate?

Muscle Biomechanics

Hill's Equation	**M = (P ⊗ L) + (BF ⊗ Lb)**
How does load affect muscle speed?	What does this equation demonstrate?

Isotonic Measurements:

✓ Plot load cell reading as a function of arm angle. Describe the pattern.

✓ Compute and plot the force in the biceps and plot it as a function of bicep muscle length. Describe the pattern.

✓ Is the maximum force in the muscle constant throughout the range of lengths (angles) tested? Explain.

Isotonic Measurements:

✓ Plot how much time it took to lift the weight as function of load. Describe the pattern.

✓ Compute and plot muscle contraction velocity as a function of load. You will need to calculate the change of length of the muscle. Describe the pattern and qualitatively compare it with Fig. 2.

✓ <u>BONUS</u>: find values for a, b, and P_0 that fit your data.

Discussions:

✓ Explain what is happening at the sarcomere level and musculoskeletal level for the bicep's maximal contraction as a function of arm angle.

✓ This experiment involved the measurements of isometric and isotonic states. What parameters are different for isometric and isotonic muscle contractions?

✓ What are the salient aspects learn with regard to theory and experimental approach from this laboratory experience?