BIOMECHANICS: LEVERS AND BONE-MUSCLE RELATIONSHIPS

Converting chemical energy in the form of adenosine triphosphate (ATP, $C_{10}H_{16}N_5O_{13}P_3$) into useful work requires the body's muscles to exert some amount of force. These muscles can be skeletal, cardiac or smooth. Skeletal muscles have the highest fiber length of all muscle types. They are striated and can be controlled through conscious effort. They grant mobility and are capable of rapid contraction through reflexes and conscious control. (1)

Skeletal muscles should be able to sustain the effects of the forces exerted during human activities without exceeding the limits of their extensibility and elasticity. The amount of force expended can range from 5 N when picking up 500 mL of water in a plastic bottle to about 5000 N when lifting a 50 kg load. The weight of a material is determined from

$$\text{Weight} = \text{Mass x acceleration due to gravity}$$

Rapid contraction of the muscles can be tiring, and exerting a large amount of force can lead to wear and tear that may be painful for children and adults. As such, it is important for scientists to estimate the forces on muscles from different activities in order to understand fatigue and optimize human performance. In fact, this is a focus of most biophysical studies. In this paper, we will demonstrate how a knowledge of physics can be joined with biology (specifically, human anatomy and physiology) to determine the force exerted by sample bone – muscle interactions. (2 - 4) This paper will discuss fascicle arrangement and leverage, useful physics principles and selected muscle mechanics problems for raised arm, weight lifting and chewing.

The bundles of fibers in the muscles are known as fascicle. Fascicle arrangements produce varying skeletal muscle shapes and functions. Common patterns include circular, convergent, parallel and pennate. Details about the many fascicles arrangements are covered in most standard human anatomy and physiology textbooks. (1-5)

The bone-muscle relationship explaining the operations of most skeletal muscles can be modelled using lever systems. A lever is a simple machine that allows one to overcome a larger load using a small fraction of the effort. The relative positions of the load, effort and fulcrum in the lever is used to classify them as first, second and third class levers. In the first class lever, the fulcrum is between the load and the effort. In the second class lever, the load is between the fulcrum and the effort. In the third class lever, the effort is between the load and the fulcrum. Scissors, wheelbarrow and tweezers are examples of first, second and third class levers respectfully. In the body, the bone acts as the lever and the muscles provide the efforts as we undertake various daily activities. The first class leverage lifts the head off the chest, involving an effort provided by the posterior neck muscles with the atlanto-occipital joint as the fulcrum and the facial skeleton as the load. A person standing on their tiptoes and the flexing of forearms involving the biceps brachi muscle are second class and third class leverage systems respectively. (1,4-6)

During muscle-bone interactions, translational and/or rotational motions are possible. When the system is at equilibrium, the conditions of equilibrium are:

1. Addition of all forces equals zero, $\sum F = 0$, and also
2. Addition of all torques equals zero, $\sum \tau = 0$.

Torque is the turning effect of a force. Its magnitude is the product of the force and the perpendicular distance from the fulcrum to the point where the force is applied.

Figure 1 shows the overlay of the lever system during a typical chewing process. The exertion of the masseter muscle provides the effort and the load is the force on the molars that break down the food. The pivot is located at the temporomandibular joint. This arrangement represents a third class system. The laws of physics enable the estimation of the force on the masseter based on how hard one is chewing. A typical value of the effort by the masseter muscle is 250 N. According to the second condition,

Effort x L_M = Load x L_C, and thus Load = 130.0 N as the force on the molars. Excessive force on the molars could damage the enamel and nerves.

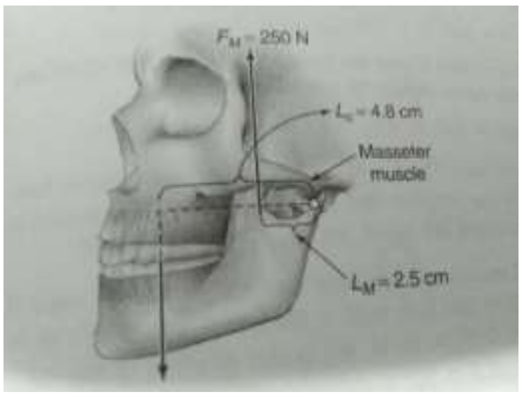

Figure 1: Chewing (5)

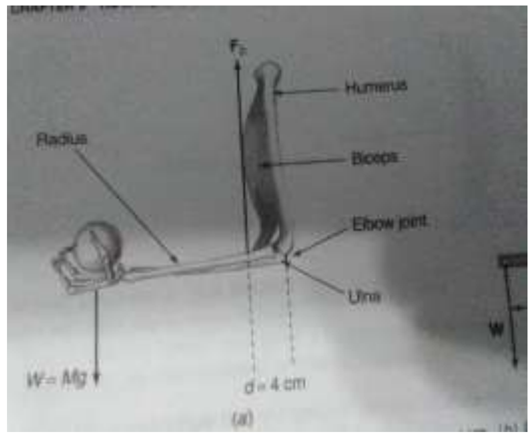

Figure 2 : Weight lifting (5)

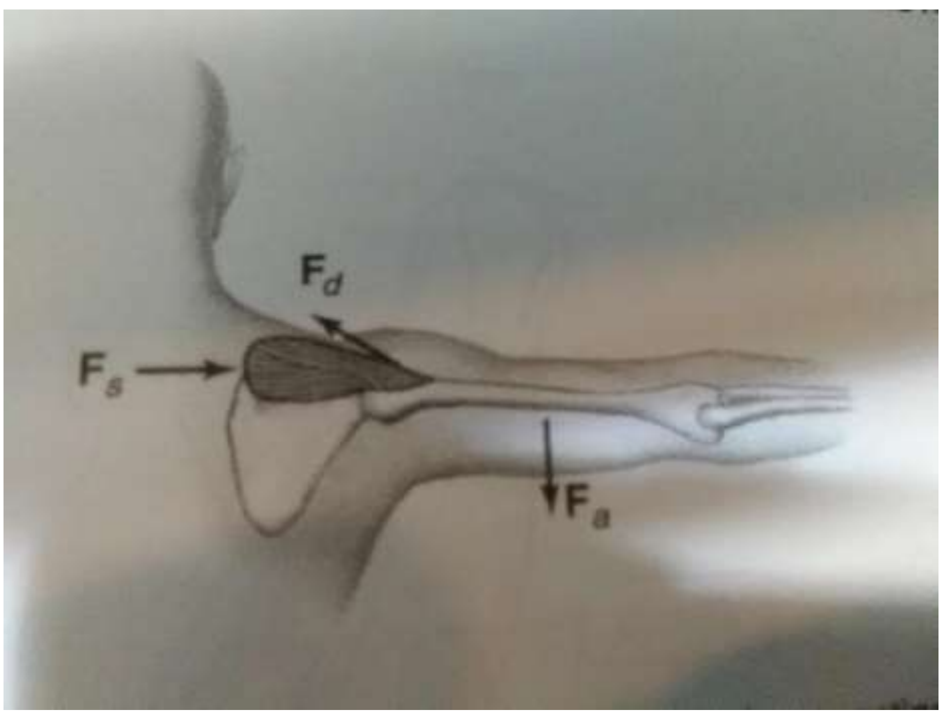

Figure 3: Forces acting on the arm.(5)

Figure 2 shows the forces acting when one holds an object such as packet of sugar. The effort is provided by the biceps. To prevent over-stretched biceps, athletes need to understand the biomechanics of levers in the body. Figure 3 shows the exertion of the deltoid muscle due to the effect of the weight of the lifted arm.

Finally, the study of human musculo-skeletal lever systems has applications in sports medicine, physical therapy and robotics (6-7). For example, good posture may help to reduce the adverse physical effects of daily routine activities such as reading, bending and lifting. It should be noted that real life situations may be more complex than the simple models shown in figures 1-3. The location of the pivot may change as joints undergo flexion (8-9). Nevertheless, the biomechanics of muscles, joints and bones provide interesting insights that are valuable as we undertake various life-required motions.

References:

1. Hoehn, K., Marieb, E.N. (2013). Human Anatomy & Physiology (9th ed). Glenview, IL: Pearson.

2. Campbell, N.A., Reece, J.B. (2001). *Essential Biology.* San Francisco, CA: Benjamin Cummings.

3. Demott, M. E. (1996). Measuring How Muscles Function In Levers. *The American Biology Teacher, 58(8), 490-492.*

4. Serway, R.A., Vuille, C. (2012). *College Physic (9th ed).* Boston, MA: Brooks/Cole.

5. Dixon, J.M., Tuszynski, J.A. (2002). *Biomedical Applications of Introductory Physics.* Danvers, MA: John Wiley & Sons

6. Focus and Torques in Muscles and Joints. College Physics. OpenStaxCollege.

7. Kilgore, L. (2010). Getting Some Leverage. *The CrossFit Journal.*

8. Rovig, M. Why Athletes Need To Understand The Concept Of Torque.

9. Scherger, J.S. The Study of Human Movement by the Application of Biomechanical Musculoskeletal Leverage Physics: Understanding the Effective Lever Arm.