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Biomechanics and Energetics in Aquatic and Semiaquatic Mammals: Platypus to Whale

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Bone as a Spring

Frank E. Fish

In the past, bone was perceived as a static component of the body, functioning simply for skeletal support. **Now** bone, both as a tissue and an organ, is viewed as a dynamic component of the body. Bone tissue is composed of cells (osteocytes) surrounded by a composite of inorganic crystals (hydroxyapatite) and organic fibers (collagen). Bones are the organs that comprise the skeleton, such as the femur, tibia and vertebrae. Besides skeletal support, bones function in movement through joints, as shock absorbers, for protection of vital organs, in force transmission, as a nutrient reservoir for calcium and as a spring.

Despite their apparent rigidity, bones have some degree of flexibility. Collagen fibers give bones their flexibility. Small amounts of bending have been detected in the limb bones of living animals during locomotion (Alexander **1988).** This bending is particularly advantageous in making bone more resistant to fracture.

In addition to flexibility, bones display elastic (spring-like) behavior (Alexander **1988).** Elasticity refers to the property whereby an object returns to its original shape after it is deformed. For example, a stretched rubber band or spring will return to its resting length after the force (load) that stretched it is removed. An advantage of elasticity is that energy can be stored in deformation and subsequently recovered during recoil. The idea that animals possess natural springs has been examined in the field of biomechanics. Scientists have analyzed the elastic properties of such structures as the cuticle of a click beetle, the hinge of bivalve shells, and the tendons of horses, humans and kangaroos. For these animals, energy recovered from elastic deformation can be used to rapidly accelerate body parts and make movement more economical.

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Recent studies of bird flight have shown that the furcula acts like a spring (Jenkins et al. **1988;** Bailey & DeMont **1991).** The furcula or "wishbone" is composed of the fused clavicles; it helps to brace the shoulders, and it serves as a site for muscle attachment. The furcula is flexible and elastic in most small- to medium-sized birds. During flight, the two shafts of the furcula are spread laterally during downstroke **of** the wing followed by recoil of the furcula during the ensuing upstroke. Elasticity of the furcula is hypothesized to aid in the respiratory mechanism of birds in flight (Jenkins et al. **1988;** Bailey & DeMont **1991).**

In this experiment, students will test the furcula of a bird for spring-like properties. This property will be observed if the bone performs elastically; that is, if the deformation of the furcula caused by loading is reversed when it is subsequently unloaded.

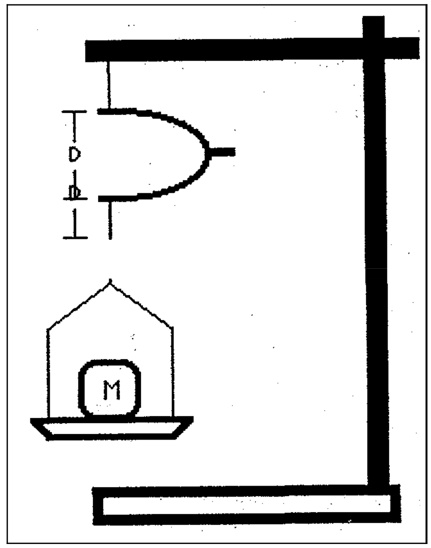

Figure 1. Setup for testing furcula. The furcula is suspended from a horizontal rod camped to a ring stand. The lower arm of the furcula is tied to a pan for weights. D represents the distance to be measured between reference marks, and M represents mass.

Procedure

Instruct the students on the flight movements of birds and on the skeletal anatomy of the bird. Indicate the position of the furcula and its articulations with other skeletal elements.

Dissect out the furcula from a whole, uncooked chicken, cutting the ligamentous connections with the sternum and the coracoids. The furcula should be placed on ice **or** refrigerated until needed for the experiment.

Make small marks on the distal ends of the shafts of the furcula with a pencil or needle probe. These marks will be used as reference points to measure deformation of the bone. Tie one end of the bone to a ring stand, and tie a string to the other end to hold a pan for weights (Figure **1).**

Using calipers, measure the initial distance between the two reference marks. Measure the new distance between reference marks after a 0.2 kg mass is placed (loading) on the pan. Add additional masses to the pan, repeating the measurement with each additional mass. Limit the total amount of mass so that the distance between marks is no greater than 120% of the initial distance.

From the maximum load, reverse the procedure and measure the distance between the furcular shafts as each mass is incrementally removed (unloading).

Make a plot of the force as a function of the furcular deformation on graph paper (Figure 2). Force, in newtons ($kg \cdot m \cdot s^{-2}$), is computed as the **mass** in kg times the gravitational acceleration (9.80 $m \cdot s^{-2}$). Deformation, which is measured in meters, **is** the distance between reference marks when masses are suspended from the bone minus the initial distance. The curves

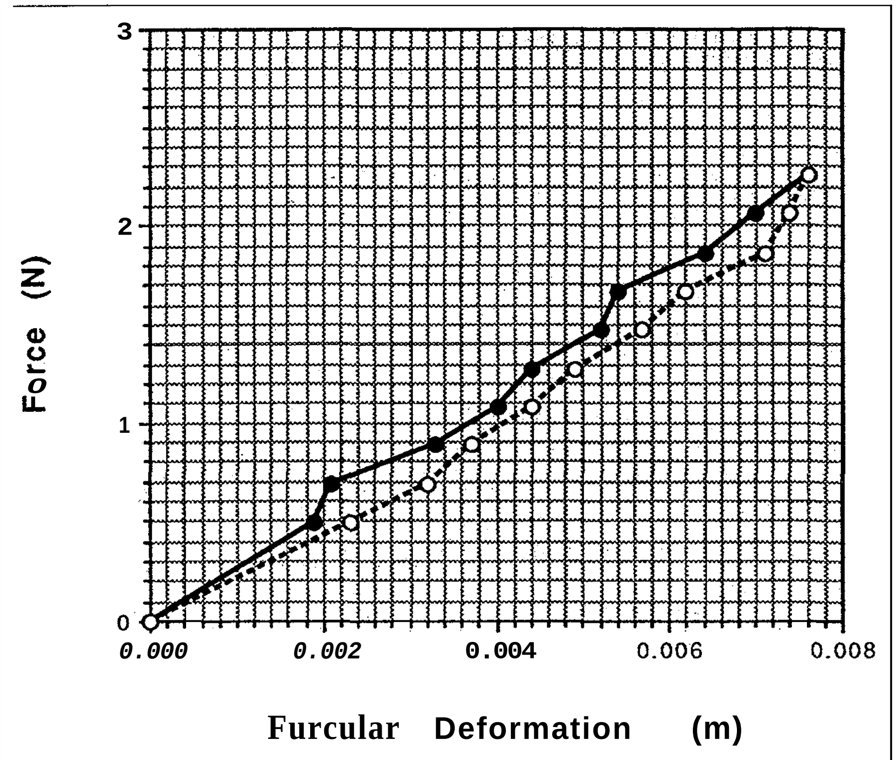

Figure **2.** Plot of force and furcular deformation from test data. Loading is illustrated as the solid line with closed symbols; unloading is illustrated as the broken line with open symbols. The curves form a narrow loop or hysteresis. The area under the loading curve is equal to 429 squares (0.009 joules), whereas the area under the unloading curve is equal to **379** squares (0.008 joules). The difference between the two curves indicates that **12%** of the energy is lost as heat, but much of the energy used to deform the wishbone is recovered in elastic recoil like a spring.

for loading and unloading will form a loop so that each curve does not retrace the same path. This loop is **termed** a hysteresis (Figure 2). The narrower the loop, the more spring-like the furcula.

The work done in stretching the furcula is given as the area under the loading curve. The work recovered by elastic recoil is represented by the area under the unloading curve. **A** simple method for students to estimate the areas is to count the squares on the graph paper under each curve. Because each square has units of force (weight in newtons) and distance (furcular deformation in meters), the area of each square is a unit of work performed or energy (N·m or joules).

The difference between the work of loading and unloading the furcula is the energy lost to heat. Calculate the proportion of energy lost by dividing the energy lost to heat by the work performed in loading the furcula.

Repeat the procedure using a small wire spring which is substituted in place of the furcula. Compare these results with those for the furcula.

The experiment can be modified by examining ***a*** cooked furcula, by comparing furculas that are of different sizes or by comparing furculas from different species of birds.

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