Focusing on the Hard parts: A Biomechanics Laboratory Exercise

Jonathan Fingerut[1,*], Kristina Orbe[1], Daniel Flynn[2], and Piotr Habdas[2]

[1]Department of Biology, [2]Department of Physics, Saint Joseph's University, 5600 City Avenue,
Philadelphia, PA 19131

*Corresponding Author: jfingeru@sju.edu

Abstract: As part of a biomechanics course aimed at both upper-division Biology and Physics majors, this laboratory exercise introduces students to the ingenious ways in which organisms vary the composition and form of support and defensive structures such as bone and shell to maximize their strength while minimizing the energetic cost needed to produce them. Students design and build physical analogues that take advantage of strategies found in nature such as the use of composites and variations in form and internal structure. These are then tested in a competition to determine whose design can withstand the greatest force with the lowest mass per unit length (a proxy for the energetics of production). From this exercise students gain a better understanding of how these structures can be optimized, as well as providing an opportunity to discuss basic biological concepts such as fitness, variation and evolution.

Key words: Biomechanics, bone, physics, biological materials

INTRODUCTION

The study of biomechanics provides biology students with an opportunity to apply their education in physics to a biological context and bring together biological concepts normally spread across a wide range of coursework (e.g. evolution, physiology, behavior). At Saint Joseph's University the course in biomechanics covers a broad range of topics including fluid dynamics, biomaterials and locomotion. Lectures taught by members of the Physics and Biology departments are broken into weekly units that cover the physical concepts and theories as well as their biological applications. This manuscript describes a three-week laboratory exercise designed to help students understand the effects of material composition and form on the strength of solid biological structures.

The module on “hard parts” starts with an overview of the relevant material mechanics including stress (the force per area deforming a solid), strain (a measure of the degree of deformation), the elastic modulus (the ratio of the former to the latter), strength (the force which a material can withstand before fracture) and elasticity (the ability of a material to return to its original shape after deformation). Descriptions, examples and supporting information on these topics can be found in any college physics textbook, and many students may already have been exposed to them during their high school or undergraduate courses.

In contrast to the physics involved, the biological implications of those properties are usually only understood at a very basic level: e.g. that structures such as skeletons, snail shells, and carapaces need to be strong and light and energetically efficient in their production and use. To help the students develop a deeper understanding of how material properties can affect an organism’s fitness we use examples that illustrate two dichotomies: offense vs. defense and composite materials vs. blended materials. Examples of offense are teeth and claws, both of which provide examples of the latter dichotomy. Teeth use the combination of two materials: enamel and dentin. The outer layer of enamel is made of a tough but brittle crystalline form of calcium phosphate called hydroxyapatite. Enamel resists fracture under sudden impact but is prone to fracture with little to no deformation. To balance the strengths and weaknesses of the enamel, it is bonded to the more energy absorbing dentin. Dentin, like enamel, is also a calcified tissue, but mixed with collagen to change its properties (Vogel, 2003). Claws, such as those used by scorpions or crabs, use a different strategy, namely changing the composition of a single material rather than layering two separate materials. By doping the tips of their claws with metals such as zinc they produce material that is much more chip-resistant (Schofeld, 2005). This is particularly important for those that use their claws as forceps to pick up and manipulate food items, since a fracture at the tip may limit their effectiveness till the next molt, thus reducing fitness.

The development of any offensive capability on the part of a predator is usually countered by the evolution of a corresponding defensive adaptation in the prey. Here we focused on two examples, the snail shell and mammalian bone, to illustrate how different biomaterials can act in isolation and in combination. Snail shells provide an excellent example as their strength arises from three levels of organization: the materials used, the arrangement of those materials, and the overall shape of the shell. Shells of most gastropods are composed primarily of calcium carbonate bricks that are arranged in an offset pattern and held together along their long axis by proteinaceous glue. This arrangement allows the strength of the bricks to be augmented by the energy absorbing qualities of the protein, similar to the arrangement in teeth. Absorption of impact energy occurs by allowing any cracks to travel over a tortuous pathway through the shell, thus dissipating more energy than would otherwise take place if the crack traveled directly through a monolithic piece of calcite (Menig et al., 2000). The strength of the shell is increased by its arched shape, which helps to distribute and redirect forces placed on it over a larger area, just as an arch helps distribute the weight of a roof. A final "trick" that has recently been found in a deep water gastropod is to cover the outside of the shell with a layer of hard metal crystals which are thought to dull the claws of would be predators, increasing the area over which their crushing force is transmitted and thus lowering the force per unit area they can impart to the shell (Yaoa et al., 2010).

Mammalian bones, in spite of their very different evolutionary lineage, arrangement, and location, use similar strategies for dealing with impact and fracture. Long bones such as the ulna or femur use properties of their constituent materials and overall shape to provide the greatest strength with the least weight. This is particularly important for land-based organisms that cannot take advantage of water's buoyant assistance to support their bodies. Similar to the shell's brick and mortar approach, mammalian bones use concentric layers of mineralized material arranged in osteons which are in turn connected to other osteons via a proteinaceous glue (Fung, 1993). These osteons can absorb the energy of impact through both delamination and "pulling out" whereby entire osteons break their connection along their entire length, thus dissipating energy. The presence of "spongy" trabecular bone in the ends and core of the bone provides additional energy absorption. This webbing of bone forms a matrix that shatters and dissipates energy while the overall integrity of the bone is maintained by the outer layer of compact cortical bone. Additionally, bones are often non-circular, reflecting the anisotropic (unequal along different planes) forces they encounter either from the weight of the organism or stress placed on them by muscular action. By increasing the size or thickness of the bone in the direction of the greatest stress, and by maximizing the mass of material at the outer rim, the flexural stiffness of the bone is increased, allowing it to resist bending when under load (Fung, 1993).

By presenting these examples, we aim to impress upon the students that a few basic strategies to increase the strength of structures, however complicated their implementation may be biologically, can be found across a wide range of taxa. Lamination, tortuous crack propagation, combination of strong but brittle with soft but energy absorbing materials, changing material composition and the specific shape they form, can all produce strong structures while minimizing the materials, and therefore the energy, needed to produce and maintain them.

This exercise was developed to allow students to experiment with the biological strategies that organisms have developed to resist impact forces. The students are asked to design and construct analogues of biological structures using their knowledge of biomaterials and the ways in which organisms use them to resist fracture. To increase student interest we ran the exercise as a competition with two-person teams. Each team was allowed to produce and test as many prototype bones as they wished, but could only enter one design in the final competition. These constructs were then tested for their ability to withstand both static loading and impact. To emphasize the idea that most biological systems are limited in the energy they can put into building and maintaining elements of their body, designs were scored based on the force they withstood divided by their mass per unit length. The mass, in this case, represented the energy necessary to produce the structure.

Students were given free rein to develop their own designs, many of which were rather complicated. In this manuscript, however, we present data for a series of simple designs to illustrate specific comparisons: 1) the effect of hollow vs. solid bones of similar size, 2) the effect of similar masses being arranged as either solid or hollow bones, 3) the effect of a trabecular-like matrix and 4) strength of an ellipse along either of its axes.

METHODS

The competition was designed to challenge students to design and build a structural analogue to bone, shell or other hard biological structure (hereafter referred to as a "bone") that would withstand the greatest force without failure. Failure was defined as a complete break, or sufficient fracture to leave the structure without the necessary rigidity to bear weight along its long axis. This included situations where the bone was only held together by flexible material or flopped over but did not separate into two pieces.

Bones were limited to a cross-sectional area of 5 cm^2 and a length of 15 cm to preclude students from building giant objects that would be impossible to break. In order to make the results more biologically relevant, the bones could not have any internal elements that were greater than 10% of their length or width. Bones were constructed out of plaster of Paris, available at any home improvement or hobby store.

Fig. 1 Cylindrical bone construction techniques. A. Sand bed with shower rod cover pieces being prepared for filling with plaster. B. Sand bed with shower rod cover pieces with straws added to produce hollow cylinders. The straws are removed after the plaster cures.

To limit students from simply coating a mass of foreign objects in plaster, we dictated that the bone must be greater than 50% plaster by volume. Aside from this and the size rules, we left it up to the students' imagination to apply the biological concepts and examples covered in class to their designs.

Depending on the desired shape, bones could be molded either in tubes or in sand molds. For the former, a plastic shower rod cover was cut to length and taped shut along its length. These tubes were then plugged at one end with modeling clay and held vertically in a bed of moist sand where they could be filled and allowed to cure (Figure 1A). As long as the inside of the tube was smooth no release agent was needed. To produce hollow cylinders, large greased straws were inserted into the molds before the plaster was added (Figure 1B). The straws were removed after the plaster cured to leave a hollow cavity running the length of the cylinder. To produce more complex shapes, plastic storage containers were filled with wetted sand into which depressions could be made. These molds were then lined with plastic wrap to keep the plaster in the mold and aid in the release of the bones after curing. This allowed layers of the bones to be poured at different times or with different "additives" in different places. For both methods, bones were allowed to cure overnight, after which they were removed from their molds and allowed to air dry for at least a day. The laboratory exercise took place over a three-week period, allowing students to build and test a number of prototypes before settling on their final design.

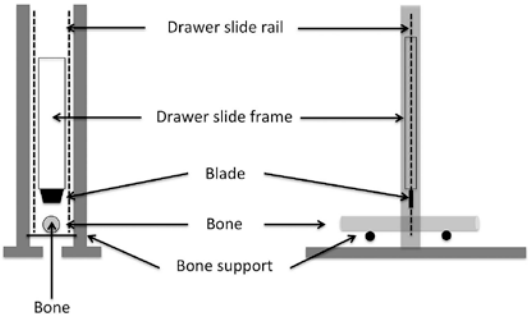

Fig. 2. Schematic of the guillotine used to load the bones.

Bones were tested under both static and dynamic loading, recreating a crushing force from a claw or jaw and an impact from a strike, respectively. Static loading can be difficult as the bones are quite strong. The problem was solved by using a metal guillotine (Figure 2) onto which a container was hung and slowly filled with water from a second spigoted container (Figure 3). This allowed for large masses to be applied to the bones (students are often surprised how heavy water is) and easy measurement of the load. After the bone failed, the water was drained into a third receptacle and the mass determined. Using this method a bone could be tested and the load determined in about a minute. Dynamic loading was accomplished using the same guillotine, dropping its blade from increasing heights. Testing of the blade's impact in clay blocks showed that the depth of the indentation, and therefore the forces produced, were relatively consistent between replicate drops and at different heights (RMS values of 0.17, 0.13 and 0.17 for heights of 10, 20 and 30 cm respectively).

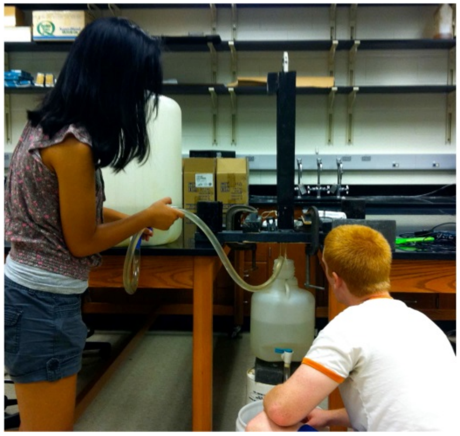

Fig. 3. Students using the guillotine with three reservoirs for filling, weighing and measuring the water mass.

Bones were scored according to the following formulae: Static Score = maximum mass supported/mass per unit length of the bone, and Dynamic Score = maximum height from which the mass was dropped/mass per unit length of the bone. This made it possible to compare across designs regardless of size and shape. Larger, heavier bones might resist more force, but they would be penalized for their increased mass. Though the force exerted on the bones during static loading was easy to quantify using the formula F=*ma* with *m* being the loading mass and *a* the acceleration due to gravity, determining the force exerted by dropping the mass onto the bone was less straightforward. The time it takes for the falling mass to come to rest determines the force exerted per unit time on the bone. This would vary from bone to bone, and within bones between heights. As we could not measure this parameter, we could not determine the forces exerted during the dynamic testing and therefore could not make direct comparisons between the two scores.

Students in the course came up with a range of designs that changed cross sectional shape, types of material mixed into the plaster, moisture levels of the plaster mix and even the curve of the bone along its length. Time constraints prevented us from testing more than three replicates of any given design, limiting statistical power in analyzing their results. We therefore present additional data for six designs which represent modification of both the shape and material composition: 1) round solid, 2) round hollow, 3) round small cylinder with the same mass as the round hollow, 4) round hollow filled with "spongy bone" (plaster mixed with 10mg of powdered bicarbonate for every 250 ml of water), 5) ellipse tested along its longer axis and 6) ellipse tested along its smaller axis. Ten replicate bones were tested under both static and dynamic loading.

RESULTS

Though replicates were very consistent in their mass/unit length within treatments (RMS 4-13% average 8%) there was considerable variation in the force they could withstand (Table 1). Therefore, bone scores within each design under both testing schemes varied more (RMS 13-33% average 22%, Figure 4). Even with this variation, significant differences (one-way ANOVA) in three out of four comparisons of interest were seen under the dynamic loading, and in two out of the four under static loading, though hollow vs. filled results were the opposite of expectations (Table 1).

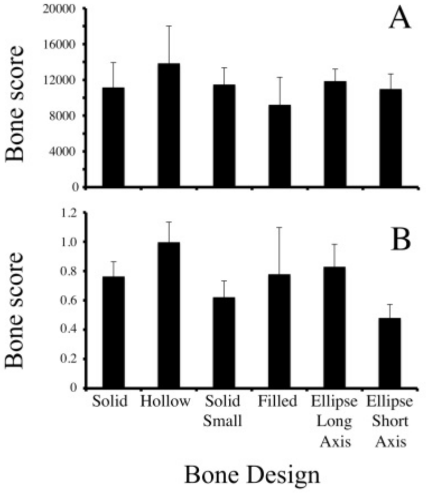

Fig. 4. Bone Scores (average ± standard deviation) for both static (A) and dynamic (B) loading of all six designs. Note that bone scores are not directly comparable between testing schemes as static loading used maximum mass before brekaing and dynamic loading used maximum height before breaking.

DISCUSSION

This lab was the most popular exercise of the semester. Without any pressure from the instructors, students spent a significant amount of time planning, building and testing their bones both in and out of scheduled laboratory times. Though it was a fun

Table 1. Results of testing for all treatments under both static and dynamic loading. Score was calculated as loading (the maximum mass before breakage under static testing or the maximum height under dynamic testing)/the mass per unit length of the bone. Averages and standard deviation for all parameters are provided in addition to the results of one-way ANOVA's for the four comparisons of interest.

Design	Average Score	S.D.	Average mass (g/cm)	S.D.	Maximum Loading (g or height in cm)	S.D.	ANOVA
Static							
Solid	11164	2754	4.5	0.4	37869	14122	df = 1.19 F = 11.9 p < 0.01
Hollow	13842	4166	2.4	0.3	34059	11521	
Hollow	13842	4166	2.4	0.3	34059	11521	df = 1.19 F = 6.7 p = 0.02
Filled	9206	3084	4.1	0.4	40489	11455	
Hollow	13842	4166	2.4	0.3	34059	11521	df = 1.19 F = 2.7 p = 0.12
Solid Small	11480	1876	3.2	0.1	36472	6502	
Ellipse Along Long Axis	11861	1345	3.8	0.2	44892	1345	df = 1.19 F = 1.69 p = 0.21
Ellipse Along Short Axis	10969	1709	3.6	0.2	10969	7022	
Dynamic							
Solid	0.76	0.10	4.6	0.4	3.4	0.5	df = 1.19 F = 20.4 p < 0.01
Hollow	1.00	0.14	2.8	0.4	2.8	0.6	
Hollow	1.00	0.14	2.8	0.4	2.8	0.6	df = 1.19 F = 4.1 p = 0.06
Filled	0.78	0.32	4.0	0.5	3.2	1.6	
Hollow	1.00	0.14	2.8	0.4	2.8	0.6	df = 1.19 F = 46.7 p < 0.01
Solid Small	0.62	0.11	2.9	0.2	1.8	0.3	
Ellipse Along Long Axis	0.83	0.15	3.8	0.2	3.1	0.5	df = 1.19 F = 36.1 p < 0.01
Ellipse Along Short Axis	0.50	0.09	3.6	0.2	1.7	0.3	

exercise, to keep the students centered on the concepts we wished to emphasize, each bone entered into the competition was accompanied by a one-page explanation of the design, construction and the biological examples it was based on. The students' writing showed that they had a firm grasp on the adaptations we discussed in class and that they understood their purpose as well as the mechanisms by which they worked.

Student designs tended to be quite imaginative adding various glues, reinforcing elements (e.g. mesh, fibers), and mass-saving additives (e.g. foam, pearlite). The limitations of the students' resources and experience lead to crude approximations of natural structures, and though most of those designs were unsuccessful, we do not consider that a weakness of the exercise. We encouraged students to try for relatively complex designs both to keep their interest and to illustrate a specific point, namely that though the concepts may be fairly straightforward, (e.g. a mix of different materials can make the structure stronger), the implementation of that concept is exceedingly difficult. Students came away from even the worst failures with a better appreciation for both the ability of biological systems to produce marvelously engineered structures and the remarkable evolutionary processes that have led to those abilities.

For this manuscript the authors chose designs that illustrate some of the basic characteristics of solid biological elements adapted to withstand large forces. The first of these strategies is placing much of an element's mass as far from the central axis as possible, thus increasing its area moment of inertia. The significantly higher scores for the hollow design illustrate the efficacy of this design. Though the solid rod held more mass under static loading than the hollow rod of equal diameter (Table 1), its extra mass did not add enough to its strength to make it energetically efficient and thus it produced a lower score. Similarly hollow bones performed much better than solid bones of similar mass. The failure of the filled bones, which were designed to mimic the pairing of dense cortical and spongy trabecular bone, was a surprise. This may have been due to the necessity of adding the spongy plaster mixture after the hollow cylinder had been produced and dried. The introduction of a considerable amount of moisture to the outer cylinder as well as the stress placed on its walls by the expanding spongy plaster may have weakened the final combined product even after allowing it to re-dry.

A second comparison that we set out to illustrate was differential growth (in terms of length of axes) in response to anisotropic forces. Though the ellipses did not perform differently under static loading, there was a large, statistically significant difference when ellipses were tested against impact along their long and short axis. As expected, larger forces could be withstood if delivered against the long axis of the ellipse. This strategy can be seen in the shape of long bones, such as the ulna or femur, which adapt over time to resist stresses along a specific axis. The difference in responses between the two loading schemes may reflect the different failure pathways initiated under each type of loading. Static loading causes failure through bending of the beam and an inability of the structure to withstand compressive forces along the top, tensile forces along the bottom, or shear forces along the cross-section. Dynamic loading, however, would most likely cause fracture (and therefore failure) through alternative scenarios, the specifics of which are beyond the scope of this manuscript, and likely most biomechanics courses aimed at biologists. The lack of a significant difference between the two ellipse orientations under static loading is probably due a combination of the differences in their second moment of inertia being small, the inherent between-bone variability, and the sensitivity of the testing apparatus.

Though trends did exist in many of the non-statistically significant comparisons, the presence of large variances themselves provided a teaching moment. Variation between the strength of replicate bones is a useful example of how small changes in construction techniques, materials, or moisture levels can make a large difference in the properties and success of the final product. This variability, which was more pronounced with the students' bones compared to ours, provides a perfect opportunity to discuss some of the basic concepts of evolution (e.g. variation, differential fitness) which can be particularly useful if non-biologists are part of the student body since they may not think about this important topic as much as biology majors.

Though this relatively simple exercise was very successful, more complicated variations could introduce further "trade-offs" that biological systems often face. In the current version the major trade-off was between weight and strength, a common biological theme. However, there are other examples, such as the need to maintain a certain amount of flexibility or resilience as well as strength, or the ability to withstand forces along different axes. Such a two-part testing scheme would provide an opportunity to introduce further discussion and appreciation for the challenges faced by organisms using solid biological elements and the ingenious methods by which they respond to those challenges.

Overall, we feel that this exercise provides a number of opportunities for student learning. First, it provides students a chance to apply physical and engineering principles to a biological issue. Such interdisciplinary opportunities are rather rare, in our experience. Second, as students struggle to successfully apply these principles, they develop a greater appreciation for how well organisms are able to do so. Lastly, students in this exercise have the opportunity to work hands on, prototype, test, revise and otherwise go through the process used by science, engineering and other real-world applications of their education. While there are rules, the students are allowed to work towards their goal on their own, instead of following a set recipe. We feel that this kind of exercise is very important for students to experience and one that is all too rare in many curricula.

ACKNOWLEDGEMENTS

The authors wish to thank the Howard Hughes Medical Institute for their support in developing this course and laboratory exercise and the Saint Joseph's University Summer Scholars program for funding the students' research.

REFERENCES

FUNG, Y.C. 1993. Biomechanics: Mechanical properties of living tissues. Springer, New York.

LIN, A. AND M.A. MEYERS. 2005. Growth and structure in abalone shell. *Materials Science and Engineering A* 390: 27-41.

MENIG, R., MEYERS, M.H., MEYERS, M.A., AND K.S. VECCHIO. 2000. Quasi-static and dynamic mechanical response of Haliotis rufescens (Abalone) shells." *Acta Materiala* 48: 2383-2398.

SCHOFELD, R.M.S. 2005. "Metal-Halogen Biomaterials." *American Entomologist* 51: 45-47.

VOGEL, S. 2003. Compariative Biomechanics: Life's Physical World. Princeton University Press, Princeton, NJ.

YAO, A.H., DOA, O,M., IMHOLT, B.T., HUANG, A.J., WHEELER, A.K., BONILLA, C.A., SURESH, A.S., AND C.A. ORTIZ. 2010. Protection mechanisms of the iron-plated armor of a deep-sea hydrothermal vent gastropod. *Proceedings of the National Academy of Sciences* 107: 987-992.