# AC 2011-1556: TOWARDS AN ARTIFICIAL BULLFROG: DEVELOPMENT OF A KINEMATICALLY REALISTIC, ARTICULATED SKELETAL MODEL

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# Towards an Artificial Bullfrog: Development of a Kinematically Realistic, Articulated Skeletal Model

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## Introduction

A primary role of the engineering discipline is to use scientific knowledge to create useful products and solutions for society. As such, engineers often work very closely with scientists to incorporate new knowledge and insight. However, in many cases, undergraduate engineering education lacks such interdisciplinary training. This is unfortunate as creative and groundbreaking design concepts often arise from investigations that span academic boundaries. Indeed, even learning to communicate effectively between engineering and other sciences can be a precious learning experience. In this study, we report on a unique collaborative effort between organismal biology and mechanical engineering that was undertaken to provide an undergraduate cross-training experience. The project involved the creation of an articulated physical model of a bullfrog skeleton with mechanical joints that mimicked realistic prey strike movements. To carry out this research, our team, a sophomore mechanical engineering student, a manufacturing lab instructor, and a professor of comparative biomechanics, began with three-dimensional medical imaging data and high speed videos and ended with a useful product; a rapid-prototyped plastic bullfrog skeleton used for teaching.

Why might an engineering educator look towards basic biology for project ideas? Frequently, biologically-inspired or biomimetic designs represent evolutionary solutions to mechanical problems that have not been considered previously. There are a number of such examples: Boston Dynamics' DARPA-funded BigDog robot may provide battlefield troop support and is designed using stability characteristics identified in quadruped locomotion[1] and Endolite's blade-style running prosthetic was designed to mimic natural elastic energy storage and rolling movements of the foot[2]. Because biological structures are built using components with materials that exhibit significantly different properties than those commonly used in engineering designs (for example, muscle's tunable, non-linear elastic properties[3]), their consideration within an undergraduate mechanical engineering program is often limited. However, functional biology can provide a wealth of design ideas useful in mechanical and biomedical engineering projects[4] that are not only suitable for undergraduates, but also fit seamlessly into the engineering design process. This is an important feature as exercising these design skills represents the central distinguishing activity of engineering[5]. Dym et al.[6] outlined the critical skills that we assess here; the generation, specification, and evaluation of concepts for our production workflow and skeleton device, the form and function of which achieves the biomechanical movements observed in the living organism while satisfying the set of constraints imposed by the thee-dimensional printing process. Ultimately, our goal was to provide a cross-training experience that would give our student the tools to begin using biological structures as a source of novel mechanical concepts for use in the design process.

The specific goal of this biomechanical design project was to create a skeleton model for teaching and surgery planning; a high-resolution, realistically-articulated, physical model of a bullfrog skeleton using mechanical joints that were designed to capture all the three-dimensional movements that were seen to occur in biplanar light and X-ray videos of frogs performing prey strikes. The educational experiences to which our undergraduate student was exposed were manifold: First, she was introduced to biological materials by considering the strength and flexibility of the composite material bone, the non-linearly elastic properties of connective tissue and the contractile and elastic properties of muscle. Next, she learned to describe biological morphology through frog dissections and joint manipulations. She then analyzed the kinematics of the biplanar video recordings in order to identify crucial joint characteristics. Finally, she learned to visualize medical imaging data and use the workflow described here to import 3D mesh geometry into Computer Aided Design software in order to design and articulate the skeleton with biomimetic mechanical joints. The product was built using a 3D rapid prototyping machine and will be used to teach anatomy, plan surgeries, and perhaps even serve as the platform for a realistic frog robot.

## The Design Process

We analyzed the design process in the context of a multidisciplinary research collaboration. Without going into methodological detail (a description of the project workflow follows this section), the skills that we evaluated are described below:

*Definition of the problem.* We required our student to define the problem by stating the objectives in concise sentences. In order to develop these objectives in response to an expressed need, our student interviewed our biologist. Our student quickly found that perhaps the greatest challenge of design was the amount of knowledge that needs assimilation and that the multidisciplinary aspect of this collaboration compounded this amount of required knowledge. To overcome this challenge, we spent an initial period by introducing and defining biological and engineering terms and jargon in order to give all team members a common set of tools to communicate effectively. Following this, our student defined the problem:

1. Prototype an ABS plastic skeleton model based on medical imaging (CT) scans.
2. Replace natural soft tissue joints with mechanical joints in order to articulate the bones of the model.
3. Design the joints to reflect actual joint motion seen in bullfrog feeding behavior.

*List of Specifications.* After our student translated the needs described by our biologist into problem definition objectives, the next step was to prepare a list of specifications. The specifications included both required and desired design characteristics and were categorized as follows:

1. Performance (definition of the eleven major flexible joints in the skeleton and characterization of their degrees of freedom and range of motion)
2. Geometry (optimal spatial resolution and scaling, data management and portability)
3. Materials (analysis of the material properties of ABS plastic and post-printing processing to improve durability of finished model)
4. Manufacture (material and machine time cost, color, size, post-printing assembly)

The bulk of our student's efforts were expended in satisfying the performance specifications and so we assessed her on that criterion in the following design skills.

*Generation of Alternative Concepts.* Next, we tasked our student with generating multiple concepts for each design specification. The concepts were expressed as sketches that were documented in an engineering logbook. Each sketch was detailed enough to understand how the concept worked but not necessarily enough to model or build it. During this phase, we encouraged our student to develop concepts and then meet with the whole team, and even with additional interested design students, in order to critique the concepts and brainstorm further ones. After all ideas were presented, with advisor aid, the student selected the most promising concepts. These concepts were then revised and developed with more detailed concept sketches. These dimensionless sketches were hand or computer generated and had all parts labeled and rendered in multiple views.

*Literature Search.* While some ideas are truly original, most are built on previous work. While generating alternative concepts, we encouraged our student to comb through the pantheon of simple and compound joints to select the strongest and most appropriate mechanical joint designs. This was done by completing a literature search of engineering and biology journals, electronic databases, and the web for existing design solutions. In addition to this, however, a creative search for previously designed concepts takes on an especial significance when collaborating with biologists. We encouraged our student to reverse engineer biological joints for inspiration. As an example, our student found herself analyzing the design of a crab claw, taking it apart, figuring out how it works, and considering how to adapt the dicondylar hinge joint as a design concept. Another unique aspect of the "literature search" phase of this collaboration was the ability to consultation of the biology of the actual animal. This consisted of manipulating the joints of a real frog and reviewing video of it performing behaviors. In this case, hours of videos featuring hungry, lunging frogs were observed and three-dimensional movements and angular displacements of the joints were quantified.

*Evaluation and Selection of a Concept.* On average, our student developed three concept sketches for each of the eleven joint specifications. A decision matrix was used to evaluate the strengths and weaknesses of each concept. The best designs were found to have a number of characteristics:

1. The joint could be uniquely specified using the least amount of information.
2. Easy to manufacture using the rapid prototyping machine.
3. The design was robust with the fewest stressed points.

Having selected a joint concept for each of the eleven joints specifications required in the complete skeleton, a detailed overview sketch was completed and the medical imaging bone geometry was then translated into virtual solids that were appropriate for manipulation in a computer aided design software package.

*Design Defense.* Our student was asked to defend her final concept choices, prior to the manufacturing phase, in an effort to convince the team that the design was of the best overall possible quality. This was done to minimize manufacturing material costs as well as consultation time of team members. Our student was asked to show how she followed the design process and to describe the details of how the final concept is supposed to work.

*Manufacturing and Testing.* Following rapid prototyping, we asked our student to test her prototype to gain some measure as to how her final product matched the original specifications. Her first test of the prototype was to measure the possible motions of each of the eleven joints. Using a goniometer and a caliper, our student measured the range of motion associated with each of the eleven joint designs within the skeleton. She then compared their measurements with the designated values of the original specifications to assure the team that both full range of motion was possible and that slop in the joints was minimal. A second test she devised was to allow others to manipulate the skeleton in a manner somewhat more roughly than it would experience as a teaching model. This provided assurance that joints were robust enough to stand up to their final purpose. Our student also made some less tangible assessments and critiqued the research process and experience. Of these, her two main conclusions were that the biological diversity of organisms should be considered as a major source of creative concept ideas and that time tables, scheduling and organization, while important to all engineering projects, is especially crucial to collaborative multidisciplinary projects.

Project Workflow

A. Joint Characterization

The first step in the workflow was to interact with a freshly euthanized bullfrog. We started by letting our student palpate and manipulate the bullfrog's body and fore and hind limbs. She did this to develop an intuitive familiarity with the external morphology as well as to gauge the range of motion and degrees of freedom possible by the various joints in the body. Following this she performed a dissection using a common dissection manual[7] in order to observe the bone and joint morphology as it exists in an intact animal. Because bullfrog joints use fluid-filled sacs (known as synovial bursae) and cartilaginous pads in their construction, it became clear that the natural joint construction would not be replicable using a 3-D printer. We therefore decided to use computer-aided design software to modify the bones with mechanical articulations or joints. As a result of these observations we developed a list of eleven of the most mobile joints (see fig. 1 below & table 1 in the next section) for characterization in the next step.

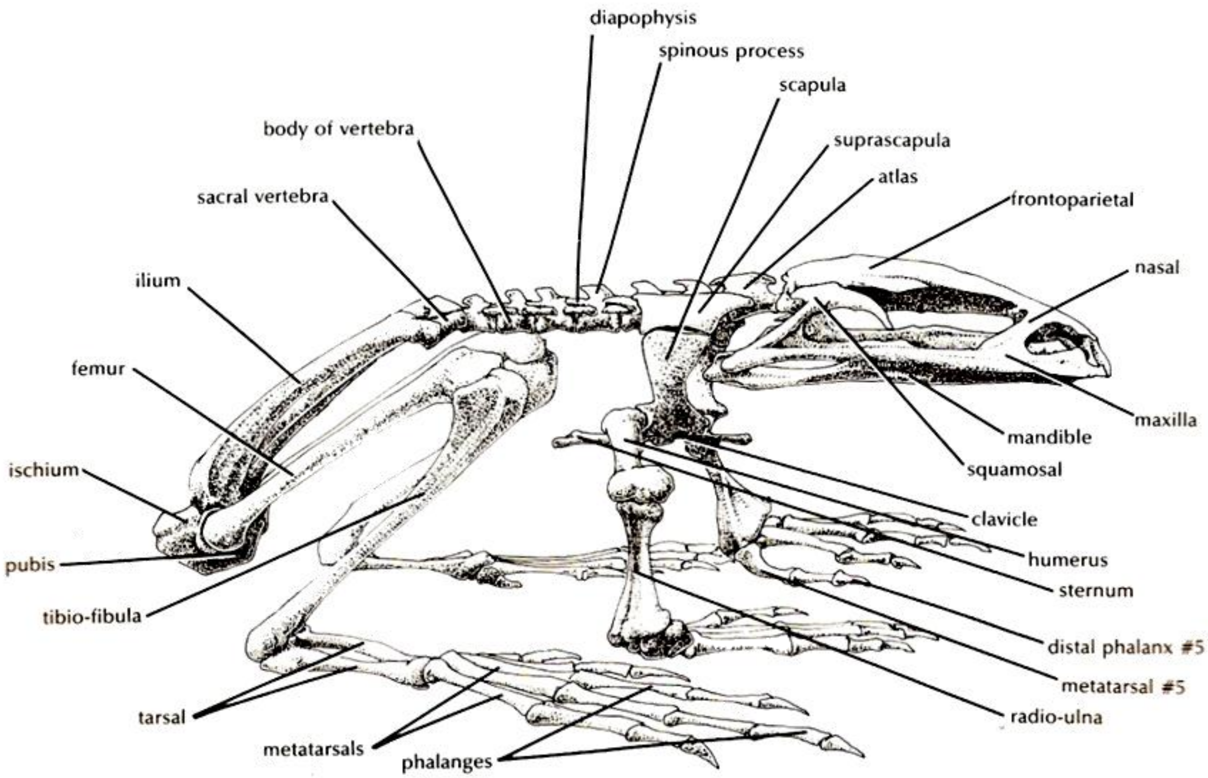


Figure 1: Bullfrog skeleton (From Wingerd, 1988)

After familiarizing herself with the gross morphology, our student filmed the behavior of interest, the prey strike of a bullfrog feeding on a cricket, using high-speed videography (Dr. Kiisa Nishikawa, Northern Arizona University). Our setup used two high-speed phantom cameras (Vision Research, Wayne, NJ) positioned for simultaneous and synchronous recording of lateral and dorsal views at 1500 frames per second. Our frogs were trained to feed on crickets in front of the bright camera lights so that she could capture their stereotyped feeding movement. This prey strike consisted of a forward lunge during which the mandible would be triggered to open, resulting in the tongue being thrown out of the mouth along a ballistic trajectory[8] to make contact with the prey (fig. 2).

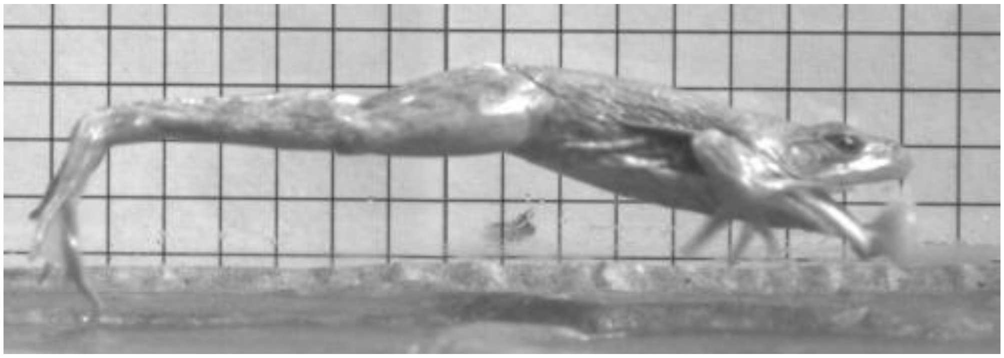

Figure 2: Bullfrog midway through prey strike showing the tongue being thrown from the mouth.

By analyzing changes in body position between frames, our student was able to calculate changes in various joint angles during the prey strike. To calculate these ranges of joint motion and degrees of freedom, our student used Didge (A. Cullum, Creighton Univ.), an image digitizing software package that allowed us to analyze the video frame-by-frame to find the minimum and maximum extension of each selected joint. For each endpoint exhibited by a clearly visible joint, she would identify the center of rotation of the joint and two points along each bone connected by the joint. These three points defined the angle of the joint for that given extension. Calculation of the joint angle at each of the minimum and maximum extensions characterized the range of motion for that joint in that plane (figs. 3 & 4).

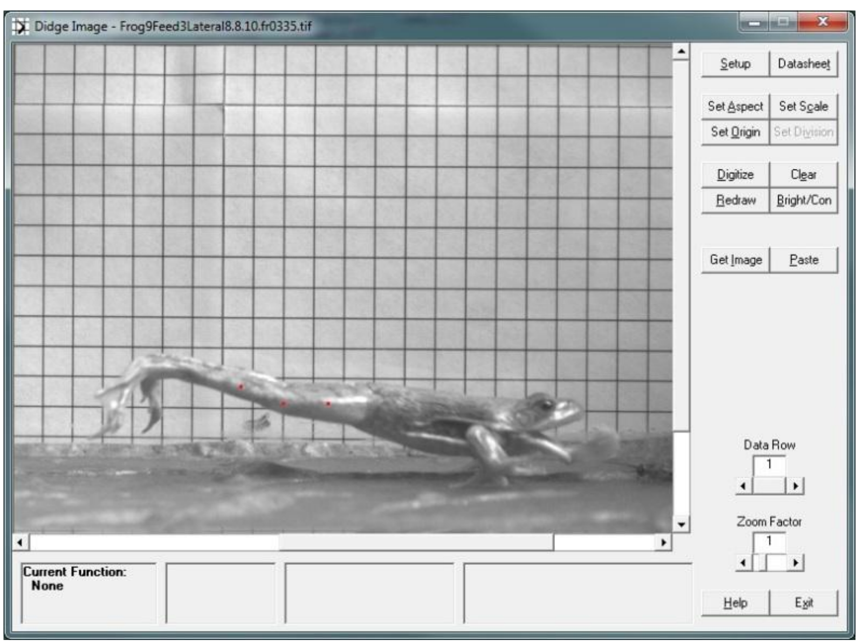


Figure 3: Screenshot of the Didge image digitizing software used to calculate changes in joint angle.

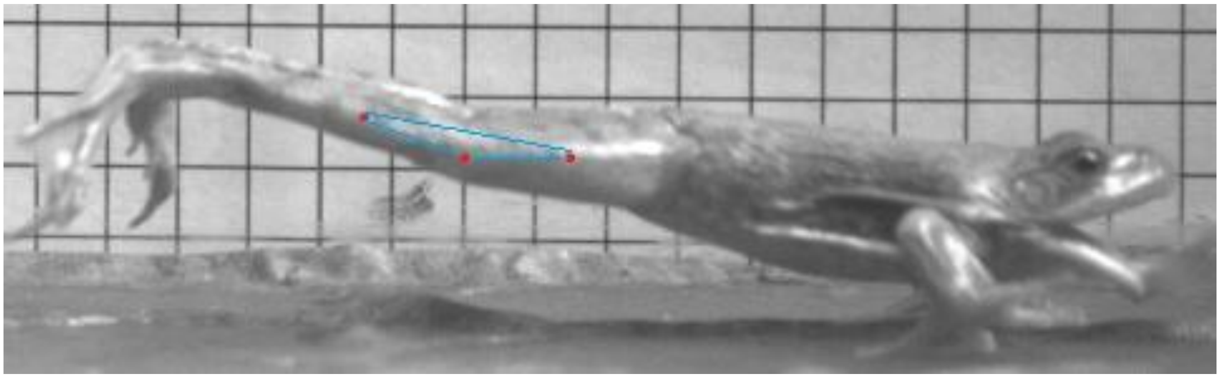

Figure 4: Calculating the joint angle of maximal knee extension using Didge.

The Didge software kept track of the x and y coordinates of each red point placed on each frame of video. The x and y coordinates were then used to calculate the joint angle (fig. 5).

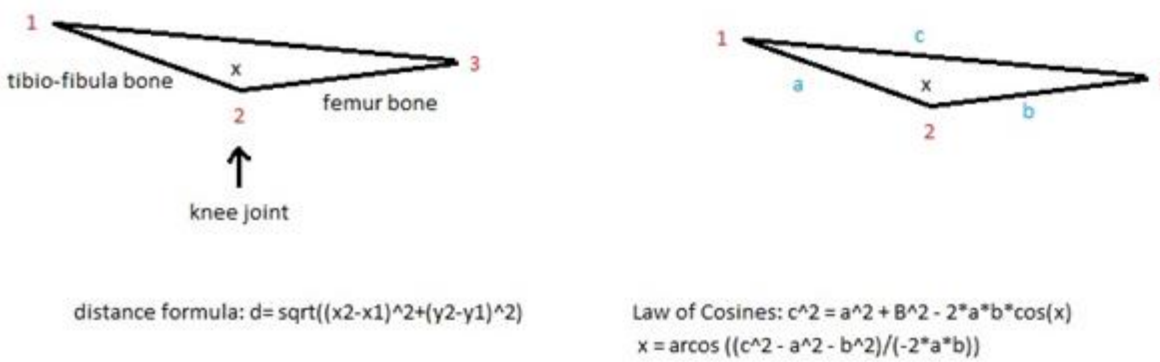


Figure 5: Example angle calculation for knee joint.

A number of joints within the bullfrog's body were not externally visible in light videography. In these cases, we used high-speed X-ray videography (Dr. David Lee, Univ. of Nevada, Las Vegas) to capture joint and bone motion as they performed prey strikes (fig. 6). The X-ray cameras were setup in a fashion similar to the light videography, with simultaneous and synchronized horizontal and vertical recordings of the prey strike. The X-ray cameras recorded 1000 Hz. Prior to filming the frogs, we placed radio-opaque platinum beads at various points on the frog in order to facilitate automatic recording of joint positions. This automatic digitization of bone geometry to marker positions was performed using XROMM techniques[9, 10] and software (XROMM.org, Brown Univ.).

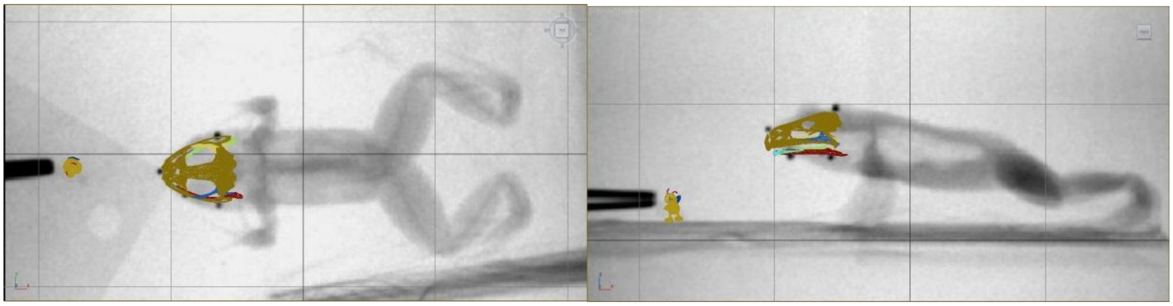

Figure 6: X-ray frames of frog near the beginning of its prey strike (Note: 3-D skull model is aligned to radio-opaque marker beads).

We again used Didge as a complementary technique to analyze these X-ray recordings, which were particularly useful for measuring the range of joint motions between some of the thinner, fainter, and deeply buried bones. Between using Didge to analyze the light videography and both XROMM and Didge software techniques to analyze the X-ray video recordings, we were able to define the range of rotational motion for all the joints of interest (table 1).

Table 1: List of Bullfrog joints under investigations and their ranges of motion.

| **Names of Bones** | **Range of rotation in degrees** | | | **Range of translation** |
|---|---|---|---|---|
| | **X** | **Y** | **Z** | |
| Skull to Spine/Atlas | $72^o$ | $120^o$ | $10^o$ | None noted |
| Skull to Mandible | $110^o$ | $0^o$ | $0^o$ | 3mm in dorsoventral plane |
| Mid Mandible Joint | $26^o$ | $0^o$ | $0^o$ | None noted |
| Chin Joint | $0^o$ | $0^o$ | $83^o$ | None noted |
| Superscapula to Humerus | $54^o$ | $160^o$ | $0^o$ | None noted |
| Humerus to Radio-ulna | $0^o$ | $180^o$ | $0^o$ | None noted |
| Radio-ulna to Hand | $87^o$ | $0^o$ | $0^o$ | None noted |
| Pubis to Femur | $0^o$ | $160^o$ | $0^o$ | None noted |
| Femur to Tibio-fibula | $180^o$ | $0^o$ | $0^o$ | None noted |
| Tibio-fibula to Tarsal | $0^o$ | $0^o$ | $153^o$ | None noted |
| Tarsal to Foot | $0^o$ | $0^o$ | $117^o$ | None noted |

B. Recovery of Geometry

The data that were used to build the three-dimensional computer model was recorded (by Mr. David Hammond, W.L. Gore & Associates, Inc.) using a clinical Computer Tomography Scanner (GE Lightspeed VCT scanner, Fairfield, CT, resolution: 512 pixels x 512 pixels x 302 slices). This resolution was fairly low, but ideal for this project as it corresponded well to the printing resolution of the 3D rapid prototyping printer that was used in the last stage of the workflow. The data was saved as a standard medical DICOM format image stack (fig. 7A). These data were then processed by Dr. Benjamin Gilles (Univ. of British Columbia) using Amira 5.0 (Visage Imaging, San Diego, CA), a medical visualization and analysis package. This software included an algorithm, to threshold and isolate the bones, a semi-automatic segmentation algorithm used to differentiate individual bones and finally a suite of standard algorithms to create an isosurface (marching cubes, mesh smoothing, and mesh decimation). The resultant mesh model was then imported into the three-dimensional animation package, 3D Studio Max 2011 (Autodesk, Inc., San Rafael, CA). 3D Studio Max allowed further cleaning and positioning of the bones as well as rendering animations and still images of the model (fig. 7B).

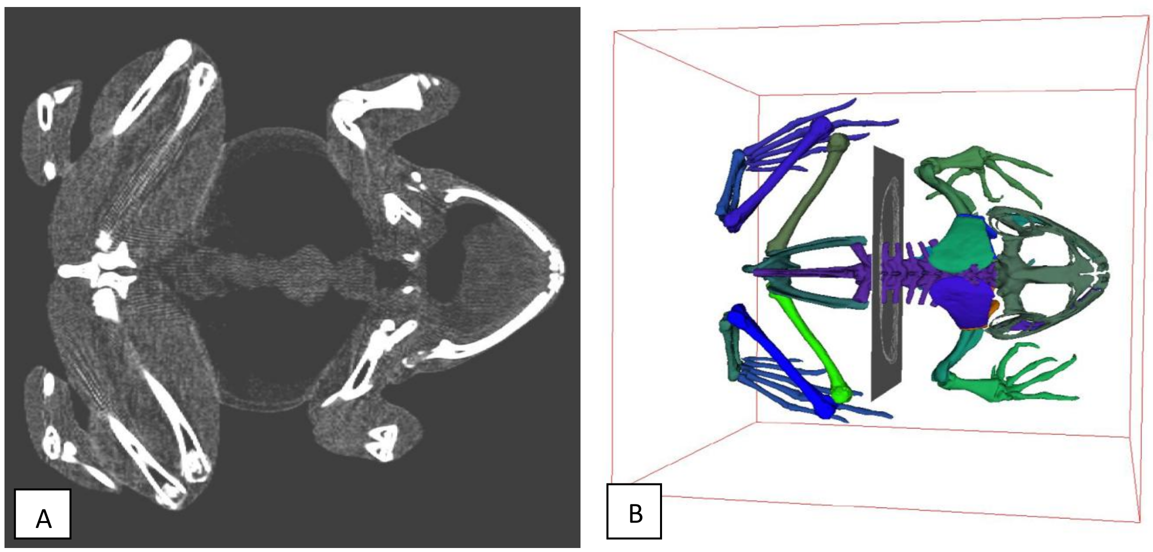


Figure 7: A) Single, mid-frontal slice of the clinical CT scanner DICOM image stack, B) Reconstruction of segmented 3D mesh model of the Bullfrog skeleton.

In order to use the 3D mesh model as input into a standard computer-aided design software package (SolidWorks, Dassault Systèmes SolidWorks Corp., Concord, MA) our student needed to clean the model up by normalizing all the surface normals and making a watertight (manifold) surface model. This was done using MeshLab (Paolo Cigoni, University of Pisa, Italy). Additionally, as many computer-aided design packages cannot modify mesh models, she needed to convert the model to a solid format using the software package Mesh-To-Solid 3.0 (Sycode, Goa, India). Our student was then finally able to input the bone geometry into SolidWorks (Dassault Systèmes SolidWorks Corp., Concord, MA), in order to design the mechanical joints.

C. Building the Model

The next step in the workflow was to utilize the range of motion and degrees of freedom that our student measured for each joint in designing replacement mechanical joints. We began by brainstorming ideas for mechanical joint designs to match the rotational, and in the case of the jaw joint, translational movements, of each individual joint. After choosing the most appropriate sketch, our student then used SolidWorks to modify the bone geometry to create the joint (fig. 8). Depending on the motion required, modification of the bones involved: A) replacing the space that contained the synovial bursa with a mechanical joint, such as a revolute or spherical joint; B) fusing the bones to mimic the lack of movement we saw during the prey strike behavior; or C) physically attaching the bones with flexible connectors, such as rubber bands or springs, so that the joint exhibited many degrees of freedom and a wide range of motion. Once all the joints were designed and implemented in SolidWorks, she then created an assembly of the full skeletal model.

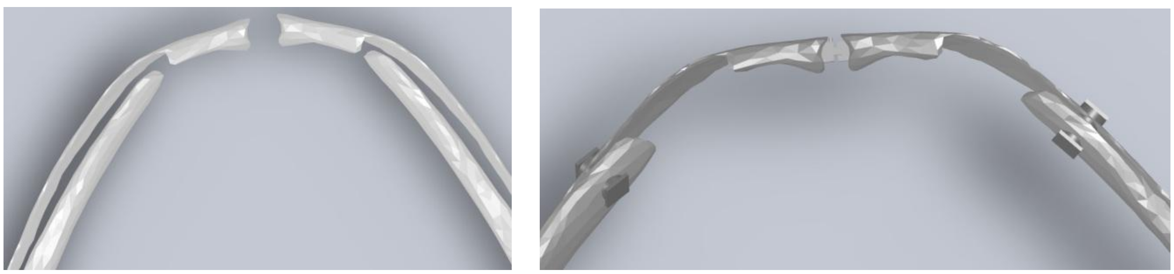

Figure 8. The jaw bones before modification (left) and the chin joint after modification (right).

Within the SolidWorks assembly, our student confirmed that the mechanical joints moved as required by the biological joint characterizations. To achieve this, she made a number of final corrections, modifications, and additions to the skeleton as a whole and finalized the kinematically accurate, geometrically sound computer-aided model ready for 3-D printing. The assembly was then imported into 3D printer's management software (CatalystEX, Dimension, Inc., Eden Prairie, MN). The printer was a fused deposition Dimension SST 1200es series printer capable of 0.254 mm resolution (Dr. John Tester, NAU). To ensure a structurally sound physical model, we increased the size of the skeleton by 2.5 times life size in order to match printer resolution to minimal part thicknesses (fig. 9).

Figure 9: NAU Mechanical engineering undergraduate student Amy Cook holding a prototype, 2.5x life-size skull.

## Conclusions

In summary, we have outlined a successful, unique, and multidisciplinary project that was completed in two semesters by a sophomore undergraduate mechanical engineering student. The workflow developed was suitable for building realistically articulated skeletons using geometry derived from a common medical imaging technique, and a practical application; the process will be used to generate other three-dimensional models of organismal structures of interest. These resultant models will be used to teach introductory anatomy and advance topics in comparative biomechanics (e.g. locomotory mechanics). The models can also be used to plan complex research surgeries and may also serve, when paired with artificial muscles and tendons, as a realistic robotic platform to test hypotheses of function and control.

From a pedagogical standpoint, this type of hybrid biology/engineering problem not only gives undergraduate engineering students expertise in communicating with non-engineers, but also real-world experience in the use of skills learned in introductory design courses. The design courses that were completed by our sophomore mechanical engineering student provided ample background to successfully perform almost all the design process skills that we evaluated. Outside of these design courses, only an introductory series of tutorials in biological theory and medical imaging was required to brainstorm and select a viable design concept. As such, we feel that interdisciplinary projects are quite feasible at the sophomore level and could be implemented on a larger scale. Thus, based on our experience, we recommend that closer interactions between mechanical engineering and biological sciences departments at universities should be fostered and that it would be beneficial to offer students the opportunity to work on projects with a focus on functional biology at some point during their undergraduate mechanical engineering program.

From a practical standpoint, we have found some real benefits and a few surmountable drawbacks to interdisciplinary collaborations. The first benefit is that collaborations allow a student to partake in a project that depends on a wide range of skills and areas of expertise. Since no person has mastery over any one aspect of the project, working in collaboration provides an opportunity to share the talents and experiences of both mentors and students to tackle a design problem. While we found that efforts expended by our advisors was as taxing as any traditional solo advisor project, a second benefit to collaborating was that, with strict organization and scheduling, a comparatively more complex project was completed in a relatively short period of time. However, working in a collaborative project is both a joy and a challenge. To ward off friction before it starts, team members cannot assume that others have an appropriate conceptual understanding without good communication skills. Also, schedules must be carefully organized and rigidly adhered to otherwise informal meetings can fall through cracks and duties can be lost at the bottom of daily job lists. All members of our team felt that this experience was a positive one because of two conclusions that we offer as suggestions to similar projects in the future:

1. Assign clear roles and work assignments – organization of tasks and scheduling of concrete deadlines were crucial and should be done as soon as possible and as part of the project workflow. As in any undergraduate project, it is important for the student to have clear goals and duties, but this is also especially true for collaborating advisors. It is critical for each member of the team to be assiduously responsible for his or her assigned responsibilities. We recommend selecting a single "lead" advisor to ensure continuity in the project for the student regardless of the task that he or she is currently performing. To us it seemed appropriate to choose the non-engineer as the lead advisor so that the engineering student could view the leader as the customer to whom the final product would be delivered.

2. Communication is key – A few things are best done as a team, such as brainstorming and evaluation of concepts. However, most work is done by the student alone or with a single advisor. As such it is important to update all members of the team with brief and regular accountings of completed tasks and assigned responsibilities. This communication encourages an atmosphere of trust and respect in which team members feel free to express their ideas.

In conclusion, an introduction to biomechanics may serve undergraduate mechanical engineering students well. This type of cross-training provides an avenue to a relatively understudied area of "evolutionary engineering" that holds the potential to provide students of mechanical design with a plethora of novel solutions and design ideas. Such training stimulates creativity by encouraging mechanical engineering students to consider organismal or bio-mechanics as part of their domain from which they can draw inspiration to solve a problem. Indeed, identifying the functional mechanism behind how a certain animal performs some behavior with surprising efficiency or how some organismal mechanism can be used for a task for which we do not yet have a human-engineered counterpart represents an important educational skill to be taken advantage of by our undergraduate engineering students.

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