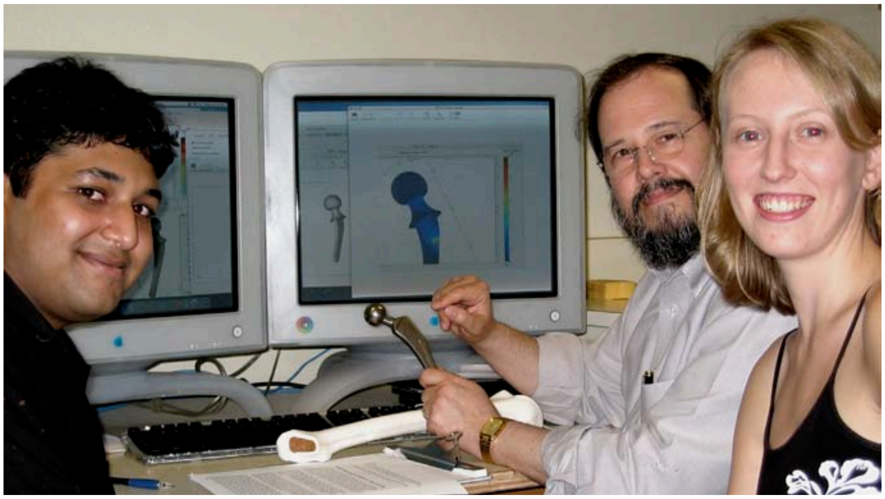
Biomedical Engineering and Multiphysics:

Joined at the Hip

"Traditional" engineering curricula teach foundational principals based on either technical disciplines (chemical, electrical, materials, systems/control) or thematic disciplines (aeronautical, civil, computer). In contrast, newer fields such as biomedical engineering—a field for which leading-edge institutions have set up separate departments with a status equal to traditional degreed programs—are interdisciplinary; they require students to become familiar with basic principles in a wide range of topics. In this sense, biomedical engineering is an excellent example of multidisciplinary and multiphysics applications, and innovative educators are turning to software such as COMSOL Multiphysics for everything from entry-level courses to post-doctoral research

by Paul G. Schreier

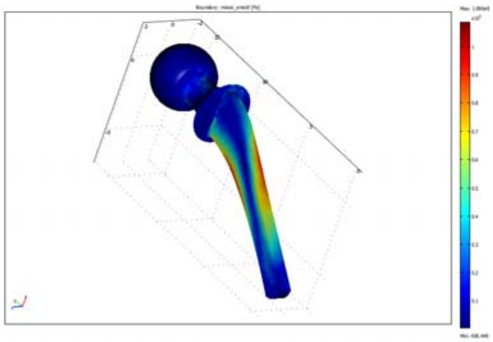
A striking example comes from Dr. Richard T. Hart, Chairman of the Department of Biomedical Engineering at Tulane University in New Orleans, Louisiana. At the basic level, he teaches a freshman-year introductory course called "Elements of Biomedical Engineering Design," whose purpose is to introduce students to all the varied aspects of engineering that enter into biomedical-engineering projects. As part of the course, he gives assignments that require the students to create models in COMSOL Multiphysics. In addition, graduate students and post-doctoral researchers working under Dr. Hart use the software to find new knowledge about how bones react to physical stress and other stimuli.



Professor Richard Hart (middle) discusses the simulation of a hip replacement with two undergrad members of the "BoneHead Lab," Apu Borcar (left) and Katie Nobes (right).

Dr. Hart has been using finite-element software in his graduate-level biomedical engineering classes for two decades, although he started with self-written codes for structural analysis. "I discovered COMSOL Multiphysics just a few years ago, and I was struck by how cool it would be to have a biomedical finite-element course that could incorporate not only structural aspects but also thermal, electromagnetic, and other physics." Adds Dr. Hart, "I've never known a program that is so powerful and intuitive at the same time," which made it a perfect candidate for classroom use as well as for research assignments.

One class project consists of using COMSOLMultiphysics to design and analyze a hip-replacement assembly. The first-year students follow a series of step-by-step instructions that lead them from geometry creation to post-processing analysis. "My colleagues were quite skeptical," notes Dr. Hart, "they said there's no way freshmen can do finite-element analysis. After all, the students haven't yet even studied statics or covered differential equations." Dr. Hart, on the other hand, felt that his students at



The hip-joint replacement that freshman biomedical engineering students create with COMSOL Multiphysics. This plot reveals the locations of concentrated stress and help predict where the initial failures on the metal stem might appear.

such an early stage don't need details of those and other topics. Instead, he uses modeling to give them an intuitive feel for engineering and thus provide a strong motivation for digging into specific topics when they study them in later semesters. In fact, he told his students about his colleagues' skepticism and turned that fact around, literally challenging his students to work through the models, review the results, come up with good questions, and prove the sceptics wrong.

The result? The finite-element project was a highlight of the academic year for the students. A typical comment was, "This is really cool, this is real engineering!"

How bones respond to stress

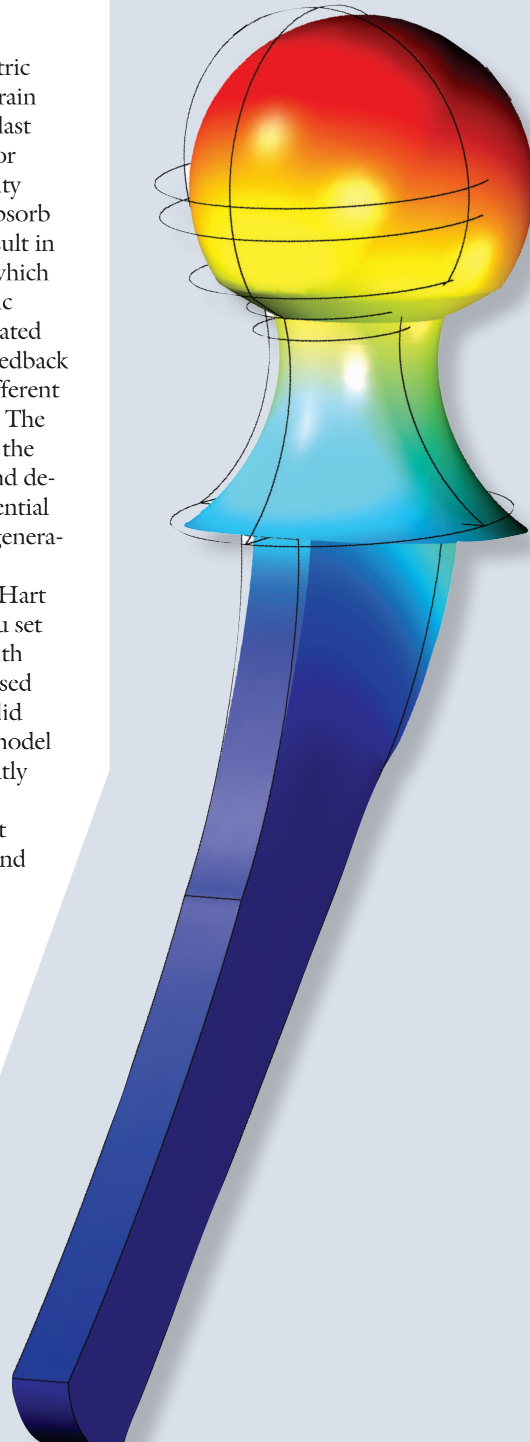
With his graduate students, Dr. Hart is performing COMSOL Multiphysics studies to determine what factors are most important in triggering the body to create new bone mass and to predict how bone responds to various stimuli; he wants to model and predict bone adaption, perhaps leading to new therapeutical treatments.

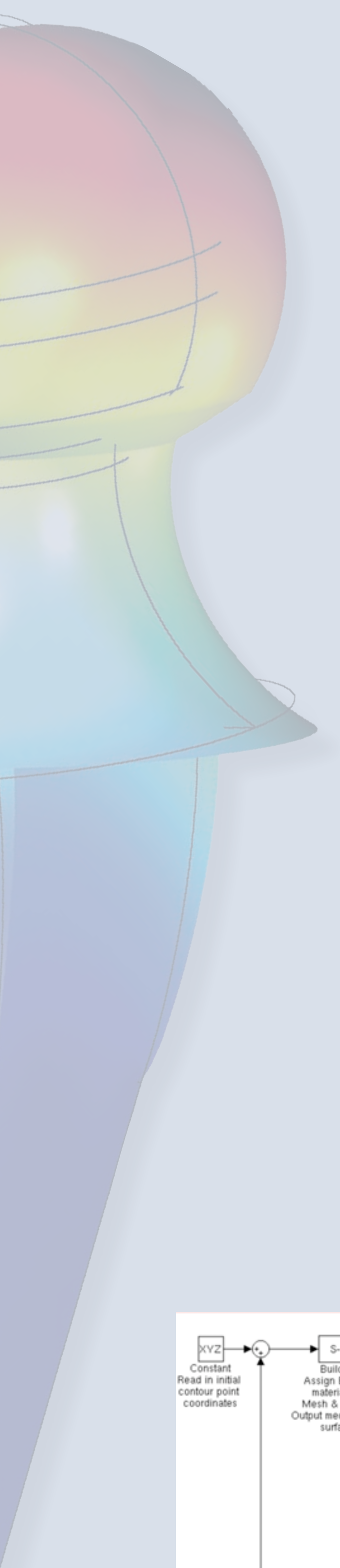
"Bone is not at all an inert, dead material," he explains, "and the skeleton is very dynamic." Bones change in size and composition due to stimuli such as exercise. He continues, "consider a professional tennis player. The bone in the arm used for serving can be as much as 30% greater in diameter than that in the other arm. On the other hand, we know that astronauts lose bone mass in space due to weightlessness. We also know that the skeleton undergoes remodeling, whereby the body replaces the entire skeleton every 7 to 10 years. For most people there's no net change in bone volume, but we are all familiar with bone loss in the elderly. What we as scientists don't know is which stimuli have the largest impact on bone growth. It's also amazing that a load that happens in a matter of seconds can have effects that don't appear for weeks."

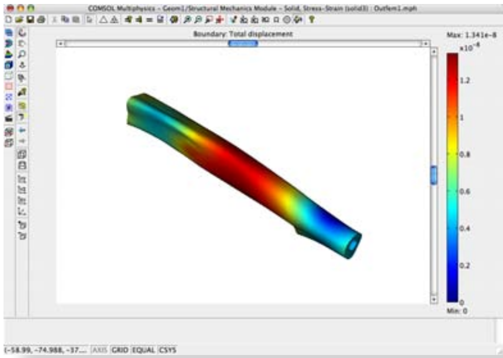
Bone changes size in response to stimuli such as a load, hormonal levels, and metabolic health; other factors include the addition of an implant, when a person takes a pharmaceutical agent, or the lack of gravity. Based on the bone's geometric and material properties, a certain strain results. This strain results in osteoblast activity (creating cells responsible for building bone) and osteoclast activity (creating cells that degrade and reabsorb bone). These concurrent actions result in some degree of bone remodeling, which in turn impacts the bone's geometric and material properties such as elevated Young's moduli, thus closing the feedback loop because the load now has a different effect on the remodeled bone mass. The key unknown, explains Dr. Hart, is the "transducer" that reads the strain and determines the strain remodeling potential that is a factor in dictating bone regeneration or deterioration.

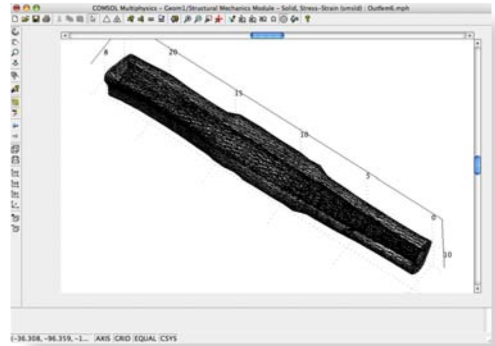
To study this phenomenon, Dr. Hart and post-doctoral researcher Xia Liu set up a SimuLink model combined with COMSOL Multiphysics. A script-based procedure iteratively generates a solid geometry and finite element (FE) model from these contours and subsequently performs a stress analysis. Then the model updates bone shape to reflect surface formation and resorption, and from these contours it reconstructs the bone geometry, remeshing at each time step.

In these studies, they use SimuLink to set up and define the parameters in this feedback loop, at this time using only loading as an external stimulus. That program calls COMSOL Multiphysics and the Structural Engineering Module to perform the structural analysis. The students find it easy to link the two packages because COMSOL Multiphys-







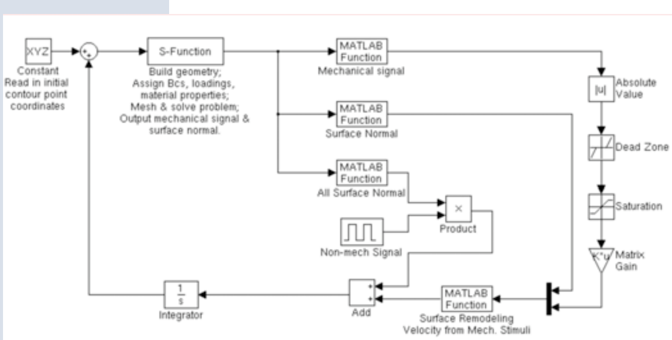


Initial shape and displacement plot for an experimental tibia (left). Mesh for the adapted model showing simulated addition of bone in the cross-section of the midshaft (right).

ics allows for quick, easy integration into SimuLink without any coding. In addition, although the existing model is relatively simple so as to explore global ideas, COMSOL Multiphysics makes it easy for members of the group to increase the model's sophistication such as by adding details of cell diffusion and nutrient uptake to better determine bone response.

Many researchers are trying to come up with a good model of bone growth, measuring the depth of bone formation vs. various signals. A key goal for Dr. Hart is determining to which signal the "transducer" is most sensitive. Today, most people have selected the strain energy. As an exercise in verifying his model, Dr. Hart worked with Michael Roberts, a recent doctoral student, on running simulations with many possible signals, looking for the one with the highest correlation to the real world. "Much to our surprise, the mid-principal strain, which has a relatively small magnitude, was the signal with the highest correlation. This is puzzling, and we now have to create an experimental model sophisticated enough to confirm or refute this initial result. After that we plan to add multiphysics aspects to the model to account for dynamic loading and physical effects such as diffusion and cell signaling to take the simulations from phenomenological models towards mechanistic models that incorporate observable biological parameters. These next-generation efforts will only be possible with the use of sophisticated multiphysics capabilities. The potential to learn from the modeling efforts—and the measured parameters needed to drive the simulations—is really exciting!"

"I've never known a program that is so powerful and intuitive at the same time."



SimuLink model, with calls to MATLAB and COMSOL Multiphysics, to simulate adaptation to mechanical loads simultaneously with non-mechanical growth.