Replacing Nature’s Shock Absorbers

Scripps Health researchers use Abaqus to optimize new knee replacement designs and explore surgical alternatives

Tiger Woods’ infamous knee injury occurred in 2008, around the same time that the Shiley Center for Orthopaedic Research & Education (SCORE) at Scripps Clinic in California published a study of knee replacement patients with tiny computer chip implants added at the time of surgery. The chips sent radio telemetric data to receivers that recorded the stresses on the knee joint while golfing. “The force we measured in our patients—who were nowhere close to Tiger’s skill level—was four and a half times body weight on the leading knee when they were hitting a drive,” says the laboratory director, Darryl D’Lima, M.D. Ph.D. “So his injury came as no surprise to us.”

The researchers are now monitoring the same implant patients as they ski. “It is our goal to study the effects of a whole range of movements on knee health,” says D’Lima.

Knees Are the Body’s Achilles Heel

Your knees are at risk for damage and/or arthritis over time because of something that everyone does: grow older. “Mother Nature designed the human knee to last about 30 years,” points out D’Lima. “But the human lifespan has expanded much further than that, and evolution hasn’t caught up.”

Tiger Woods’ ACL (anterior cruciate ligament) injury responded positively to microsurgery and physical therapy. But many people do not fare so well if they sustain damage to a critical cartilage deeper inside the knee: the meniscus.

The meniscus is made up of two C-shaped pads of cartilage tissue, located between the joints formed by the bottom of the thigh bone (femur) and the top of the shin bone (tibia). When a meniscus is torn, or wears out, the knee can lock up, making walking impossible. Because the meniscus has a very poor blood supply, it does not heal well on its own.

Fifty years ago, surgeons solved the problem by removing the entire damaged meniscus because they thought it didn’t serve any purpose. Patients walked out the hospital door, but five years after meniscus removal they were back—with osteoarthritis (OA). Removing only damaged parts worked better, but OA still developed after 15 years.

“If we’d only had FEA back then, surgeons would have known that tissue removal was the wrong way to go because it takes away key biomechanical support of the knee,” says D’Lima. The meniscus turns out to have a very important function as both a spacer and a shock absorber, providing load sharing, contact stress amelioration, and stability—all of which can be studied with FEA.

FEA and MRI Help Model the Knee

D’Lima’s research team is using Abaqus FEA to make “virtual” computer models of human knee components on which they can test a

variety of potential replacement parts and surgical techniques. “I’ve only been able to solve the complex material and contact problem to my satisfaction in the last couple of years since I started using Abaqus,” he says.

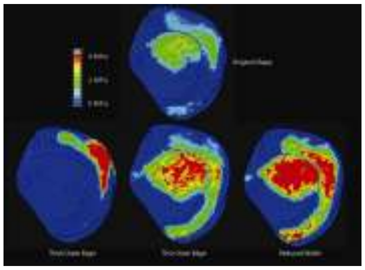
Some of the data used to set up the FEA models comes from those earlier implant patients who golfed and skied while sending out radio telemetry. “The sensors in our patients’ knees provided us with force measurements that we were able to use as load inputs,” D’Lima says.

Meniscal replacements are the holy grail of a number of research projects, at Scripps and elsewhere, that aim to help patients with damaged menisci avoid knee arthritis entirely by implanting allografts (from cadavers), artificial biomaterials, or even tissue engineered from the patient’s own cells.

Whatever the materials being proposed for meniscus replacement, a number of problems need to be solved in order to achieve optimum knee function. Among these are duplicating complex material properties, matching the size and shape of the replacement to the patient, and figuring out how to attach it in place. “For each of these challenges we are finding that FEA, combined with magnetic resonance imaging (MRI), provides the tools we need to study the alternatives,” says D’Lima.

The pairing of MRI and FEA has greatly benefitted medical R&D in recent years for accurate modeling of human body parts. Design engineers can now convert two-dimensional MRI “slices” into stacked 3D CAD models detailing bone, articular cartilage, other soft tissues (like the ACL) and meniscal cartilage. During the process of modeling, SCORE found that the golfing, skiing knee-replacement patients again proved useful, this time providing data for boundary conditions.


A 3D CAD model was created from two-dimensional MRI images of a knee joint.


Abaqus FEA models of knee menisci demonstrate the importance of dimension (size and shape) to optimal stress reduction in the knee.

It’s All About the Materials

The first modeling challenge was representing the material properties of the meniscus accurately. “One of the reasons it’s difficult to study biological tissues, especially the meniscus, is that every possible complexity exists within the same material,” says D’Lima. “Abaqus FEA can represent any characteristic we need and also stack all of the material properties into the same model.”

Once their models were set up, the group validated the contact algorithms, using pressure data physically recorded inside actual joints of cadaver knees, against their MRI/FEA model predictions.

SCORE next turned its attention to shape. It turns out that the variation of thickness of the meniscus is critical. “Small changes in dimension, even just ten percent, mess things up,” says D’Lima. “If the outer edge of the meniscus is too thick or too thin, when you run the FEA analysis you see excessive stress creep in. Nature gets it right during development because everything—bones, ligaments and cartilage—grows to fit each individual.”

FEA Helps Evaluate Alternative Surgical Techniques

Another research challenge was the question of how best to fix a replacement meniscus (with either bone plugs or stitches) in its new knee environment. Here again, FEA provided a useful analysis tool: The SCORE group researched suture materials to get strength and stiffness data and incorporated “virtual stitches” into their FEA knee models to study the contact stresses. They determined that a suture stiffness of about 50 Newtons per millimeter approached the performance of bone plugs (a more complicated surgery). “So you can get the same mechanical fixation with less invasive surgery,” says D’Lima.

Optimizing Custom Meniscal Replacements

“Now that we have the design pipeline in place, we can essentially begin optimizing knee replacement to each person who needs it,” says D’Lima. “We can identify what shape is best for a particular individual, what are the material properties that will work best in that person’s knee, and make recommendations about securing the implant surgically.”

To generate and explore the algorithms that best describe the “perfect” meniscus for a single patient, D’Lima’s group has recently begun employing SIMULIA’s Isight for simulation process automation and design optimization. “Isight is a very useful tool for customization,” says D’Lima. “We’re using it to optimize the material properties and shape of the meniscus. With our experimental data in hand, we can keep changing the characteristics of our finite element model until we identify that particular complex material model that satisfies all our conditions.”

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