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BRINGING SIMULATION TO SURGERY:
IMPROVING THE SUCCESS RATE OF HIP REPLACEMENTS
Joint replacement surgery is one of the most successful procedures in medicine because it can relieve pain and permit patients to return to productive lifestyles. However, there are times when joint replacements need to be redone because of loosening or wear. One way to enhance the conventional joint replacement process is to evaluate the effects of an operation prior to surgery. What is the correct type of implant for this patient? Where, precisely, should it be placed? How should it be installed and secured? Surgeons currently cannot address these issues except by trial and error and clinical experience, which can take years to develop. Yet their decisions may determine the success or failure of these operations.

This is the promise of computer simulation. By studying the outcome of a joint replacement operation in software prior to surgery, surgeons can evaluate different options to find the best surgical plan for each individual. This is the goal of surgeons and researchers at the Center for Orthopaedic Research (COR) at Shadyside Hospital (Pittsburgh, Pennsylvania) and the Center for Medical Robotics and Computer Assisted Surgery (MRCAS) at Carnegie Mellon University (Pittsburgh, Pennsylvania).

The research team is developing a computerized surgical simulation system that will predict the outcome of patient-specific hip replacement procedures. Their ultimate aim is to provide as many tools to surgeons as possible so the joint replacement process works every time. Finite element analysis (FEA) software, which makes it possible to simulate physical behavior using a computer, forms the system's foundation.

Why Hips

Each year, orthopaedic surgeons in the U.S. perform 250,000 hip replacement operations. Worldwide the number of these surgeries is close to 800,000. At a cost of about $25,000 each, hip replacements are typically performed to restore movement to an arthritic joint. (If the procedure has to be repeated, the cost runs between $50,000 and $75,000.)

In a hip replacement operation, the top portion of the patient's femur (upper leg bone) is removed. This is the “ball” portion of the ball-and-socket hip joint. Also removed is the cup within the pelvis into which the ball fits. These diseased bones are replaced with artificial devices called implants. The rounded end of the femoral implant fits into a new socket in the pelvis, similar to the way the original, diseased bone did.

A hip replacement operation is one of the more difficult joint replacement operations for several reasons. First, its outcome has a tremendous effect on the patient's quality of life. Second, there is much variation from patient to patient in terms of bone geometry and mechanical properties. Third, many surgical parameters may vary as well; for example, there are different types and sizes of implants and different ways to prepare the bone during surgery.
Research at Shadyside Hospital/Carnegie Mellon University is presently focused on one particular type of hip replacement procedure—the cementless, press-fitted implant. This implant accounts for approximately one-third of all femoral replacements and nearly all socket replacements.

This technique relies on bone growing into the porous implant over time to hold it in place. However, to achieve initial stability the surgeon selects an implant that is slightly oversized with respect to the cavity cut into the bone. The relative sizes of the implant and the bone cavity are critical. If the cavity is too small, the surrounding bone may deform when the implant is pushed into place, leading to fractures. On the other hand, if the cavity is too big, the implant will be loose and bone growth into the implant will not occur. This will cause the implant to loosen and cause pain. In fact, gaps as small as 0.25 mm between the implant and bone have been shown to prevent bone ingrowth.

Another factor that complicates this procedure is installation force. To get the implant into the smaller cavity, substantial force is required. Consequently, some deformation of the bone occurs. Too much force increases the risk of cracking the bone, while too little force poses the risk that the implant may not be situated properly creating residual gaps, so that bone ingrowth will not occur.

Ideally, a computerized surgical simulation system will let surgeons work out issues such as these in advance. The research team at Shadyside Hospital/Carnegie Mellon University has studied the mechanics of normal, diseased, and replacement joints in their efforts to create such a system. The goal is to give surgeons a tool that allows them to determine clinically meaningful issues such as proper implant fit, the ideal amount of bone to remove when creating the cavity for the implant, how the bone will react to the installation, and so on. Ultimately, they hope to give the system the ability to predict the long-term behavior of the implant as well.

Simulation Method

The first step in simulating a hip replacement operation is acquiring geometric representations of both the patient's bone and the implant. The geometry of the implant is relatively easy to come by. Most vendors have modeled the device in a CAD system and this data can be read into the FEA system very easily.

Obtaining a geometric representation of the patient's bone is somewhat more difficult, but critical because this is what makes a simulation patient-specific. Currently, the patient's Computerized Tomography (CT) scan (which represents bone outlines in the form of voxels) is converted to a solid model using published algorithms. The solid model is then converted to IGES format for input to the FEA program. Although this process works well, one aspect that the Shadyside Hospital/Carnegie Mellon University research team is working on is improving the conversion of CT data to solid models—creating algorithms that are able to differentiate between different types of bone tissue, for instance.

Once the necessary solid models are available, the next step is preparing them for analysis. This includes converting them to meshed finite element models, specifying material properties, and applying boundary conditions. (Boundary conditions are loads and restrictions applied to the simulation so that it mimics real life.)

The research team chose the finite element method, and the ANSYS program in particular for several reasons. First, the finite element method can reproduce the complexity of biological structures, joints, and materials. Second, the bone-implant system exhibits highly nonlinear behavior, both in terms of geometry (large deformations) and materials. (The nonlinear nature of the problem is one reason the surgeon's job is so difficult, and why there is such a need for a surgical simulator. Results of actions in the operating room, since they behave nonlinearly, are not always intuitive.) Not all FEA packages can perform nonlinear analyses; ANSYS, is particularly strong in this regard.

ANSYS supports a certain type of finite element that is critical to understanding contact between bone and implant. This is the "point-to-surface" contact element. This type of element is needed because the position of the implant immediately after surgery cannot be predicted. It must be obtained by a finite element analysis of the interference fit between bone and implant. Most FEA systems provide only "point-to-point" contact elements that require that the location of interference be known before the analysis begins.
As the first step toward a full-fledged patient-specific hip replacement simulator, the research team developed a non-linear, axisymmetric, contact-coupled finite element model of the implant and the acetabulum (portion of pelvis that contacts the implant). Although the geometry of the acetabulum was idealized to reduce the complexity of the model, other factors were included to add realism to the analysis, such as nonlinear material properties, large deformations, and general frictional contact coupling.

In the initial analysis, the implant was placed outside the bone and directed toward the prepared cavity. Incremental displacements, which in effect drove the implant into the cavity, were applied to the implant to simulate the forceful insertion that happens during surgery. The final image in figure 3 shows the implant at rest in the final position with no external forces or joint loads applied.

The analysis, which was performed on a DECstation 5000/240, showed radial strains and hoop strains in the bone for the four steps of the implantation procedure. This particular simulation predicted significant strains in the bone and a large gap between the implant and the bone in the polar region.

Because model geometry was described using several basic geometric parameters, researchers were also able to perform parametric studies to evaluate the influence of the implant size. The results made it clear that larger implant oversizing may result in excessive strains, especially in the periphery of the acetabulum.

This data, unavailable to surgeons in the past, gives valuable information about the immediate post-operative state of the bone-implant system. The clinical consequences of these findings imply probable cracking of the bone in the areas of large strain and reduced possibility of bone ingrowth into the porous area of the implant. Researchers also learned that the assembly strains in the bone due to implant insertion can be as much as an order of magnitude larger than those caused by normal joint loads.

Beyond Pre-Operative Planning

Once the basic simulation system has been perfected, the research team has exciting plans for expanding its functionality and usefulness. One idea is to use the design optimization capabilities of the FEA software to let doctors examine more surgical options than they could by simply running a handful of analyses and viewing the results.

The first part of this idea involves using the software's sensitivity analysis capability to determine which variables are most critical to the success of a particular operation. A sensitivity analysis investigates the effect of selected variables on the desired outcome. In a hip replacement operation, the desired outcome might be that the installation process not exceed a certain, patient-specific level of stress on the bone surrounding the cavity. ANSYS will look at all the surgical variables and indicate the degree to which they affect the stress levels. The surgeon might learn, for instance, that for a particular patient, the size of the implant may be relatively inconsequential compared to the location of the cavity. This sort of information can be critical to pre-operative planning.

The second part involves using the automatic optimization capabilities of the software to run through all combinations of possible surgical variables, automatically evaluating each variable throughout its entire specified range. There is no way a surgeon could do this manually, running a separate analysis for every combination of variables. But ANSYS does this automatically and returns optimal values for each variable in a patient-specific surgery optimization. A tool such as this may improve the success rate of hip replacement surgery.

Another extension of the surgical simulator system is to use the results of the optimization process to guide surgical robots or other "smart" tools. By coupling the robot with the surgical simulator, a surgeon can not only plan an "ideal" surgery but also ensure that it is carried out using data from the optimized ANSYS model to guide a robot or other new image-guided surgical tool.

Future Directions

Two issues still need to be resolved before a hip replacement surgical simulator system gains widespread use. One is to make it fast enough to be feasible. Currently, the system takes too much time to be a vital part of the surgeon's planned operation. But the research team expects this to change in just a few years thanks to continual improvements in both the hardware and software components of the system.

For example, powerful computers able to simulate the complexities of the human body are now affordable for appli-
cations such as this. And FEA software now delivers results far faster than before. The latest release of ANSYS includes a faster analysis methodology, called PowerSolver, that cuts solution time by at least an order of magnitude compared to conventional solver technology. These improvements have made it possible to run analyses on a scale that can reproduce the complexity of biological structures, joints, and materials. As hardware and software improve even further, real-time surgical simulation will become possible.

A second issue is the simulator’s user interface. As the research team shows this technology to other surgeons, they find that although the surgeons may know nothing about FEA, they immediately grasp the information in an FEA results plot. A picture, or FEA output, is worth a thousand words to these medical professionals. However, unless they also have a background in engineering, as the research team does, they are not able to perform an analysis on their own since the ANSYS user interface is geared to engineers. The research team plans to package this technology in a way that medical doctors can more easily understand.

The medical community is excited about the potential of a hip replacement simulator, in part because it isn’t necessarily limited to hip replacements. Operations involving everything from knee and shoulder replacements, artificial limbs, heart valves, and artificial hearts might someday be simulated to improve the outcome.

Typically, FEA software is used to help companies design better products, including everything from jumbo jets to cars to electronics equipment. This application of FEA, while somewhat unusual, means ANSYS software will be used to directly improve people’s lives.