

SIMULATION OF IMPLANT FITTING IN THE FEMUR BONE

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ABSTRACT

This research aims to simulate implant-fitting procedures in the human femoral anatomy. Three-dimensional models of the femur and metal femoral implants are used to build a custom-fitted implant model, with the aim of benefiting medical practitioners and patients.

Key words: Computer simulation, femur bone.

INTRODUCTION

Computer-aided surgery is becoming common in today's world, as trends toward geometrically precise and minimally invasive surgery accelerate. These trends are driven by the desire for better clinical results, and to lower overall costs through shorter hospital stays, shorter recovery times, and reduced need for repeated surgery.

Advances in medical imaging technology such as computed tomography (CT) and magnetic resonance imaging (MRI), combined with the advances in computer-based image processing and modeling capabilities, have given physicians the ability to visualize anatomic structures in live patients. Physicians can now use this information to improve diagnosis and treatment planning. A number of systems have been developed for various forms of neurosurgery, orthopedics, ophthalmology, craniofacial surgery, and otolaryngology, among others. A common characteristic of these systems is that they rely on position sensing during the surgical procedure to enhance the surgeon's ability to manipulate surgical instruments very precisely and to accurately execute a plan based on three-dimensional (3D) medical images. By combining human judgment with machine precision, such systems permit a surgeon to perform critical surgical tasks better than can an unaided surgeon (Taylor et al., 1996).

Computer simulation of surgery is not only limited to the femur; various works have been carried out for facial reconstruction. For example, computer simulation has been used to simulate maxillofacial surgery and to predict the outcome of the surgery (Girod et al., 2001). This helps the patient to visualize the outcome before surgery. Researchers (Morris et al., 2005) have developed a real-time interactive craniofacial simulation system for various facial reconstruction processes.

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PROBLEMS FACED AND OBJECTIVES OF RESEARCH

Patients have been exposed to risk of infections, repetitive or even failed surgeries using the current trial-and-error approach in orthopedics. According to Rockwood et al. (1996), surgeons have measured the femur bone on the operating table, and repeatedly tried to insert the implants in hopes of achieving an exact fit. This method also includes removing some amount of the bone surface from the front, ends, and back of the femur.

The financial cost of an implant insertion procedure and the post-operative treatments may increase as some patients need to undergo corrective surgeries. As financial cost increases, so do the time taken to perform the surgeries and the time for the patient to fully recuperate.

The femur possesses a rich vascular supply. Therefore, major blood-loss into the thigh is present in most cases. If a surgeon is not cautious while inserting the implants, severe damage could occur in the blood vessels resulting in delayed healing or even worse, paralyzing the thigh and knee movements (Rockwood et al.,1996).

At present, simulation of femur implant surgery is carried out using synthetic bones. Medical students and surgeons conduct trial surgeries by cutting these synthetic bones and fixing implants on them. This technique is considered useful, but proves to be expensive since the bones are non-reusable and it usually takes hours of practice to achieve the required skills (Sourina and Sourina, 2000).

Most implants are currently manufactured in Europe, tailored to meet the anatomical needs of Caucasians. Asians however, have different skeletal structures where the lateral groove and lateral epicondyle are curvier.

The current method of orthopedic surgery imposes high financial costs and long recovery periods. With the aid of computer simulation, the actual procedure would take minimal time, hence reducing the financial burden.

The responsibility of carrying out a perfect surgery is very tedious whereby surgeons have to measure and cut/drill the femur repeatedly to ensure an exact fit of the implant. This research contributes to a less tiresome approach.

METHODOLOGY

The Knee Implant

The knee is considered as a hinge joint because of its ability to bend and straighten like a hinged door. However, it is much more complex in reality because the surfaces actually roll and glide as the knee bends. The first implant designs used the hinge concept and literally included a connecting hinge between the components. But newer implants have recognized the complexity of the joint and attempt to replicate more-complicated motions and to take advantage of the posterior cruciate ligament and collateral ligaments for support. Figure 1 shows the implant fixation of the knee.



Figure 1. Implant fixation of the knee

In the following subsections, the two major steps involved in the simulation process are described using the femoral knee implant as an example:

- Reverse engineering, for producing a virtual 3D model of the metal femoral implant component.
- Transformation and fitting in a 3D modelling environment to carry out the necessary transformation.

Reverse Engineering

Reverse engineering is the process whereby scanned data of an implant are transformed into a 3D model. As shown in Figure 2, the implant model (acquired by laser scanning) was initially a point cloud data set, and no further manipulation can be done in this format. Thus, reverse engineering is needed to resurface the model for import into 3D modelling platforms.

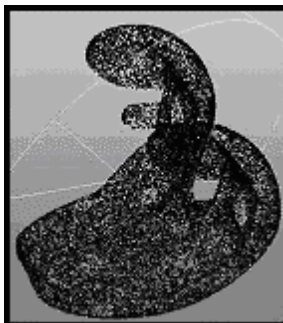


Figure 2. Implant in point cloud form

In reverse engineering, the following steps are carried out:

1. Noise reduction

Noisy elements are frequently introduced into scanned data. This is due to factors such as small vibrations in the scanning device, inaccurate scanner calibration, or poor preparation of the physical object's surface. The noise can be identified by a rough, uneven appearance on the surface model.

Statistical methods were used to determine where the points should be and to move them to their proper location. Since the implant is an organic shape, freeform shapes were chosen to reduce noise with respect to surface curvature. Smoothness level was set to medium to avoid losing too much data.

2. Sampling

Uniform sampling uniformly reduces the number of points in a point set. It subdivides the model space into equally sized cubical cells and deletes all but one point from each cell. However, it still maintains the accurate representation of the point cloud model.

Curvature sampling samples points based on surface curvature to produce an accurate wrap model with fewer points, thus reducing computation time. Points that lie in a high-curvature region are retained in order to maintain the accuracy of the surface curves. On the other hand, points on flat regions are more likely to be deleted because these regions require less detail. Figure 3 shows that points on curved areas are more prominent after sampling is done.

Sampling processes can be considered as a trade-off between accuracy and storage space. The data might not be 100 percent accurate anymore, but they will take up less memory space, leading to an increase in the processing speed.

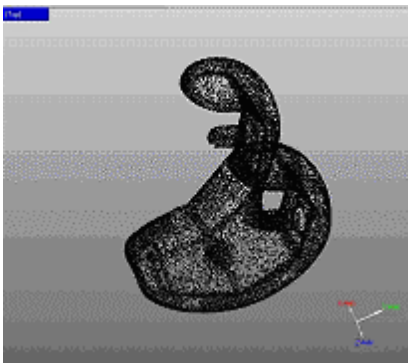


Figure 3. Implant after curvature sampling

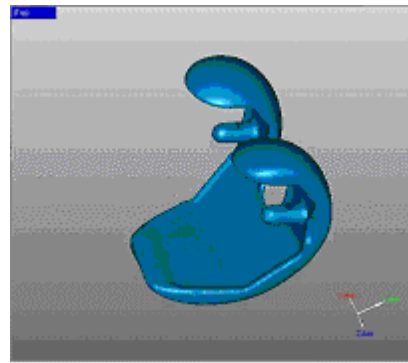


Figure 4. Implant surface wrapped polygonal model

3. Surface wrapping

The wrap operation is done to construct a polygonal surface as seen in Figure 4. The process of surface wrapping takes the implant model after curvature sampling, joins disconnected

surfaces, and removes interior and overlapping surfaces. The main benefit of this process is that it drastically reduces time spent on surface preparation.

4. Filling up the holes

Regions with missing data are filled. After holes are filled up, the number of points decreases whereas the number of triangles in the model has increased.

5. Creating a non-uniform rational B-spline (NURBS) surface

The complexity of the geometry model was automatically detected to create the NURBS surface. The result is shown in Figure 5.

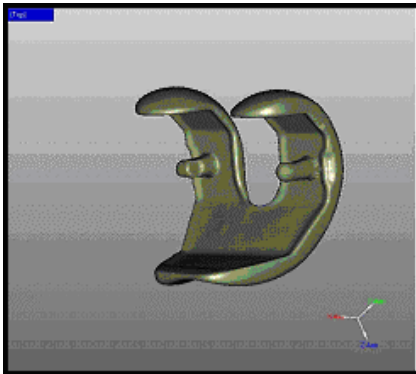


Figure 5. Surfaced implant model

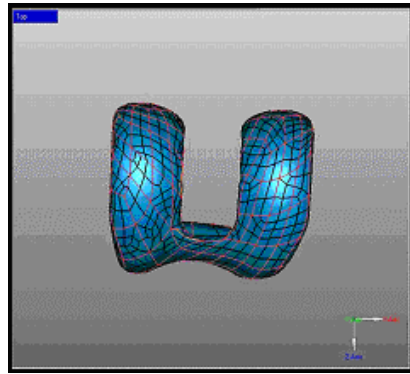


Figure 6. Patched implant model

6. Relaxing the surface

The relax operation smoothens the surface of the polygon model by changing the input vertices. This was to obtain a fairly smooth surface without compromising the accuracy of the original data.

7. Constructing patches

Patches need to be constructed on the surface of the model to create curves. Contours were simplified so as to obtain perfect shuffle patches. Figure 6 shows the implant after the surface had been patched.

8. Creating curve model

Curves are created because they are very important features in the fitting module. These curves will be transformed (bent, scaled, etc.) for the implant to be fitted on the bone specimen.

9. Analyzing the curve model

The curve model can be analyzed to obtain important statistics as shown below.

Radius (in mm):

| | |
|-----------------------|------------------------------|
| Minimum: 0.0004164346 | Average: 24.01663 |
| Maximum: 11102.62 | Standard deviation: 88.68865 |

Curvature (in mm):

| | |
|----------------------|------------------------------|
| Minimum: 9.006884e-5 | Average: 0.3243133 |
| Maximum: 2401.338 | Standard deviation: 7.084274 |

Transformation and Fitting

The main objective of the transformation module is to achieve fitting of the implant to the femur condyle as in Figure 7.

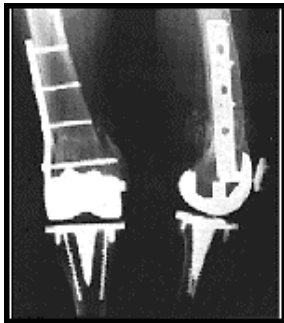


Figure 7. Implant is fitted to the femur condyle



Figure 8. Asian femur bone model to be used in the project

Figure 7 is an X-ray image of a Caucasian patient who has undergone a knee arthroplasty surgery. However, Asians have a differently shaped femur condyle. The front part of an Asian femur condyle is slightly curvier, making it difficult to achieve a good fit with a European-made implant. The femur bone specimen from an Asian patient is used in this research and is shown in Figure 8. The following are steps carried out in the transformation and fitting stage:

1. Alignment of models

The bone and implant models are both in the curve format (Step 8 in the Reverse Engineering process). This is to ensure that correct transformations can be achieved. Both the bone and implant models are aligned together using different viewports. It is best to give priority to the side views, as it will be easier to compare the curved part of the bone with the implant structure. This is because the curved front part is the most important feature to be considered.

2. Comparing the structures of both models with each other

Before proceeding with the transformations, the models were overlapped and compared with each other to get a rough view of how much resizing should be done to the implant. Figure 9 shows how the femur model and implant model overlap.

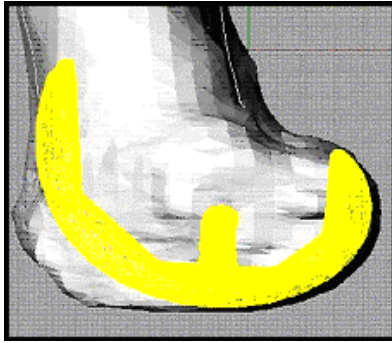


Figure 9. Models being overlapped together in the right viewport



Figure 10. Models from different angles when overlapped together

As shown in Figure 9, the implant (shaded in yellow) is smaller compared to the bone. Therefore, it can be concluded that it has to be enlarged so that the inner surface can conform to the curvature of the condyle. However, some parts of the implant can be seen protruding out of the bone structure (Figure 10) because the latter is not a symmetrical object.

3. Scaling the implant

The difference in the horizontal dimension between the inner surface of the implant and the outer structure of the condyle is measured as shown in Figure 11.

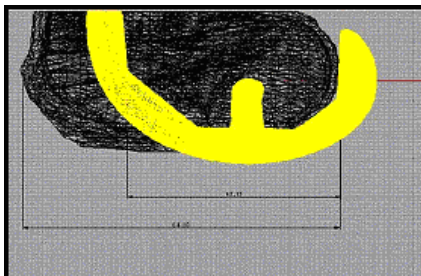


Figure 11. Measuring the horizontal dimensions

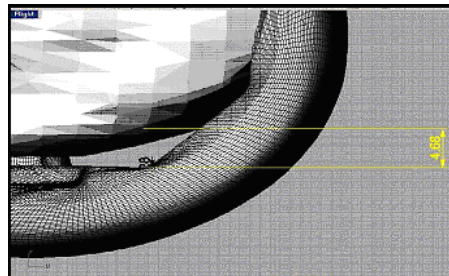


Figure 12. Clearance dimension value

The horizontal dimensions (in mm) are: implant, 43.13; and bone, 64.20. From these measurements, we are able to obtain the scaling factor from a simple calculation.

$$(\text{Bone} - \text{Implant})/\text{Implant} \times 100 = \% \text{ difference}$$

or

$$(64.20 - 43.13)/43.13 \times 100 = 48.85\%$$

Therefore, the scale factor is 1.49.

4. Bend transformation

After being scaled, the part of the implant to be fitted with the front part of the condyle was bent to conform to the shape of the condyle. Although bending can be done, it may lead to imperfect fittings at other parts. This problem has been anticipated and it is still acceptable since the clearance between the two objects will help us determine the healing progress after the surgery. A large clearance value will lead to slow healing, while a small value will ensure faster healing time. From Figure 12, it is shown that the clearance value between the two objects is 4.68 mm, which is sufficiently small for the bone to grow for comfortable fitting.

5. Fitting

Three points were marked on each model for fitting purposes. The three points would align to obtain the fitting shown in Figure 13.

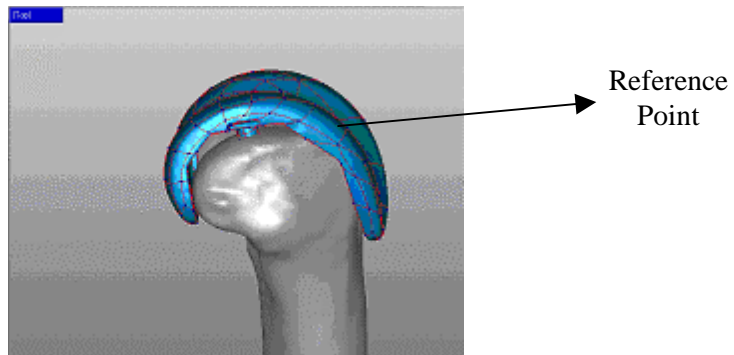


Figure 13. Fitting of implant model and femur models

It can be clearly seen that the two objects do not accurately fit each other. We conclude that the patient has to allow some time for the bone to grow back before it is completely healed.

CONCLUSION

Fitting would never be 100% accurate as the human anatomy is never symmetrical. The clearance value between the femur and implant would determine the healing time of the patient. However, with computer simulation, the clearance value can be minimized.

A surgeon need not reinsert the bone or cut the bone surface to fit the implant. This would reduce surgery time, healing time, and the cost of repeat surgery.

It would be more practical to come up with a standard-size implant based on a population study as it would be impractical to custom manufacture implants for patients. On the other hand, patients with deformities can obtain custom-fitted implants as the system allows the implants to be modeled based on the patients' bone structures.

Future work would include a study of the femur from different Malaysian ethnic groups, for example, Malays, Chinese and Indians. The results of the study would be used to design standard-size knee and other femur implants. Simulation of various other femur implant fittings can be carried out before the actual surgery is performed. The implant designed would fit Asian patients more comfortably as it could be designed and tested specifically for Asians.

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