Construction of Custom-made Artificial Knee Joint By Means of Contact Information

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Abstract: Custom-made artificial knee joints will play a very important role in the future. Aside from the differences on the geometry and dimensions of different human knee, being accustomed to sitting cross-legged, the smoothness of actions, the life of the product and the progress in the design manufacturing technology are actually closely related. This study was conducted in accordance with the specifications of the product, considering the relative curvature between the mesh surfaces of the femoral condyle cartilage and artificial meniscus as the main criteria. It hopes that the artificial knee prosthesis can have characteristics as close as the original human knee. It also hopes that the operated knee joint can be a better match to the muscles, ligaments and organizations around it to improve the compatibility between the new implants and tissue. In order to achieve this purpose, the study constructed a human medical imaging data with three-dimensional reconstruction of the knee and system assembly. Then, it constructed the finite element model to complete the contact area and contact stress characteristics and used these data as the target geometry model. On the other hand, it chose the specifications of the prosthesis replacement according to the user's bone size and geometry. It compared the contact characteristics of the above target geometry with the mesh surfaces characteristics of the prosthesis hoping that the relative motion of the prosthesis and the morphology of the original bone are close after modifying the radius of curvature on the surface of the artificial meniscus base to enhance life of the artificial knee joint. The modeling, analysis and simulation work is completed in the software, in order to shorten the design cycle and to lower the curved modification costs which may bring great convenience for the users. This provides a new practice for custom-made artificial knee design.

[ChinYu Wang, HanCiang Jhao, ChienFen Huang. **Construction of Custom-made Artificial Knee Joint By Means of Contact Information.** *Life Sci J* 2013;10(2):254-258] (ISSN:1097-8135). http://www.lifesciencesite.com. 40

Keywords: Contact stress, LifeMod, Artificial Knee Joint

1. Introduction

Biomechanics is a new theory based from the integration of mechanics, biology and medical science. Biomechanics mainly researched on living objects including the correlation of individual organisms, tissue, organs, cells and molecules. The correlation includes the different conditions of motion, deformation, growth and loads. Biomechanical study can help researchers understand the function of a variety of life and in a different environment to make corresponding adjustments on human tissues or effectively design a variety of devices and equipments to improve the quality of life of people. The different researches and different research tools of biomechanics caught the attention of the industry and academia and many creative products were developed accordingly.

In optimized modeling, analysis, simulation and system, the software plays a powerful role in functionality and efficiency. In the R&D of custom-made artificial knee, Pro/E constructs the geometric model of knee joint, Adams conducts the kinematic and dynamic analysis, ANSYS conducts the contact stress analysis between meshing bones and Workbench completes the overall analysis of the knee system. As long as correct motion and initial position load and bounded conditions are added, the software can complete the analysis of the whole system. LifeMod is the software that implements the modeling and analysis of the body's bones, muscles and ligaments. It allows researchers to no longer confines in the understanding of a researcher on problems of mathematics. Researchers can conveniently complete the product development.

With regards to researches on customization, Corin [1] introduced a total knee design system in 1987 where the CT films and X-rays of patients were input to the computer by means of a digital device to serve as a design reference. It can automatically correct the existing joint size to serve as basis for customization. After 1996, custom-made knee often use CT/MRI methods to obtain the geometric size of the patient's knee, tibial plateau and distal femoral articular surface, and provides surgical and processing simulation.

Shivani and Sathasivam [2] used the X-ray image of the patient integrating with the reverse engineering molding technology to create a parametric design of the knee. Hannover and H. M. Overoff [3] used the ultrasound image segmentation techniques to reconstruct the 3D model of the knee. Ma[3] also used ANSYS and LifeMod to design the biomechanical analysis and simulation of the artificial knee prosthesis. Lu [4] also has similar research results. With regards to the biomechanical researches on the femur and tibia of knees, in 1983, Moeinzadeh [5] is the first to establish a dynamic model based on the anatomical structure of the human knee and fixed to the femur. The model can be used to describe the tibiofemoral relative to the femur relative motion and calculate the contact force of the knee joint when femur is fixed. In 1984, Wongchaisuwat et. al [6] established another knee dynamic model, in which the femur is fixed while the tibia is modeled as a pendulum in order to analyze the control strategy of the tibia relative to the sliding and rolling of the femur. Komistek [7,8] (1992) adopted Kane method to establish the model that obtained the peak value of the contact force between the femur and tibia through the analysis of different walking speed. Wang et. al [9 to 12] (1993) released the femur and create a 2D free motion knee joint model containing femur and tibia.

Tumer and Engin [13] (1933) established a 2D knee dynamic model of a femur-patella-tibia system. This model simulated the motion of femur and patella relative to tibia when the femur is fixed. Wang et. al [14] (1998) then established a 2D free motion of the femur-patella-tibia knee model when femur is in free motion. In 2004, Jia et. al [15] establish a 3D model of a human lower limb to calculate the force and moments of the femoral and tibial articular surface during a gait cycle.

Unlike the above studies, the flowchart of this study is illustrated in Figure 1. First, the study constructed a contact stress of the artificial knee joint according to a patient's knee geometry. These stress characteristics can be used to compare the goodness of fit of the stress characteristics of the artificial knee joints prosthesis.

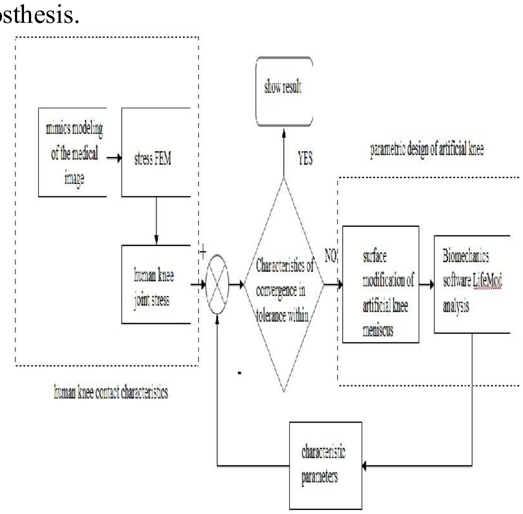

Figure 1. The flowchart of this study

On the other hand, the designed artificial knee prosthesis is input into the ANSYS to complete solving of stress and this feature is compared to the stress characteristics of the actual human knee. If the difference value is less than the tolerance, then, the designed prosthesis is allowed on the acceptable degree of goodness of fit. If not, the curved surface of the artificial meniscus should be modified to match the allowable tolerance.

2. Hertz's theory of elasticity

This study identified the relative curvature of the the contact surface by means of bone image morphology using the theoretical method to calculate the contact stress and area. It used ANSYS to construct the finite element contact analysis and used biomechanics software called LifeMod to complete the analysis. The medical images show the sagittal of the relative change in curvature between the curvature radius of the three sections of the arc and the curvature radius of the meniscus. The elastic Hertz theory can calculate the initial contact area and contact stress distribution.

The tissue morphology of the femur and tibia within the joint is shown in Figure 2. The distal femur and the tibial plateau is not pure rolling meshing relationship by flexion posture and ligaments stretching and the buffer of the meniscus often has a rolling and sliding motion. Each bone to its range of motion restrictions, thus, designing variable curvature geometry and constructing a elasticity model can improve to the peak contact stress and contact area morphology.

Assuming, E_f, μ_f are knee engagement elastomer femoral elastic modulus and Poisson's ratio, respectively. E_t, μ_t are knee mesh elastomer tibia elastic modulus and Poisson's ratio, respectively. R_f, R'_f are the two main radius of curvature of the elastomer femur mesh contact surfaces, respectively. R_t, R'_t are the two main radius of curvature of the elastomer tibia mesh contact surfaces, respectively. a and b are the semimajor and semiminor of the elastic contact surface of the knee's tibia-femur combination. δ is the relative displacement of the elastic center of the femur and tibia. q_0 is the maximum compressive stress of the elastic contact surface of the knee's tibia-femur combination. P is the axial static pressure. Thus, according to the Hertz theory, this study can derive the maximum compressive stress between knee meshing contacts. Under the definite solution of the resilient engaging contact region and deformation, the equation for maximum compressive stress is $q_0 = \frac{3P}{2\pi ab}$ where a and b are separately shown as the ellipse axle in Figure 3. The definition is as follows:

$$q = q_0 \sqrt{1 - \frac{x^2}{a^2} - \frac{y^2}{b^2}} \tag{1}$$

$$\delta = \lambda \sqrt[3]{\frac{9}{128} A P^3 \left(\frac{1-\mu_f^2}{E_f} + \frac{1-\mu_t^2}{E_t}\right)} \quad (2)$$

where, q can calculate the contact stress distribution and δ can calculate the amount of deformation of the contact surfaces.

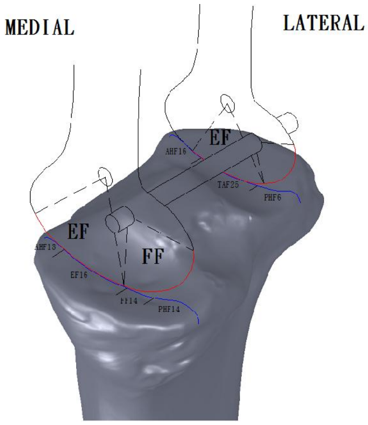

Figure 2. The morphology of the intraarticulars

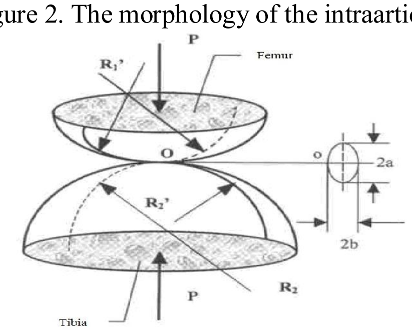

Figure 3. The biomechanic model of the elastic mesh contact of the artificial knee

3. The contact stress of the artificial knee joint

The results of the previous study can construct finite element model of a whole knee joint system, as shown in Figure 4. It can also obtain the femoral condyles contact area and contact stress distribution, as shown in Figure 5 and the contact stress of the meniscus, as shown in Figure 6.

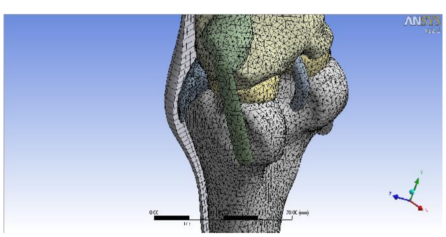

Figure 4 Gridding of the whole knee joint

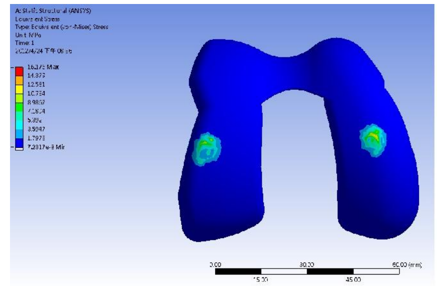

Figure 5 Femur contact analysis

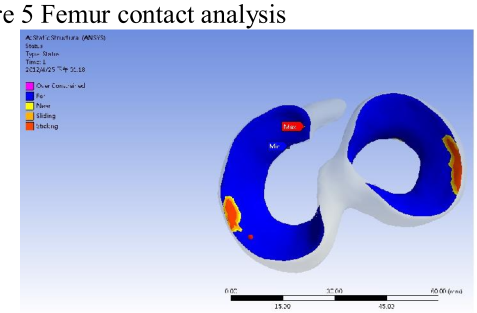

Figure 6 Meniscus contact analysis

Because human knee joint is different than of the robots, even if the same action is repeated, the human knee contact state does not possess a high precision of reproducibility either. After adding different three-dimensional reconstruction of the organizations, the assembly precision can't be constructed through any uniform standards. Therefore, a part of this study uses the smallest surfaces modification as foundation, and minimum repeated assembly to the joint contact stress is used as convergence value. This hypothesis would search for the minimum energy position based on the joint posture as the most stable state.

4. Parametric design of the custom-made knee joint

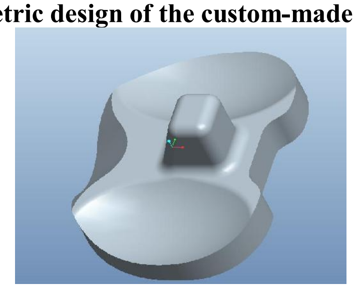

Figure 7

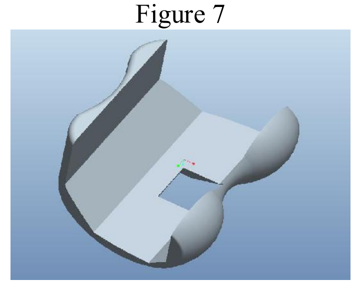

Figure 8

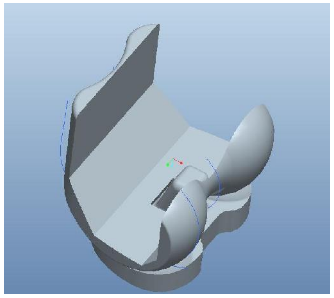

Figure 9

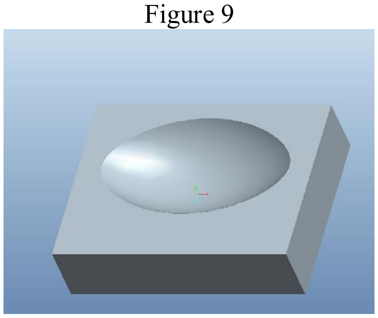

Figure 10

First, construct artificial knee geometry and position parameters completing the first generation prototype artificial knee joint as shown in Figure 7 and Figure 8. Figure 9 shows the finite element model of the knee. Figure 10 shows the optimized design of artificial meniscus surface design variable. The entire prosthesis remains the same, it just needs to modify the surface curvature into the desired contact feature of the original knee hoping to complete a low cost custom-made requirement.

5. Software Simulation of the Biomechanics

Although accurate geometry is reproduced, the finite element modeling under correct attributes and conditions can make the knee analysis more accurate. But, if the construction of the muscles and ligaments in the joint system, especially if the relative motion of the bones is not just making regular rolling and sliding motion of the rules, analysis work will become very difficult when the motion capture equipment needed for assistance can't combine the relevant analysis detailed regulations by the special purpose analysis software. This study used LifeMod analysis software where the muscles and ligaments data is inputted to the system, as shown in Figure 11 and Figure 12.

Then, the designed artificial knee system is constructed to lower limb system, with lower limb motion sensing devices to capture the relative motion and relative position of the bones, as shown in Figure 13 and Figure 14.

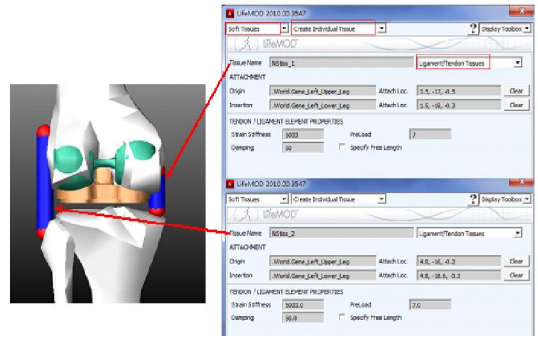

Figure 11 Establishing the attributes and conditions of the ligament

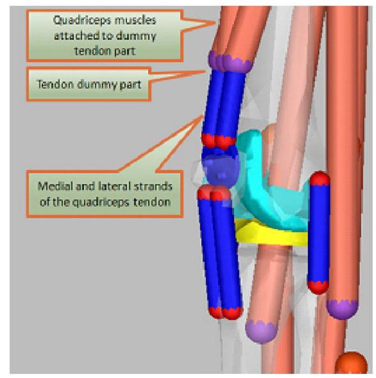

Figure 12 Establishing the quadriceps tendinitis and peripheral organizations

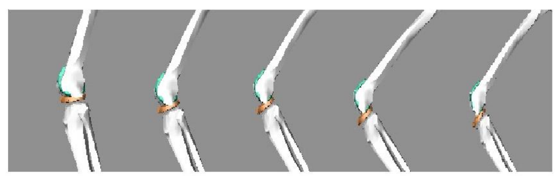

Figure 13 The motion of the lower limb model

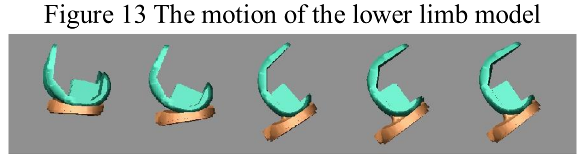

Figure 14 The changes in the posture of the contact surfaces

The relative motions and relation position data among the femur, meniscus and tibia is returned to ANSYS and Adams to complete a more accurate contact stress and motion analysis.

6. Conclusions

The requirement of customization is based from the different geometric and functional demands. How many possibilities can it obtain? Patient's medical images message: the design/analysis/simulation software functions, processing equipment and methods can provide custom-made products' quality and reduce cost. Thus, design and product value often become the conditions or the point of view in looking a product. If the key point of the creativity or innovation is obtained, the geometric design, analysis and manufacturing of the product and market acceptance is not so difficult to solve. Custom-made artificial knee is a product the goodness of fit of the contact stress is characterized by the modification of the meniscus surface conforming to the simple practice and low-cost requirements.

The contributions of this study are as follows:

1. It provides designs, analysis, simulation and system modification methods.
2. By modifying the meniscal surfaces, the smoothness in the actions of the users can be improved.
3. The contact features of the different relative positions can be learned from the radius of curvature based from the patient's medical imaging (ex.: X-ray, MRI/CT).
4. It can complete the contact analysis of the different postures between femoral/tibial through geometric reconstruction and finite element model.
5. By integrating the motion capturing equipment, it can accurately construct a complete contact stress change of the patient's motion.

Acknowlegements

The authors would like to thank the National Science Council, Taiwan, R.O.C., for financial support under grant No: NSC 99-2632-E-230-001-MY3.

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