

Surface Modification and Software Design of Customized Knee Joint

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Abstract: This paper used the medical image of a patient's knee joint as basis to assemble a complete human knee through geometric software. Because this model can't precisely align the position, local contact will occur which would cause stress concentration. It should undergo the tension adjustment of the ligaments to adjust the relative positions of the cartilage of the femoral condyle, the meniscus and the femoral cartilage to the minimal relative position of the contact stress to comply with the lowest energy or stress allowed by the law of nature for our body needs. First, this study used the spring simulation in the ligament tension and used the software, RecurDyn, to find the relative position of the minimum contact stress of the knee system. Second, the customized man-made knee was imported in the biomechanical software called LifeMod to build muscles and the ligaments system to simulate the ligament tensions of the artificial knee under a variety of sports. Aside from being the basis for the spring coefficient setting of the human knee, the tension can also select the specific posture of the knee in the model and then convert it into a file of ANSYS stress analysis software to complete a more accurate stress analysis. Finally, we can retest the human and artificial knee joints under different postures in the above steps to know the changes in the patterns between contact stress and contact area to obtain customized artificial knee prosthesis closest to the patient's original human knee joints. The concept is the same if the original denture tooth shape is kept, we can be able to organize the most stable and compatible peripherals, prolong the life of the prosthesis and reduce its possibility of loosening.

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1. Introduction

In recent years, the quality for computer medical images on artificial prosthesis significantly improved, making the people who only rely on crutches in the past or the people who were amputated can walk like a normal person and improve their quality of life. Every year, a large number of patients undergo artificial knee arthroplasty. Currently, after undergoing artificial knee arthroplasty, the patient's limbs can do weight bearing, flexing, abduction and rotation activities with good stability.

Clinical application of artificial knee prosthesis mostly needs to be imported and only a few companies design and develop knee products. The cost for importing prosthesis is quite high and it is design based on the knee parameters of Europeans and Americans which sometimes would result to incompatibility of knees. To restore the complex activities of the knee, the designer should make sure that the articular surface of artificial knee prosthesis should conform with the anatomy, biomechanics and kinematics of the prosthesis. Stress analysis enables the prosthesis and bone to be in a more reasonable state to improve the long-term stability of the prosthesis to avoid unreasonable stress peak and contact area morphology. Similarly, because the

model of the reconstructed bones can be rotated and external forces can be applied, it provides a good approach for the patient's postoperative rehabilitation. To design a better knee prosthesis compatible to Taiwanese, customize normal knees underwent bone position extraction and movement simulation analysis to create multi-segmented meshing curved surface and set reasonable loading, binding and contact conditions in different professional softwares in order to simulate the human knee and the mechanical model of the artificial knee. In addition, the model is used to derive the maximum contact stress peak, contact area and contact deformation solutions in the meshing area. These results can serve as a reference to clinical diagnosis and customize prosthesis manufacture.

David Siu [1] measured the medial femoral condyle and its distal condyle, radius of the patellar surface and arc angle and the lateral femoral condyle and its distal condyle, radius of the patellar surface and arc angle of 5 cadaver's knee joints after CT scanning a 3D reconstruction. Elias [2] dissected 10 samples of cadavers with normal knees and compared them to 6 normal adult knees. The result of this study showed that patients of different races, different sizes or the difference in curve fitting methods result to different arcs for the femoral condyle joints. Zhou's

research [3] shows that the width of the medial and lateral femoral condyle and the width of the medial and lateral tibia plateau are very similar which proves that the width of femoral condyle and tibia plateau is related. Bigger femoral condyle width shows bigger tibia plateau width. Thus, the value of femoral condyle and tibia plateau can be used as the index to represent the size of the knees. His simplified model shows that sagittal femoral condyle can be fitted into three sections arc curves.

With regards to the biomechanical studies of femur / tibia of knee joints, Moeinzadeh et al. [4] were the first to create an artificial knee dynamic model human knee joint in 1983 and they also fixed the femur into position. The model is used to describe the relative motion of the tibia and the femur when the femur is fixed and to compute for the contact stress of the knee joints. Wongchaisuwat et al. [5] created another knee dynamic model in 1984 where the femur is fixed and the tibia is simulated as a simple pendulum to analyze the control strategy of the femur relative to tibia's sliding and rolling. Komistek et al. [6] created a model in 1992 by applying Kane's method where the spike of the contact stress between femur and tibia was obtained by analyzing different walking speeds. In 1993, Wang [7] released femur and created a two-dimensional biodynamic model of femur and tibia.

In 1933, Tumer and Engin [8] created a femur-tibia-patellar dynamic model of human knee. The model simulated that when the femur is fixed, tibia is relative to the relative motion of femur and patellar. In 1998, Wang released femur again and created a femur-tibia-patellar three knee joint 2D meshing motion mathematical model. In 2004, Jia [9] created a lower limb 3D model to compute for the force and torque of the femur and tibia during gait cycle. Wang [10] developed the geometrical dimensions of Taiwanese to use as basis in designing standard artificial knee.

2. Research Framework and Process

This paper used the medical image of a patient's knee joint as basis to recreate a complete human knee and analyze the law of motions of their everyday actions to complete the stress characteristics analysis of the human knees. In addition, this paper used the contact stress peak and contact area distributions as standards. The designed artificial knee prosthesis can use the changeable bone geometry, meniscus, curvature of the contact surface of femoral condyle and the contact characteristics between the tibia and the tibial prosthesis to create an artificial knee that has stress characteristics, as much as possible, close to the human knee. The contents of the paper are as follows:

1. Use software call Mimic to recreate the MRI medical image of the patient, rebuild a

three-dimensional geometry, assemble into a system and reconstruct a ligament through the spring element to pull the contact position of the femoral condyle and the meniscus if the stress pressure is at its minimum.

2. Use Pro/E to design a three-dimensional geometric artificial knee joint and use LifeMod to install a customized prosthesis. Then, set the conditions of the software before customization to simulate the contact posture and motion/dynamic simulation of the prosthesis.

3. ANSYS/WorkBench will complete the contact stress spike and contact area analysis of the human knee joint and separately discuss the contact posture and contact stress analysis of the bones under different law of motions of the patella in a stance and a bend of 45 °.

4. The artificial knee is transferred into RecurDyn to complete the dynamics and dynamic contact stress analysis of the multi-body system.

Compare the different design parameters to maintain the patient's contact stress characteristics to those of the best knee design before joint replacement.

The difference between this paper and other literatures is that it used specialized computer softwares to perform the geometric design, motion simulation and stress analysis. Pro/E is used to make the three-dimensional geometric model, ANSYS is used in stress analysis, Adams and LifeMod completes the biomechanical simulation and analysis and RecurDyn analyzes the dynamic mechanical properties of the system. The procedure is shown in the flowchart below.

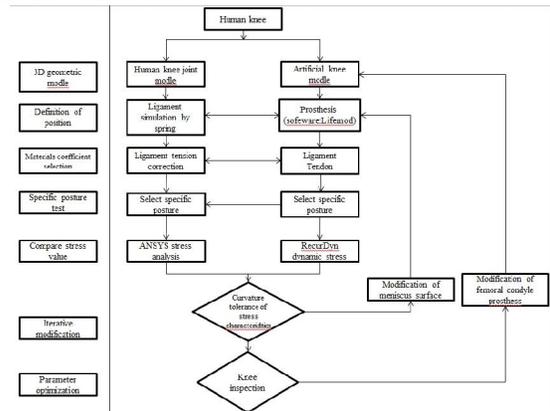


Figure 1. Research Framework and Process

3. Research Methodology

3.1 The finite element model of human knee:

ANSYS used the spring elements to substitute for the ligaments, as shown in Figure 2. The correct position of the spring can use the default setting of LifeMod or input into the exact position, The result of finite element analysis of the human knee is shown in Figure 3.

3.2 The finite element model of the artificial knee:

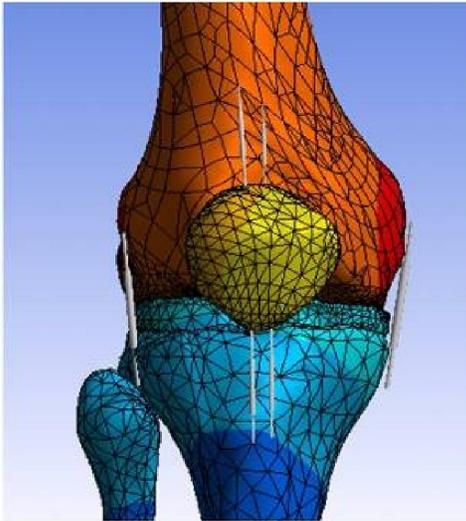


Figure 2. Spring Simulation of the Ligament

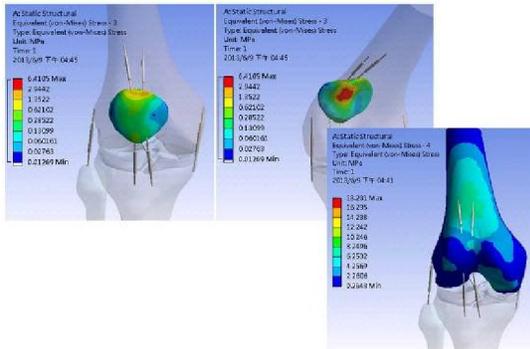


Figure 3. Finite element model of the knee system

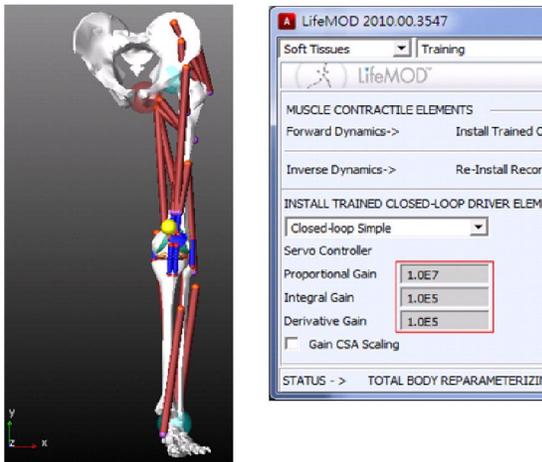


Figure 4. Customized Setting Conditions in LifeMod

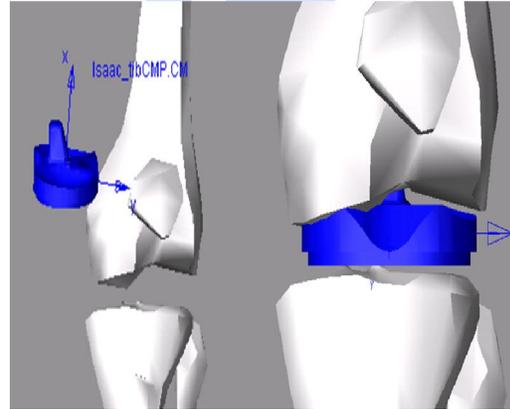


Figure 5. Application of the Customized Setting Conditions into the Knee (software used: LifeMod)

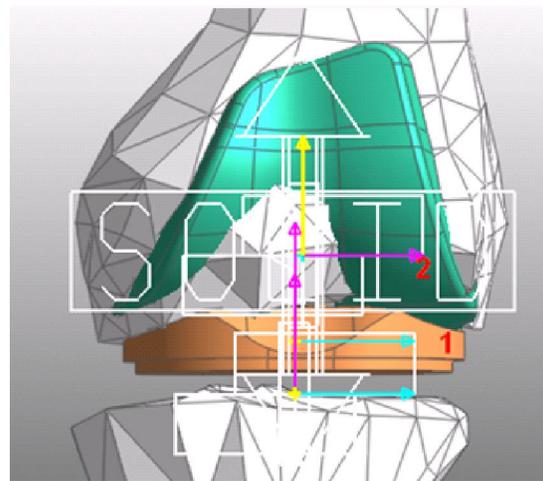


Figure 6. Setting of Contact Elements (software used: LifeMod)

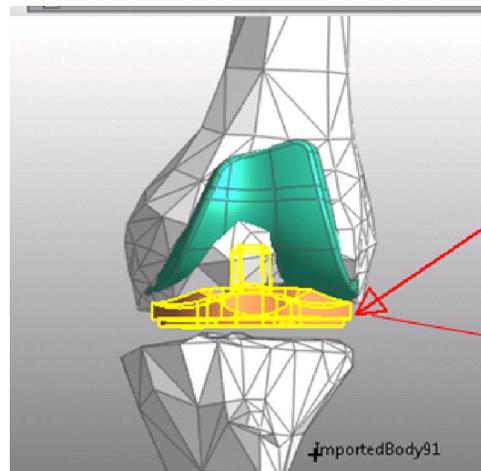


Figure 7. Dynamic Simulation of the Meniscus (software used: RecurDyn)

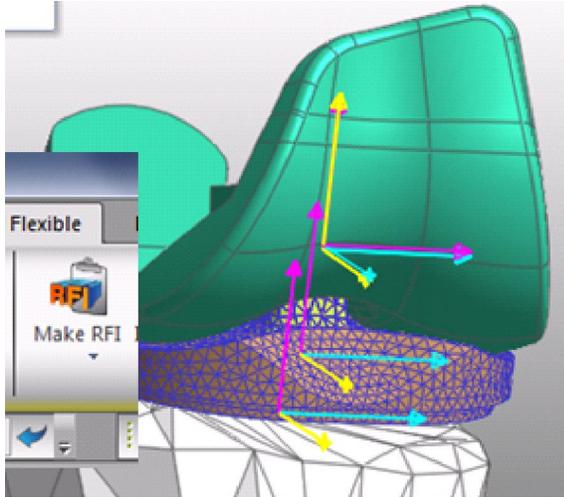


Figure 8. The Contact Analysis between Soft Body and Rigid Body

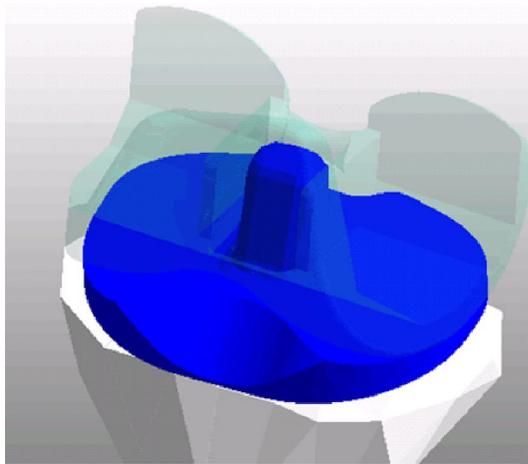


Figure 9. Stress Analysis Result after Derivation

Step1: In LifeMod, select the customized parameter design conditions, as shown in Figure 4;

Step2: Place the customized artificial knee in LifeMod, as shown in Figure 5;

Step3: Set the contact between the artificial meniscus and femoral condyle prosthesis, as shown in Figure 6;

Step4: Create a grid model of the artificial meniscus, as shown in Figure 7;

Step5: Set the contact between the rigid and soft bodies, as shown in Figure 8 and then obtain the contact stress results, as shown in Figure 9.

3.3 Motion Simulation and Analysis of Dangerous Position

The STL files of the lower limb movements captured from the human movements provided by the software can complete many motion simulation and analysis such as squatting and natural walk. If the artificial knee prosthesis user has other special movement needs such as sitting cross-leg or specific

posture of athletes, motion capture devices can also be used to completely record the movements and input the STL file in LifeMod to execute the simulation. The solution and post-processing capabilities of the software can analyze the specific positions from the excess ligament tension and meniscus contact stress. After these positions are captured, re-input the information into the drawing and the stress analysis software will correct the artificial meniscus surface to reduce the stress value of the dangerous position or the risk of local contacts.

Figure 10, Figure 11, separately describe the position and stress analysis of the human knee when bended at 40° and the artificial meniscus stress analysis result of the artificial knee when bended at 40°. The figures are shown in Figure 12 and Figure 13.

3.4 Contact Stress of Femoral Condyle Prosthesis and Bone Cutting Interface

The channel of the femoral condyle prosthesis and the column and channel contact of femoral condyle after cutting have an interference combination of big column/small channel to use the elasticity of the bone to constrain and groove the space of the solid joint without loosening it. To simulate this condition, the thickness of the compact bone must have reached certain irreversible plastic deformation and the plastic deformation area is too large. The surface between the prosthesis and the bone will loosen and thus, reducing the life of the prosthesis. The amount of interference between the cut size of the bone and the femoral condyle channel is one of the points in the customized artificial knee that this paper wants to verify. So people cut grooves femur bone size and the amount of interference between the sizes of the paper is verified customized artificial knee joint projects. The related methods are shown in Figure 14 and Figure 15.

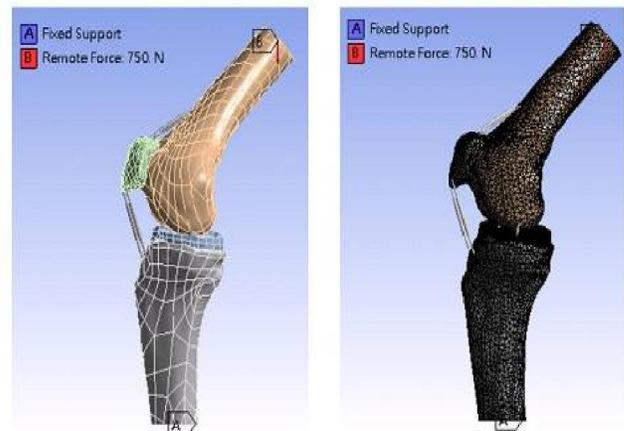


Figure 10. The Human Knee Bended at 40°

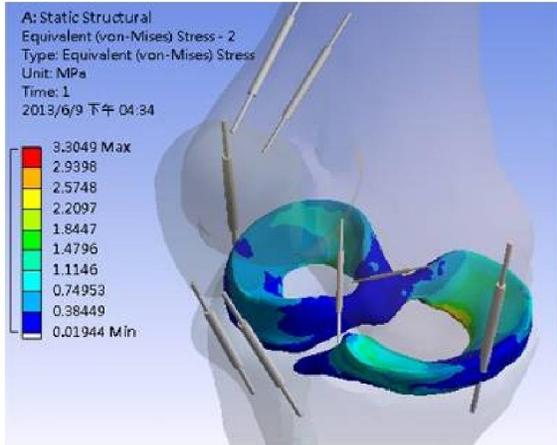


Figure 11. The Contact Stress at 40°

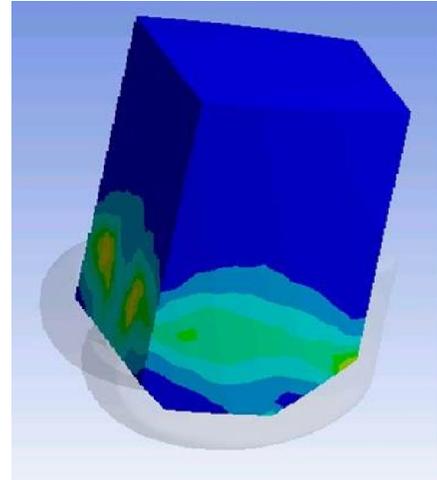


Figure 14. Contact Stress of the Compact Bone

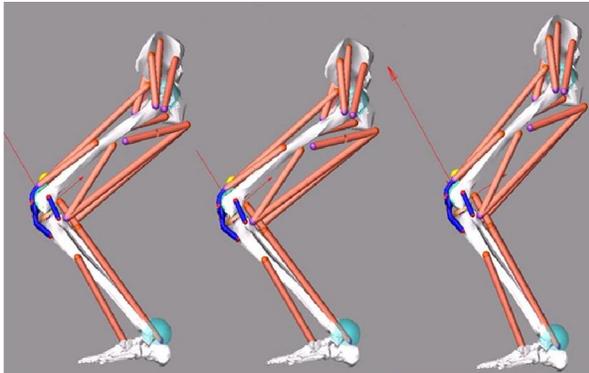


Figure 12. Movement Simulation of the Artificial Knee

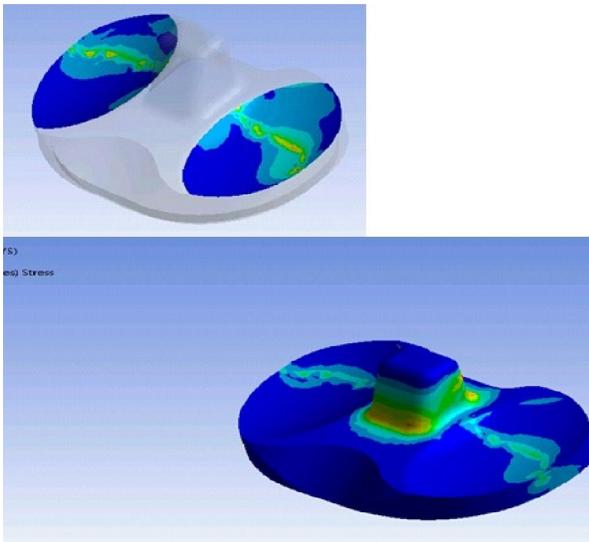


Figure 13. The Stress and Strain of the Meniscus Bended at 40°

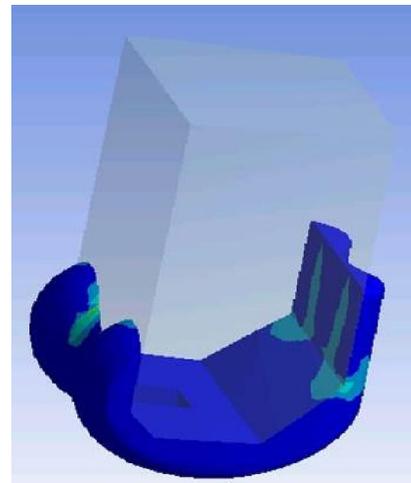


Figure 15. Contact Surface of the Channel of the Femoral Condyle

4. Results and Discussion:

4.1 Modification of Customized artificial Meniscus surface

The two parameters for artificial knee joints are RR and RS. The difference between these two radius is that one is oval and the other is curve. This artificial meniscus top surface can be used as the modification parameters of the customized knees. One, it needs micro-shape modification to obtain the purpose of adjusting contact stress. Moreover, it also shows that it is easy to process and to assemble. By modifying the parameter RR, the results of the maximum contact stress between the femoral condyle and the meniscus and the maximum stress of the entire prosthesis is shown in Table 1.

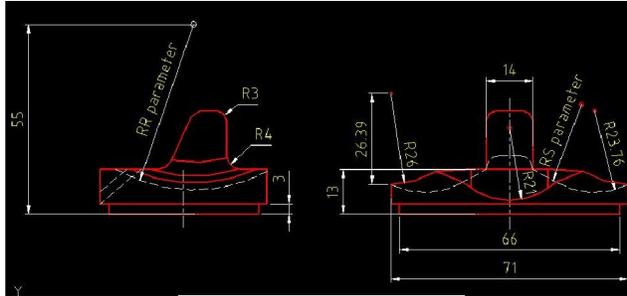


Figure 16. Artificial Meniscus Design

Table 1 (Unicompartmental force is set as 75 kg and RS is maintained at 23.76mm)

RR(mm)	Maximum contact stress (MPa) at bended angle of 0°	
	Two curved surface	Total surface
59.79	0.9964	1.979
55.37	0.94113	3.3529
52.2	1.0421	1.3947
47.91	2.0536	2.0536
45.13	2.0536	2.0536
41.81	2.1138	2.1138
39.34	2.1138	2.1138
37.47	-	-
35.8	3.2363	3.5115
34.64	7.888	12.939
RR(mm)	Maximum contact stress (MPa) at bended angle of 30°	
	Two curved surface	Total surface
59.79	6.7458	20.088
55.37	5.0141	20.367
52.2	7.2185	21.347
47.91	6.8901	11.706
45.13	1.9595	1.9595
41.81	-	-
39.34	3.8247	4.9986
37.47	15.02	32.959
35.8	11.7	26.186
34.64	4.3545	5.1882

4.2 The Interference between the Column of Compact Bone and the Channel of the Femoral Condyle Prosthesis

Table 2 explores on the prosthesis column geometry of the femoral condyle and the effect of the amount of interference on the contact stress changes between the femoral condyle and compact bone surface. If the compact bone is greater than the femoral condyles by 0.03mm and above, the contact stress between the contact surface would increase a lot. To explore the optimum value of the amount of the interference quantitatively, the thickness of the compact bone should be in the plasticity range to maintain the tight junction between the elastic

restoring force and the condylar channel but it still needs further analysis. Table 3 shows the artificial knee joint materials and compact bone material parameters in the analysis.

Table 2: The Interference between the Column of Compact Bone and the Condyle

Stress Amount of interference(mm)	120° Maximum stress (MPa)		
	Femoral condyle (whole surface)	Femoral condyle (internal surface)	Compact bone
0.01	233.15	58.313	3.7811
0.02	332.89	113.91	23.582
0.03	493.68	170.98	35.624

Stress Amount of interference (mm)	135° Maximum stress (MPa)		
	Femoral condyle (whole surface)	Femoral condyle (internal surface)	Compact bone
0.01	108.66	35.688	9.245
0.02	202.57	68.74	19.41
0.03	555.09	142.65	38.38

Table 3: Artificial Knee Materials and Compact Bone Coefficient

Materials	Characteristics	Modulus (Gpa)	Poisson ratio
Compact bone		16.8	0.3
Meniscus (ultra high molecular weight polyethylene)		8.1	0.4
Femoral condyle (cobalt-chromium-molybdenum alloy)		210	0.3

5. Conclusion

This study was inspired by a specific denture, not just any standard denture, but a complete denture. It is with X-ray identification, accurately manufactured, tooth occlusal imprint analysis and grinding to complete the customized procedure.

Customized artificial knees are limited and can't be universalized due to its high cost, its demand is not as large as the demand for teeth and the difficulty in fast high precision processing. But with the increase in income, higher quality of life, increases in the precision of the processing equipments and multifunction of software technologies, barriers with designing, manufacturing, assembly and even the cost are gradually overcome. We believed that the demand in customization will increase due to the ageing society and will inspire a great market in the future.

This paper presented a customized design concept. It is to create a customized artificial knee to

replace the deteriorating knees. This paper has the following advantages:

It can construct ergonomic biomechanical knee ligament and muscular system through Life Mod and used nonlinear spring system to simulate this system in stress analysis to create a more ergonomic knee.

Inputting the artificial knee prosthesis in Life Mod can simulate various human actions to complete movement/kinetic simulation of the ligaments and muscles.

The three-dimensional geometry of Life Mode is transferred into Recur Dyn to complete the contact stress spike and the contact area distribution characteristics analysis.

Set the radius of curvature of the meniscus as ellipsoid parameters to use the changes in the radius of curvature and angle as ellipsoid as the basis for micro modification of the meniscal prosthesis surface. It is the easiest and the quickest approach to obtain the similarity of stress characteristics.

After completing the human knee reconstruction geometry and finite element analysis, the procedures stated above then corrects the meniscal surfaces according to the normalized artificial knee model by separately converting it into Life Mod and Recur Dyn to complete the most appropriate prosthesis design information to modify the meniscus surface. The concept and method of this paper actually has a great potential for development.

Acknowledgements

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