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Stability Simulation Analysis of Unicondylar Knee Prosthesis

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Abstract: ***Unilateral knee replacement surgery is a commonly used treatment for knee osteoarthritis, but if symptoms of knee instability occur, it will seriously affect clinical efficacy. Due to the large amount of equipment required for stability research, evaluation requires a significant amount of resources. This study evaluates the stability of unicondylar knee prosthesis through finite element analysis, simulates the geometric shape of unicondylar knee prosthesis, and analyzes the stability performance of the finite element model using axial compressive loads and anteroposterior (A-P), medial lateral (M-L), and medial lateral (I-E) movements. Evaluate the stability of the geometric shape of unicondylar knee replacement, and design a unicondylar prosthesis that better restores natural knee joint mechanics, meeting clinical usage requirements.***

Keywords: Finite element analysis; Stability; Unicondylar knee prosthesis

1. Introduction

For patients with knee joint single compartment osteoarthritis, single condyle replacement (UKA) is a better treatment method. Compared to total knee replacement (TKA), UKA has smaller trauma, less bone loss, preserved anterior cruciate ligament, and postoperative joint function is closer to normal [1-3]. But like TKA, UKA also has patients who undergo reoperation due to postoperative complications. Common postoperative complications of UKA include loosening of the prosthesis, periprosthetic infection, joint wear, and instability. The reasons for instability may include insufficient soft tissue balance, joint prosthesis wear, improper joint prosthesis size, and misalignment. At present, surgeons can adjust certain designs based on experience, or adjust product design parameters through in vitro experiments to increase stability. However, there is relatively little research on the requirements for evaluating whether the current design of knee joint single condyle prostheses achieves natural stability through finite element analysis. Starting from the perspective of finite element analysis, this article simulates the knee joint single condyle prostheses under different load conditions, uses numerical simulation to construct a mechanical environment, and analyzes and studies the constraint forces of front back traction, internal and external shear, and rotational release in this situation, aiming to provide theoretical basis for clinical treatment.

2. Materials and Methods

2.1 Object model establishment

Construct a three-dimensional model of a single condyle knee joint prosthesis at different flexion angles (0 °, 15 °, 90 °, 140 °) as shown in Figure 1. The matching rate of the joint surface is shown in Table 1 and Formula (1) [4].

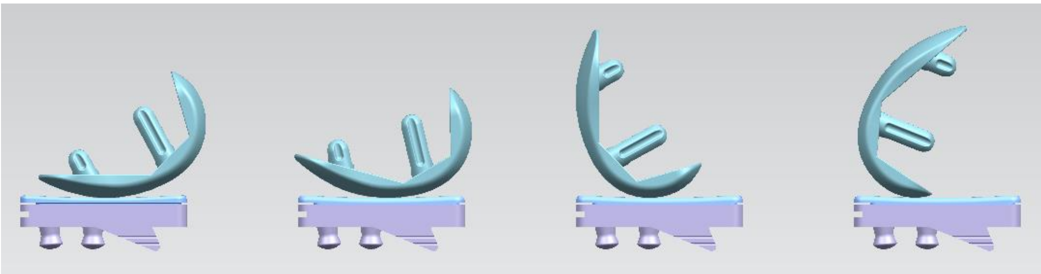


Figure 1: Single condylar knee joint prosthesis with different flexion angles (0 °, 15 °, 90 °, 140 °)

$$CI_{x^\circ} = \frac{femoral\ radii_{x^\circ}[mm]}{polyethylene\ radii[mm]} \quad (1)$$

Table 1: CI

flexion angle	0°	15°	90°	140°
CI	0. 1138	0. 1065	0. 05	0. 0425

2.2 Material assignment

Import the 3D model constructed in UG into ANSYS Workbench; The material attribute assignment is shown in Table 2. Ultra high molecular weight polyethylene is selected for the tibial pad, and cobalt chromium molybdenum alloy is selected for the tibial pad and femoral condyle [4]; The analysis program uses the Static Structural analysis model.

Table 2: Material parameters

Material	*Elastic modulus (Pa)*	*Poisson's ratio*
Cobalt chromium molybdenum alloy	2. 1E+11	0. 3
Ultra high molecular weight polyethylene	7. 0E+09	0. 46

2.3 Loading scheme

Set the alignment point of the knee joint single condyle prosthesis in a neutral position according to the flexion angles (0 °, 15 °, 90 °, 140 °) as the simulation starting point. Apply a constant compressive load of 710N below the femoral component to simulate traction, internal and external shear, and apply a torque of 25Nm to simulate rotational loosening. The loading scheme is shown in Table 3. [5] During virtual testing, component constraints were specified for the three rotations of flexion (FLX), inward outward (V-V), inward outward (I-E), as well as the three translations of anterior posterior (A-P), medial lateral (M-L), and upward downward (S-I). According to the test conditions, these degrees of freedom are either locked (L), able to move freely (F), or driven (D).

Table 3: Loading scheme parameter table

Item	*Femoral condylar constraint*						*Tibial support and pad restraint*					
Test conditions	FLX	V-V	I-E	A-P	M-L	S-I	FLX	V-V	I-E	A-P	M-L	S-I
Forward and backward translation	L	F	L	D	L	F	L	L	L	L	L	L
Inner-Outer Translation	L	F	L	L	D	F	L	L	L	L	L	L
Internal and external rotation	L	F	D	L	L	F	L	L	L	F	F	L

2.4 Grid partitioning and constraints

Perform mesh refinement and convergence analysis on knee single condyle prostheses to determine the optimal mesh element size. Using the Convergence tool for solving, set the Max Refinement Loops cycle value to 6 to determine convergence, and the Allowable Change decision amount is within 5% convergence. When the tibial pad and femoral condyle are divided into tetrahedral grids, the grid size converges and stabilizes around 1.0mm (with a grid spacing error of less than 5%). Namely, tetrahedral meshing was performed on the bone support pad and femoral condyle, with a mesh size set to 1.0mm to ensure sufficient computational accuracy. The meshing results are shown in Figure 2 and Table 4.

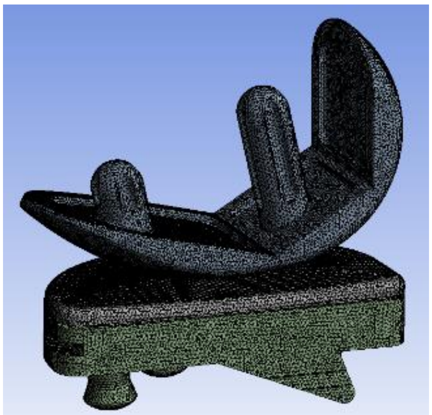


Figure 2: Grid partitioning diagram

Table 4: Mesh division results of knee joint single condyle prosthesis

Parts	*Number of nodes*	*Number of grids*
Femoral condyle	185222	98796
Tibial pad	128171	67882
Tibial support	148865	78499

Constraint setting: The bottom surface of the tibial support is a fixed constraint, the connection between the tibial pad and the femoral condyle is set to face to face contact, and the friction coefficient of the interface is set to 0.038 [6]. This study simulated the stability of knee joint prostheses, and during the simulation period, the tibial components were fixed, so there was no relative movement between the tibial pad and the tibial support. Limit all directional degrees of freedom between the tibial pad and the tibial support to 0, as shown in Figure 3. Considering the influence of ligaments on the internal and external rotation and anteroposterior movement of the knee joint, a torsion spring is applied to the tibial plateau for internal and external rotation, with a stiffness coefficient of 0.6 Nm/deg [7]. A pair of nonlinear springs are applied to the anterior and posterior directions of the tibial plateau, providing displacement constraints in the anterior and posterior directions of the tibia. The spring stiffness data is obtained through in vitro experimental data calculation, and the nonlinear spring function relationship is [8]: $F=1.9919d^2+0.0292d$. Among them, F is the spring force, and d is the spring compression amount.

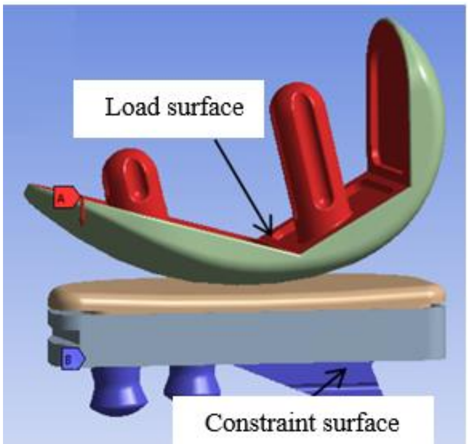


Figure 3: constraint loading

3. Result

3.1 Simulation results of anterior and posterior traction of knee joint single condyle prosthesis

Figure 4 shows that there is no significant difference in the values of traction and displacement between the analyzed data and experimental data of the prosthesis. And the constraint forces of the two sets of data at 140 ° buckling are 11.37 (N/mm) and 11.31 (N/mm), respectively, which are the weakest constraint forces under the four bending angle states.

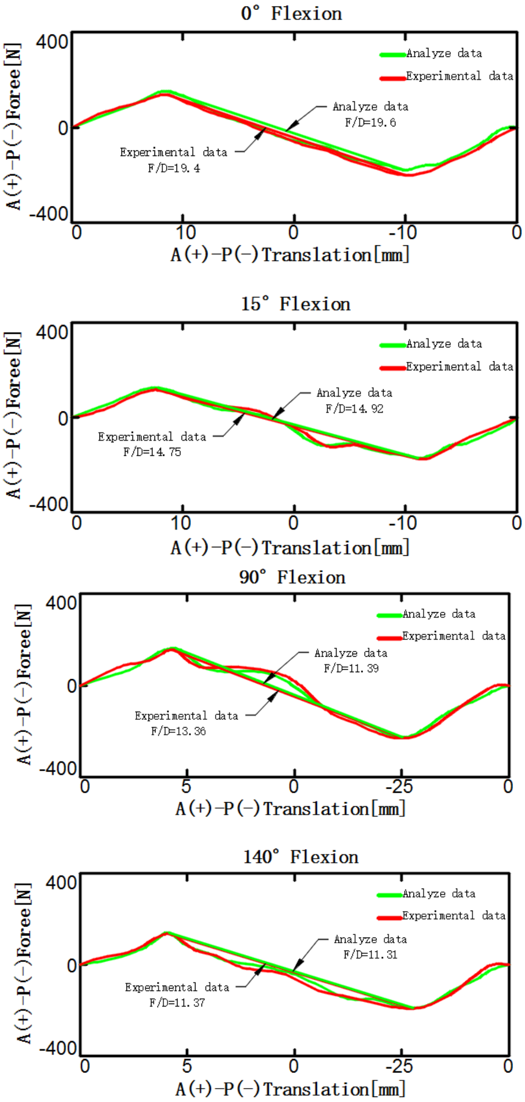
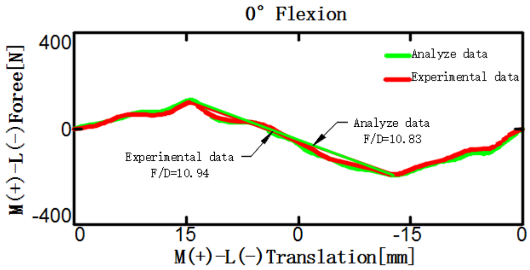


Figure 4: Front and rear (AP) force displacement data under constant compressive load and buckling at (0 °, 15 °, 90 °, 140 °)

3.2 Simulation results of internal and external shear of knee joint single condyle prosthesis

The application results, as shown in Figure 5, show the M-L simulation results for different buckling angles. There is no significant difference in the values of internal and external shear forces and displacements between the analysis data and experimental data of knee single condyle prostheses. The constraint forces of two sets of data at 140 ° flexion are 9.65 (N/mm) and 9.75 (N/mm), respectively. The constraint forces are the weakest under the four bending angle states.



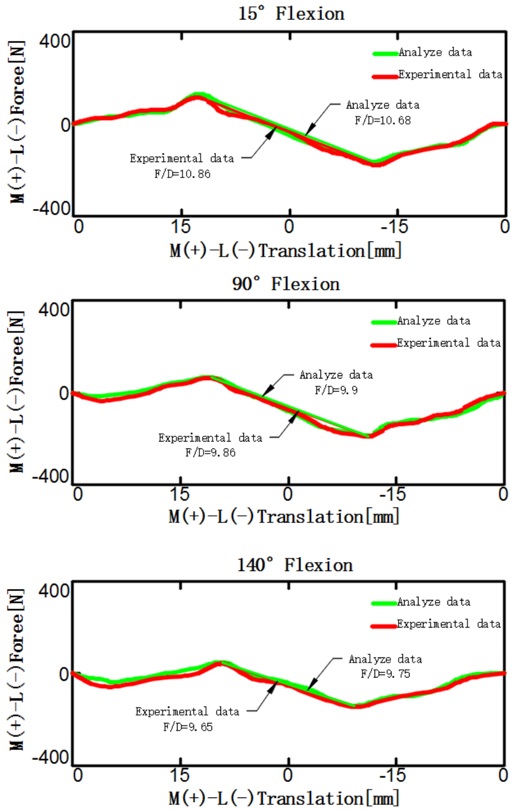
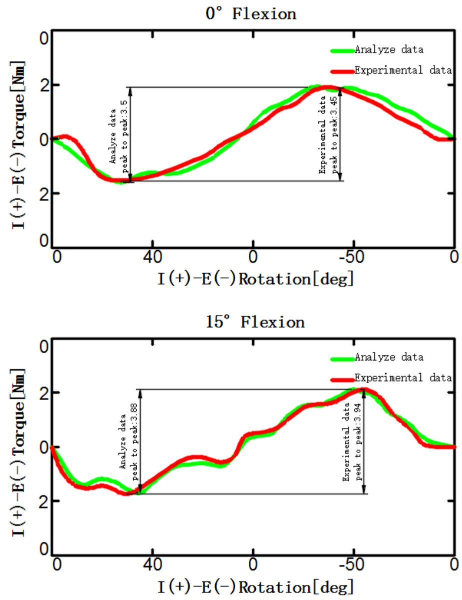


Figure 5: Internal and external (ML) force displacement data under 0 °, 15 °, 90 °, 140 ° buckling and constant compressive load

3.3 Simulation results of rotational release of knee single condyle prosthesis

The application results, as shown in Figure 6, show the IE simulation results at buckling angles (0 °, 15 °, 90 °, 140 °). There is no difference in the values of torque and rotation angle between the analyzed data and experimental data for knee joint prostheses. The constraint forces of the two sets of data at 140 ° flexion are 2.57 (Nm) and 2.6 (Nm), respectively. The constraint forces are the weakest under the four bending angle states.



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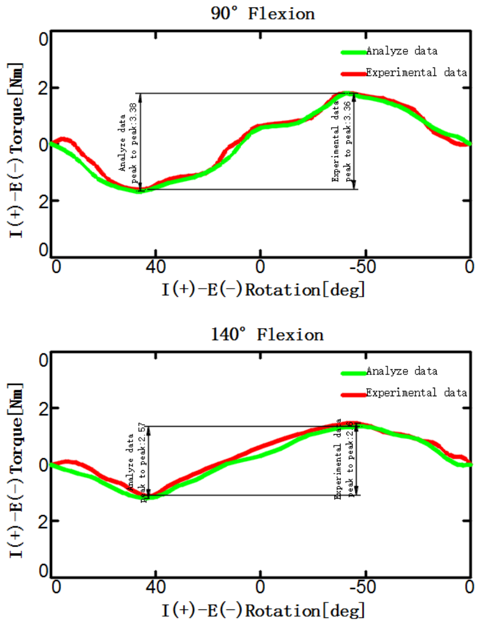

Figure 6: Internal and external (IE) torque rotation data under constant compression load at 0 °, 15 °, 90 °, and 140 ° buckling

4. Discuss

This study extracted force/displacement, torque/rotation angle curves, as well as inward and outward rotation angles of single condylar knee joint prostheses from both analytical and experimental data. The radius of the tibial support surface designed for knee joint single condyle prosthesis is greater than that of the corresponding femoral single condyle surface, ensuring smooth movement of the femoral condyle prosthesis within the groove of the tibial pad prosthesis. The radius size of the femoral condyle decreases sequentially from the anterior surface of the femur to the posterior surface of the femur, resulting in a J-shaped distribution of the instantaneous rotation center and a gradual decrease in the CI matching rate. Multiple sets of variable curvature surfaces form the femoral condyle and tibial pad, which can maintain high compatibility with natural joints, avoiding uneven stress transmission and bone loss caused by over or under coverage of the prosthesis. On the other hand, it reduces the span difference between different surfaces, improves the smooth transition between them during knee flexion movement, and ensures the stability of the movement. The simulation results show that as the bending angle increases, the CI matching rate gradually decreases, and the constraint force also gradually decreases. The simulation results are consistent with the design concept, which conforms to the natural motion characteristics of the knee joint of ordinary people, ensuring the degree of freedom during joint prosthesis movement and improving the stability and comfort of the patient's movement after prosthesis replacement.

In summary, this analysis of knee single condyle prostheses can not only maintain high compatibility with natural joints, avoid uneven stress transmission and bone loss caused by over coverage or under coverage, but also improve the smooth transition between various curved surfaces during knee flexion movement, ensuring stability of movement. By using finite element comparative analysis, it is demonstrated that the structural design meets the clinical use of the prosthesis. Faster and cheaper than physical methods, it also provides more options for clinical treatment.

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