Research Article

Kinematics and Mechanical Properties of Knees following Patellar Replacing and Patellar Retaining Total Knee Arthroplasty

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Knee injury is a common medical issue. A full understanding of the kinematics and mechanical properties of knees following total knee arthroplasty (TKA) repair utilizing patellar replacement (only the base of the patella is replaced) versus patellar retaining surgical techniques is still lacking. In the current paper, we investigated magnetic resonance (MR) imaging data from knees repaired by these two methods and evaluated total knee models created using imaging reconstruction technology that simulated gait conditions. Results revealed that patellar replacement had little influence on tibiofemoral kinematics, although the tibia-surface equivalent stress increased slightly. By contrast, patellar replacement had a significant influence on the patellofemoral joint; patellar internal rotation, external rotation, and medial-lateral translation were all increased. Moreover, the stress distribution on patellar prostheses was altered, resulting in an increased surface maximal equivalent stress on the corresponding area. Moreover, during the gait cycle, we found that the area with maximal equivalent stress shifted its position. Finally, the patellofemoral joint showed decreased motion stability. From the view of kinematics and mechanics, this paper suggests that patella should be retained during TKA if it is possible. The present study presented approaches and technologies for evaluating kinematics and mechanical properties of total knee joint after TKA under gait loads.

1. Introduction

As a major supporting joint of human movement, the knee is prone to damage. Ultimately, the best treatment method for repairing knee articular surface damage is total knee arthroplasty (TKA), which replaces the articular surface with knee prosthesis, thereby restoring knee joint functions. With the constant improvement in knee surgery techniques and the demanding requirements of joint prostheses to accurately mimic the knee function, the problems concerning knee kinematics under gait dynamic loading and contact properties following TKA have come under close scrutiny.

For instance, in 2002, Godest et al. [1] first introduced the finite element method and studied the mechanical properties of femoral and tibial implants under gait loads in TKA knees. Subsequently, in 2005, Halloran et al. [2] conducted finite element analyses of knees following TKA, the results of which closely predicted the results from a concurrent experimental study. In 2007, Knight et al. [3] extended the application of finite element method to biomechanical issues by investigating implant wear following TKA. As such, in 2012, Wachowski et al. [4] examined the effects of knee prostheses with roll back characteristics on patellofemoral joint forces and showed that the prosthesis alleviated joint pain in TKA patients and elongated the service life of the prosthetic. On a similar note, in 2011, Walker et al. [5] established criteria for evaluating knee prosthesis through studying the kinematics of three different knee prostheses.

The knee joint is a very complex structure. The complicated coupling and coordinating relationship between the tibiofemoral and patellofemoral joints during movement/gait makes it difficult to study the kinematics and mechanical characteristics of TKA-repaired knees under dynamic gait loading conditions. In this study, we analyzed and compared...
the total knee joint kinematics and mechanical properties during gait cycle following patellar replacement versus patellar retaining TKA. Then the influence of patellar replacement and patellar retaining TKA on total knee functions was assessed. The research steps include knee joint modeling, mechanical simulation of patellar retaining or replacement PS-type prostheses under dynamic gait loads, and the comparison of tibiofemoral and patellofemoral kinematics and contact stresses of knees with PS-type prostheses. The results of this study will provide novel techniques and methods for evaluating the effects of replacement surgery on knee kinematics and mechanical properties.

2. Methods

2.1. TKA Knee Joint Modeling. The knee joint model contained two parts.

(1) PS Prosthesis Modeling. The PS prosthesis was provided by Beijing Chunlizhengda Medical Apparatus Inc. A MicroScribe G2 three-dimensional scanner was employed to scan every structure of the total knee prosthesis to obtain geometry, which was then imported into Geomagic Studio 8.0 for further optimization and also into Solidworks for model repair simplification and reconstruction.

(2) Knee Modeling after TKA. Following TKA, the knee model consisted of either a patellar retaining or PS prosthesis replacing knee joint model. Initially, a normal knee joint model was created based on CT and MR data of the normal knee. Subsequently, the femur and tibia were cut according to the surgery procedure [6]. Finally, the remaining femur, tibia, and PS prostheses were assembled to create the total knee model. The normal knee joint MR data was acquired by scanning a student volunteer under the supervision of a doctor.

2.2. Total Knee Model after TKA. The simulation of the total knee joint after TKA consisted primarily of model simplification, finite element modeling, and definition of dynamic gait loading.

(1) Knee Model Simplification. According to [7–11], the ligaments (anterior cruciate (ACL), posterior cruciate (PCL), medial collateral (MCL), and lateral collateral (LCL)) and surrounding muscles were represented by springs; specifically, the quadriceps femoris and patellar ligament were represented by 2 bundles of spring elements with stiffness coefficients of 2000 N/mm and 1142 N/mm, respectively. The MCL was represented by three bundles of spring elements (i.e., anterior bundle, deep bundle, and oblique bundle), while the LCL was comprised of a single bundle of nonlinear spring elements. The medial/lateral springs’ stiffness coefficients and deformations were from [9–11] and shown in Table 1.

(2) Total Knee Finite Element Model. The finite element model was created by using ABAQUS 6.11 [5, 10–14], including the definition of material properties, connection relation, boundary conditions and constraints, and grid generation.

### Table 1: The stiffness coefficients of MCL and LCL.

| Ligament               | $K_1$  | $K_2$  |
|------------------------|--------|--------|
| MCL anterior bundle    | 10     | 91.25  |
| MCL deep bundle        | 5      | 21.07  |
| MCL oblique bundle     | 5      | 27.86  |
| LCL                    | 10     | 72.11  |

The bone tissue is simplified as isotropic linear elastic material with the elastic modulus of 17 GPa and Poisson’s ratio of 0.3. Femoral prostheses are cobalt-molybdenum alloy with the elastic modulus of 79 GPa and Poisson’s ratio of 0.3. The tibial tray prosthesis is titanium alloy with the elastic modulus of 70 GPa and Poisson’s ratio of 0.3. The UHMWPE (ultra-high-molecular-weight polyethylene) tibial insert and the patellar prosthesis use nonlinear elastoplastic deformable material properties.

Different coupling relationship between the components of the knee prosthesis is defined. The relationships between the femoral prostheses and the femoral condyle section, tibial prothesis and tibial section, and tibial prothesis and tibial liner are defined as consolidation. The contacts between the femoral prosthesis and polyethylene insert, patella cartilage, and femoral prosthesis were defined as sliding friction, with a friction coefficient of 0.004 [1, 2, 9].

The definition of the boundary conditions and constraints is as follows: the patella is not limited, the movement of femoral with prosthesis is limited to flexion and extension, the tibial with prosthesis is only limited with the outer flexion and extension, and turning and shift movement on the other directions are not limited.

C3D10 tetrahedron grid elements were employed to achieve free mesh generation, and the models of patella retaining and replacement TKA were divided into 81052 and 78397 elements, respectively. The total knee after TKA and the corresponding finite element models are shown in Figure 1.

(3) Applying Dynamic Loading. There were three main processes utilized when the gait dynamic loads were applied.

(1) According to the standard ISO 14243-1, the gait cycles were divided into four main states [12, 13, 15–19]: heel strike (HS), single limb stance 1 (SLS1), single limb stance 2 (SLS2), and toe off (TO). The gait loading curve was also divided into four areas (as shown in Figure 2) to analyze the movement and mechanical characteristics of the human gait cycle after TKA.

(2) The loading curve was transferred into discrete data by using piecewise polynomial fitting techniques to actualize the human knee gait cycle motion simulation of dynamic loading after TKA. The gait flexion and gait load were controlled by fitting functions programmed with Matlab, including gait flexion function, axial force loading function, anteroposterior force loading function, and the internal and external rotation torque loading function.

(3) A gait dynamic load was applied to the total knee after TKA. The line connecting the rotational centers...
of the femoral lateral and medial epicondyles was defined as the axis for femur flexion (Figure 2(a)), and axis force was applied to the centers of each of the femoral lateral and medial epicondyles based on the axis force loading function (Figure 2(b)), where 60% axis force was applied to the center of the medial epicondyle and 40% axis force was applied to the lateral epicondyle [20]. The anteroposterior force (Figure 2(c)) and internal rotation moment (Figure 2(d)) were applied to the tibia implant based
4. Results revealed that both patellar retaining and patellar simulation results of both models are shown in Figures 3 and 4. The relative movement curves of the tibiofemoral joint from the gait cycle are shown in Figure 3 for anterior-posterior translation of the femoral lateral and medial epicondyles. The internal-external rotation function is shown in Figure 4 for both patellar retaining and replacement models.

3.1. Kinematics of the Tibiofemoral Joint under Gait Loads.

3.1.1. Kinematics of the Tibiofemoral Joint after Patellar Retaining and Replacement under Gait Loading. The dynamic simulation of the total knee with patellar retaining and replacement during gait loading was performed in ABAQUS 6.11 by means of explicit dynamic finite element analyses. The data were collected at a 5% gait cycle interval. The effects of the patellar treatment method on joint function were analyzed by comparing the equivalent contact stress value of the patellar treatment method on joint function were analyzed by comparing the equivalent contact stress value and identified differences between the two models, though the variation tendency was similar. The patellar first moved medially to the minimal value and then laterally till the minimal value was achieved before it moved medially to the maximal value once again. The peak, minimal, and maximal values occurred at 20% (1.7 mm), 35% (0.3 mm), and 55% (2.4 mm) of the gait cycle, respectively. For both models, the second highest and maximal patellar tilting occurred at 20% and 50% of gait cycle, respectively, which were equal to 1.8° and 4.6° for the patellar retaining model and 2.8° and 8.4° for the patellar replacement model. Patellar internal rotation showed a similar tendency as tilting; the second highest and maximal internal rotation at 20% and 55% of gait cycle were 0.6° and 1.5° for the patellar retaining model and 1° and 2.8° for the patellar replacement model.

The patellar lateral-medial translation showed evident differences between the two models, though the variation tendency was similar. The patellar first moved medially to the maximal value and then laterally till the minimal value was achieved before it moved medially to the maximal value once again. The peak, minimal, and maximal values occurred at 20% (1.7 mm), 35% (0.3 mm), and 55% (2.4 mm) of the gait cycle, respectively. For the patellar replacement model, the peak, minimal, and maximal values occurred at 15%
Figure 5: Kinematics of the patellofemoral joint.

(2.6 mm), 35% (1 mm), and 55% (3 mm) of the gait cycle, respectively, values significantly higher than those in the patellar retaining model indicating a decreased knee joint stability.

3.2. Mechanical Properties of TKA Knee Joint under Gait Loads

3.2.1. Mechanical Properties of Tibiofemoral Joint under Gait Loads. The mechanical properties of the tibiofemoral joint under gait loads were investigated by analyzing the stress contour and maximal stress variations of the UHMWPE tibial tray during the gait cycle, thereby illustrating the mechanical differences between the tibiofemoral joints of two models.

The stress distributions of the UHMWPE tibial tray were represented by the stress contour at typical states, HS, SLS, and TO (Figure 6). Results revealed that the stress distributions of the two models are similar. During the gait cycle, high stress mainly concentrates on the tibial medial condyle (used dominantly during gait) at SLS2 and TO. In addition, the equivalent stress and equivalent stress area of the lateral condyle slightly increased probably due to the displacement of the center of gravity.

A histogram of the maximal equivalent peak contact stress of the UHMWPE tibial tray during the gait cycle is shown in Figure 7. Combining Figures 6 and 7, the mechanical properties of the tibial tray are listed in Table 2. Table 2 suggested that although the stress distribution of tibial tray was similar for the two models, patellar replacement resulted in elevated stress, which may aggravate the tibial tray wear.

Figure 8 shows the variation curve of tibial tray contact stress under gait loads. Results show that the two models demonstrated similar variation, peaking at 50% of the gait cycle and gaining a second maximal stress value at 20%. However, the stress was consistently higher in the patellar replacement model than in the patellar retaining model. For both models, during 0%–10% of the gait cycle, the heel strike imposed an increasing tibial axial force. Meanwhile, the tibial tray stress reached 17.1 MPa and 18.6 MPa for internal rotation movement and tibial anterior force, respectively. When the entire foot made contact with the ground the tibial axial force was slightly reduced due to forward body movement. As such, at 30% of the gait cycle the tibial tray contact stresses decreased correspondingly, with values of 13.4 MPa and 14.77 MPa for internal rotation movement and tibial anterior force, respectively. Then, as the foot began to push off of the ground and separation occurred, we found that the axial force increased, reaching maximal contact stress values...
3.2.2. Mechanical Properties of Patellofemoral Joint after TKA. The mechanical properties of the patellofemoral joint were described by using a surface patellar stress contour, a histogram of maximal equivalent stress, and a maximal equivalent stress variation curve. Figure 9 shows the stress contours of the patellar surface or patellar prosthesis surface. Considering the fact that the flexion angle can affect the patellar maximal equivalent stress, the toe off state was divided into two states: TO1 and TO2. At TO1, the tibiofemoral flexion angle was 8° and the axial force was 2434 N. Meanwhile, at TO2, when the foot is separated from the ground, the axial force reached 168 N with 56° flexion. It can be seen that compared to patellar retaining TKA, patellar replacement
Table 2: Knee tibial tray mechanical properties during the gait cycle.

|                          | Gait cycle (patellar retaining) | Gait cycle (patellar replacement) |
|--------------------------|---------------------------------|-----------------------------------|
| Heel strike              | Gait cycle | Single limb | Single limb | Toe off | Heel strike | Single limb | Single limb | Toe off |
| Flexion angle (°)        | 4        | 16          | 6           | 8       | 4           | 16          | 6           | 8       |
| Axial force (N)          | 1531     | 2482        | 1636        | 2434    | 1531        | 2482        | 1636        | 2434    |
| Peak contact stress (MPa)| 13.36    | 16.35       | 19.51       | 24.63   | 14.39       | 19.43       | 22.37       | 28.07   |
| Stress increment (%)     | 7.71%    | 18.84%      | 14.66%      | 13.97%  | 14.66%      | 13.97%      | 14.66%      | 13.97%  |
| High stress area         | Medial   | Medial      | Medial and lateral | Medial and lateral | Medial | Medial | Medial and lateral | Medial and lateral |

Figures 7 and 8: Graphs illustrating the contact stress and stress distribution for patellar retaining and patellar replacement TKA models.

4. Conclusions

In this study, the kinematics and equivalent stress of two knee models (patellar retaining and patellar replacement) were compared during the gait cycle. Results showed the following: (1) patellar replacement has little influence on tibiofemoral kinematics and mechanical properties, although it produced a slightly increased tibial tray stress; (2) patellar replacement significantly reduced the kinematics and mechanical performances in the patellofemoral joint during the gait cycle; patellar tilting, internal rotation, and anterior-posterior translation were all significantly increased compared to the
Figure 9: Continued.
patellar retaining method; meanwhile, patellar replacement altered the stress distribution in the patellofemoral joint, resulting in an increased high-stress area; finally (3) compared to patellar retaining TKA, patellar replacement has less influence both on kinematic variations in the tibiofemoral and patellofemoral joints and on the variations in the joint peak equivalent stress during the gait cycle. In conclusion, TKA was shown to preserve human knee tissue following surgery. Moreover, the results here indicate that the patellar retaining method has more beneficial long-term effects compared to patellar replacement.

But this paper only analyzes the kinematics and mechanics with simplified knee models; this is only part of properties of total knee after TKA surgery. Furthermore, if the result is verified by some experiment, the paper will be more meaningful.

Conflict of Interests
The authors declare that there is no conflict of interests regarding the publication of this paper.

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