Orthopaedic Surgery

RESEARCH ARTICLE

Tibio-Femoral Contact Force Distribution of Knee Before and After Total Knee Arthroplasty: Combined Finite Element and Gait Analysis

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Objective: To assess the tibio-femoral contact forces before and after total knee arthroplasty (TKA) in patients with knee osteoarthritis (KOA) by three-dimensional (3D) finite element analysis (FEA) models and gait analysis.

Methods: Two hospitalized patients with Kellgren–Lawrence grade IV varus KOA and two healthy subjects were enrolled in this study. Both patients underwent unilateral TKA. FEA models were established based on CT and MR images of the knees of the patients with KOA and healthy subjects. Gait analysis was performed using a three-dimensional motion capture system with a force plate. Three direction forces at the ankle joints were calculated by inverse dynamic analysis, which provided the load for the FEA models. The total contact forces of the knee joints were also calculated by inverse dynamic analysis to enable comparisons with the results from the FEA models. The total knee contact forces, maximum von Mises stress, and stress distribution of the medial plateau were compared between the patients and healthy subjects. The distributions of the medial plateau force at 2 and 6 months postoperatively were compared with the distributions of the forces preoperatively and those in the healthy subjects.

Results: During static standing, the medial plateau bore the most of the total contact forces in the knees with varus KOA (90.78% for patient 1 and 93.53% for patient 2) compared with 64.75 ± 3.34% of the total force in the healthy knees. At the first and second peaks of the ground reaction force during the stance phase of a gait cycle, the medial plateau bore a much higher percentage of contact forces in patients with KOA (74.78% and 86.48%, respectively, for patient 1; 70.68% and 83.56%, respectively, for patient 2) than healthy subjects (61.06% ± 3.43% at the first peak and 72.09% ± 1.83% at the second peak). Two months after TKA, the percentages of contact forces on the medial tibial plateau were 79.65%–85.19% at the first and second peaks of ground reaction forces during the stance phase of a gait cycle, and the percentages decreased to 53.99% – 68.13% 6 months after TKA.

Conclusion: FEA showed that TKA effectively restored the distribution of tibio-femoral contact forces during static standing and walking, especially 6 months after the surgery. The changes in the gait were consistent with the changes in the contact force distribution calculated by the FEA model.

Key words: Finite element analysis; Gait; Inverse dynamic analysis; Tibio-femoral contact force; Total knee arthroplasty

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Received 27 September 2021; accepted 20 May 2022

Introduction

Approximately 20% of patients with knee osteoarthritis (KOA) who undergo total knee arthroplasty (TKA) are reportedly dissatisfied with the surgical outcome,[1] mainly due to knee functional deficiency postoperatively.[2] Previous studies showed that knees with different deficits have different biomechanical characteristics.[3,4] One of the goals of TKA is to restore the normal biomechanics of the knee. Therefore, evaluation of the knee joint contact force before and after TKA may help to assess the surgical outcome.

Gait analysis is an important biomechanical tool that assesses knee function using kinematic and kinetic data. In comparison with healthy subjects, patients with severe KOA have a slower walking speed, slower cadence, shorter step length, longer stride time, and longer single-limb support time, which may be correlated with the loss of gait stabilization and balance.[5] Gait performance is expected to be improved after TKA, as the walking speed, cadence, step length, single-limb support time, and knee joint range of motion gradually increase with recovery time.[6,7] Previous studies have indicated that patients walk at slower speeds within the first month following TKA compared with the condition preoperatively.[8,9] As gait performance is a key indicator of knee joint functional recovery in clinical practice, it is important to conduct a longitudinal kinematics and dynamics analysis to evaluate the knee function before and after TKA. However, the internal contact force and stress on the joint interface cannot be identified by gait analysis alone.

Finite element analysis (FEA) plays an important role in the mechanical analysis of geometrically complex structures and has been extensively used in the biomechanical analysis of the knee. Since the FEA method was introduced to orthopedic research,[10] many different FEA models have been developed to evaluate the stress distribution in the knee,[11] as the geometry of the knee joint is well defined and easily extracted from computed tomography (CT) or magnetic resonance imaging (MRI) scans. Tanaka *et al.* constructed a computer-simulated knee with a tricompartmental implant to predict contact areas and contact stresses.[12] Moewis *et al.* compared the differences in medial and lateral load distribution between horizontal and anatomical implants.[13] Liau *et al.* demonstrated that contact and von Mises stresses significantly increase under malalignment conditions,[14] and Kwon *et al.* emphasized the importance of preserving the joint line during surgery to obtain improved contact stress on tibial polyethylene inserts.[15] While the application of FEA continues to increase in the field of orthopedic research, the computational investigation of knee joint contact mechanics remains challenging due to the lack of effective validation methods. Although FEA models can be validated using force-measuring tibial prostheses,[16] the application of force-measuring tibial prostheses *in vivo* is limited. An alternative is an indirect validation by comparison with the results of the previous studies.[17] Sun *et al.* showed reasonable agreement between FEA results and inverse dynamic models[18]; therefore, the same method was applied in the present study. Because inverse dynamics have been widely applied and accepted in motion analysis for decades, and the three-dimensional (3D) motion capture system with force plates is considered the golden standard for gait analysis, the FEA model can be considered effective if the results of the two models are similar.

The purpose of the study is: (i) to estimate tibio-femoral contact force distribution of knee joint before and after TKA using the FEA method combined with gait analysis; (ii) to find out how the tibio-femoral contact force distribution changes before and after TKA; and (3) to explore the relationship between tibio-femoral contact force distributions and gait spatiotemporal parameters, which has not previously been reported.

Materials and Methods

Participants

Two hospitalized patients with Kellgren–Lawrence grade IV varus KOA scheduled for unilateral TKA were enrolled in this study. The Hospital for Special Surgery (HSS) knee scores were 57 for patient 1 and 69 for patient 2. Tip-knee-ankle (HKA) angle of patient 1 with KOA was 177.34° for the left knee and 169.7° for the right knee. The HKA angle of patient 2 with KOA was 178.96° for the left knee and 171.54° for the right knee. The right knees of both patients were diagnosed with KOA. Neither of them had other musculoskeletal diseases which appeal to the criteria of the study. In both cases, the same senior chief physician performed posterior-stabilized, cemented TKA using a posterior-stabilized fixed-platform prosthesis with the patella preserved. A median approach in the anterior aspect of the knee was taken, and the articular cavity was entered through the medial side of the patella. The anterior and posterior cruciate ligaments were excised. Femoral intramedullary positioning and tibial extramedullary positioning were performed. Osteotomy was performed in accordance with the recommended standard of the prosthesis.[19] Both patients were able to walk independently without assistance before and after TKA.

Two healthy subjects without any neurological or muscular skeletal disorders diagnosed by the surgeon according to MR/CT images were also recruited (Table 1). The bilateral knee joints of the two healthy subjects (four healthy knees) and the operated sides of the two patients with KOA (two varus knees) were analyzed using both FEA and gait analysis. All participants provided written informed consent before the tests were carried out. The study was approved by the ethics committee of Capital Medical University (Biomechanical Factors Influencing the Effect of Total Knee Arthroplasty, 2017SY43).

Finite Element Model

Image Acquisition

A Somatom Sensation Cardiac 64 CT scanner (Siemens Corporation, Munich, Germany) and 3.0T MRI machine (United Imaging uMR770, Shanghai, China) were used to obtain CT and MR images of the knees of the healthy subjects and the patients with varus KOA before TKA. The

TABLE 1 Demographic information

Subject	Health 1	Health 2	Patient 1	Patient 2
Sex	Male	Male	Male	Male
Age(years)	56	63	80	70
Body weight (kg)	76	76	64	60
Height (cm)	175	173	173	158
BMI (kg/m^2)	24.8	25.4	21.4	24
Kellgren–Lawrence grade	0	0	IV	IV
HSS score before TKA	NA	NA	57	69
HSS score 2 month after TKA	NA	NA	73	78
HSS score 6 month after TKA	NA	NA	85	89
HKA angle before TKA_L(°)	177.42	177.59	177.34	178.96
HKA angle before TKA_R(°)	178.46	177.07	169.7	171.54
HKA angle after TKA_L(°)	NA	NA	177.34	178.96
HKA angle after TKA_R (°)	NA	NA	177.09	177.71

Note: Hospital for Special Surgery (HSS). Total knee arthroplasty (TKA). Hip-Knee-Ankle angle (HKA angle).

scanning layer thickness and the distance between layers were 1.0 mm for both the CT and MRI.

Development of the Models of Healthy Knees and Varus Knees

Mimics v19.0 software (Materialise, Leuven, Belgium) was used to identify and segment the structural boundaries of different parts of the knee joint based on the CT and MR images. The whole bone and cortical bone were segmented in accordance with the intensity threshold of CT images in Mimics 19.0. The trabecular bone was obtained by the Boolean operation (subtracting the cortical bone from the whole bone) in Rapidform XOR3 (3D Systems, Rock Hill, SC, USA). The femur, tibia, and fibula were reconstructed using CT images. Menisci, femoral and tibial cartilage, collateral ligaments, and anterior/posterior cruciate ligaments were reconstructed based on the MR images. The 3D models were imported into Rapidform XOR3 to reduce noise and then transformed into solid models. The solid models were assembled and meshed into 3D, 4-node tetrahedral elements using ABAQUS v6.13–4 (Fig. 1).

Development of the Post-TKA Knee Joint Model

The 3D models of the knee prostheses, including the femoral component, tibial component, and polyethylene insert, were obtained from the manufacturer (Chunli model XM, Beijing, China). Based on the surgical records and the requirements of TKA, the 3D finite element models of the postoperative knee joints were developed under the supervision of the surgeon (Fig. 1). The cutoff amounts of the femur, tibia and patella of the knee model were qualified based on the surgical record. The knee model and prosthesis model were then assembled in ABAQUS in accordance with the operation procedure. All procedures were performed under the

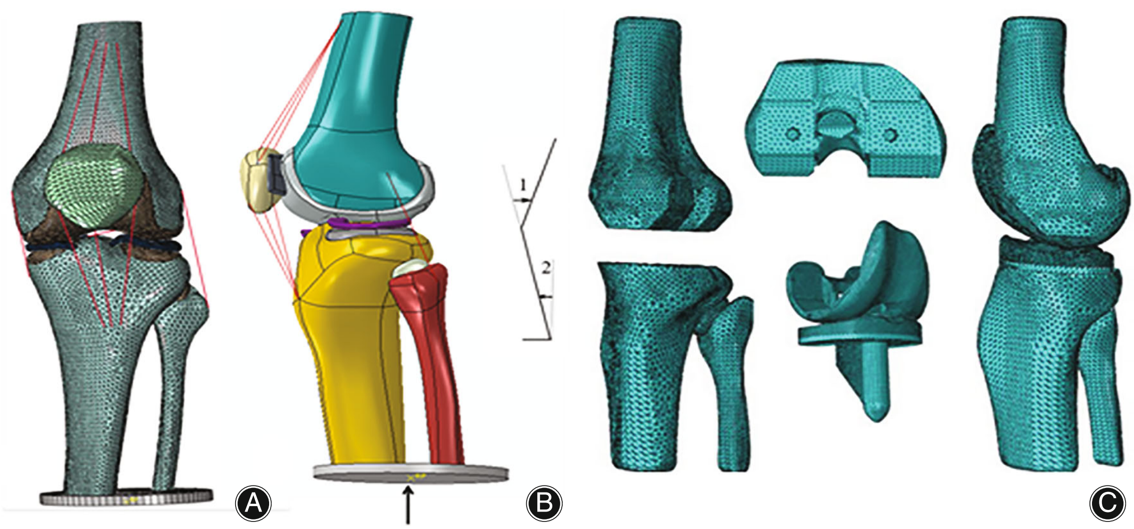

Fig. 1 Ankle forces were applied at the center of the plate at the distal end of the tibia and fibula (A: the 3D Finite element model of the knee joint; B: the knee flexion angle 1 and ankle flexion angle 2 during walking); C: the FEA model after TKA.

TABLE 2 Material properties

Structures	Elastic modulus (MPa)	Poisson's ratio	References
Cortical bone	17,000	0.3	Majumder *et al.*[21]
Cancellous bone	400	0.3	Donahue *et al.*[22]
Patella	15,000	0.3	Kiapour *et al.*[23]
Cartilage	5	0.45	Li *et al.*[24]
Meniscus	59	0.49	LeRoux and Setton[25]; Peña *et al.*[26]
Ligament	6	0.4	Siegler *et al.*[27]
Femoral Component / Tibial component	200,000	0.3	Villa *et al.*[28]
Polyethylene insert	1016	0.46	Liau *et al.*[14]

supervision of the surgeon. The leg was radiographed to correct the mechanical alignment of the FEA model at 2 and 6 months after TKA. Gait data were used as the inputs of the FEA model. The solid models were assembled and meshed into 3D, 4-node tetrahedral elements using ABAQUS.

Material Properties

All materials of FEA models were deemed to be isotropic, homogeneous, and linearly elastic to analyze the contact stress.[20] The material properties of each component were taken from the literature (Table 2). A rigid plate was added in the assembled FEA model, combining the tibia and fibula to simulate the real condition of the ankle in the human body.

Interface Contact

The contacts between the femoral and patellar cartilage, the femoral and tibial cartilage, the femoral cartilage and the meniscus, and the tibial cartilage and the meniscus were considered to be frictionless, surface-to-surface contacts with finite sliding.[18] The contact between the femoral prosthesis and the tibial polyethylene insert and the contact between the patellar cartilage and the tibial polyethylene insert were set with a frictional value of $\mu = 0.02$ and $\mu = 0.05$, respectively.[20] Interfaces between cartilage and bone and between prostheses and bone were set as tie contacts to simulate the junction of the knee joint.

Boundary and Loading Conditions

The proximal end of the femur was fixed, and a plate was added to the distal end of the tibia and fibula. For the tibial side, all rotations were free while the translation was only allowed in up and down directions. The three directional force components of the ankle joint were calculated by inverse dynamic analysis[18] and imposed on the center of the plate.

Boundary and Loading Conditions for Standing

The degrees of flexion and extension of the ankle and knee were set along the axis direction. The GRFs were extracted from the force plate. The forces of the ankle were calculated from the inverse dynamic analysis as the boundary and loading conditions for the FEA model (Fig. 1). Quasi-static analysis was conducted by the FEA models.[29]

Boundary and Loading Conditions for Walking

The degrees of ankle flexion or extension at the first and second peaks of the GRFs during the stance phase of the gait cycle were extracted as the boundary conditions. The forces of the ankle calculated from the 3D motion capture system were used as the loading conditions for the FEA model (Fig. 1). Quasi-static analysis was conducted by the FEA models, as inertia has little effect on the stance phase of the gait cycle.[29]

Gait Analysis

The kinematic data of the lower limbs and the ground reaction forces (GRFs) were recorded by a 3D motion capture system (Motion Analysis Corp., Rohnert Park, CA, USA) with six cameras and a force plate (Kistler Corporation, Winterthur, Switzerland) during walking at a self-selected pace in all tests. Sampling rates were set at 120 Hz for both the 3D motion capture system and the force plate. Nineteen reflective markers were put on the skin surface of all subjects according to the Helen–Hayes model[30] to measure lower-extremity kinematics. Before the tests, the subjects walked on the 10-m walkway to familiarize themselves with the environment. The subjects then stood on the force plate for 30 seconds. After the static standing data were recorded, the subjects walked back and forth along the walkway. Three direction forces at the ankle joints were calculated by inverse dynamic analysis, which provided the load for the FEA models (Fig. 1). The total contact forces of the knee joints were also calculated by inverse dynamic analysis to enable comparisons with the FEA results.

Model Evaluation

The FEA model was evaluated by comparing the total contact forces of the knee joints in the FEA model *versus* the inverse dynamic model.

The inverse dynamics method was used to calculate the equivalent forces applied at the knee joint and the ankle joint during standing and walking. The gait parameters were obtained from the motion analysis system. The force analysis

TABLE 3 The percentage of total tibiofemoral contact forces on medial and lateral tibial plateaus (%)

		Patient 1			Patient 2		
	Healthy subjects	before TKA	2 months	6 months	before TKA	2 months	6 months
Medial							
Static standing	64.75 ± 3.34	90.78	61.63	61.63	93.53	69.99	69.99
Peak 1	61.06 ± 3.43	74.78	74.78	65.98	70.68	85.19	53.99
Peak 2	72.09 ± 1.83	86.48	79.65	68.13	83.56	81.41	64.65
Lateral							
Static standing	35.25 ± 3.34	10.22	38.37	38.37	6.47	30.01	30.01
Peak 1	38.94 ± 3.43	25.22	16.76	34.02	29.32	14.81	46.01
Peak 2	27.91 ± 1.83	13.52	20.35	31.87	16.44	18.59	35.35

Notes: Peak 1: the moment of the first peak of ground reaction force.; Peak 2: the moment of the second peak of ground reaction force.; Total knee arthroplasty (TKA).

diagram and the translational kinetic equations were detailed in our previous study.[18]

Results

Adjusted Tibio-Femoral Contact Force Distribution after TKA

The FEA models of the knees with varus KOA contained 42,972 nodes and 169,815 elements. The models of the healthy knee joints contained 32,335 nodes and 127,773 elements. During static standing, the medial plateau bore most of the total contact forces in the knees with varus KOA (90.78% for patient 1 and 93.53% for patient 2) and bore 64.75% ± 3.34% of the force in the healthy knees (Table 3). At the first and second peaks of GRF during the stance phase of a gait cycle, the medial plateau also bore a much higher percentage of contact forces in the knees with varus KOA (74.78% and 86.48%, respectively, for patient 1; 70.68% and 83.56%, respectively, for patient 2) in comparison with healthy knees (61.06% ± 3.43% at the first peak and 72.09% ± 1.83% at the second peak) (Table 3).

During static standing, the maximum von Mises stress on the medial plateau in varus knees (1.26 MPa for patient 1 and 1.31 MPa for patient 2) was much higher than that on the lateral plateau (0.49 MPa for patient 1 and 0.52 MPa for patient 2) (Table 4). A stress nephogram showed that the stress was evenly distributed in the healthy knees, whereas there was an obvious stress concentration on the medial plateau in the knees with varus KOA (Fig. 2).

The FEA models of post-TKA knees contained 49,411 nodes and 227,874 elements. The percentage of total contact forces on the tibial plateau during static standing following TKA (61.63% on the medial plateau for patient 1 and 69.99% for patient 2) was close to the load-bearing mode of healthy subjects (64.75% ± 3.34% on the medial plateau). Two months after TKA, the medial tibial plateau still bore more than 79% of the total contact forces at the first and second peaks of the GRF during the stance phase. However, 6 months after TKA, the percentages of the total contact forces on the medial tibial plateau changed to 65.98% and 53.99% at the first peak, and 68.13% and 64.65% at the second peak for patients 1 and 2, respectively (Fig. 3 and Table 3). The nephogram showed obvious improvement in the medial and

TABLE 4 The maximum von Mises stresses on the medial and lateral tibial plateau (MPa)

		patient 1			patient 2		
	Healthy subjects	before TKA	2 months	6 months	before TKA	2 months	6 months
Medial							
Static standing	1.07 ± 0.13	1.26	8.71	8.71	1.31	4.49	4.49
Peak 1	1.61 ± 0.35	2.53	9.19	12.84	1.94	12.56	20.38
Peak 2	1.63 ± 0.33	2.77	9.02	14.35	2.52	17.61	18.08
Lateral							
Static standing	0.87 ± 0.20	0.49	6.77	6.77	0.52	2.96	2.96
Peak 1	1.45 ± 0.27	1.26	4.63	8.74	1.6	8.25	9.61
Peak 2	1.07 ± 0.02	1.05	4.88	7.86	1.36	7.19	12.46

Notes: Peak1: the moment of the first peak of ground reaction force.; Peak 2: the moment of the second peak of ground reaction force.; Total knee arthroplasty (TKA).

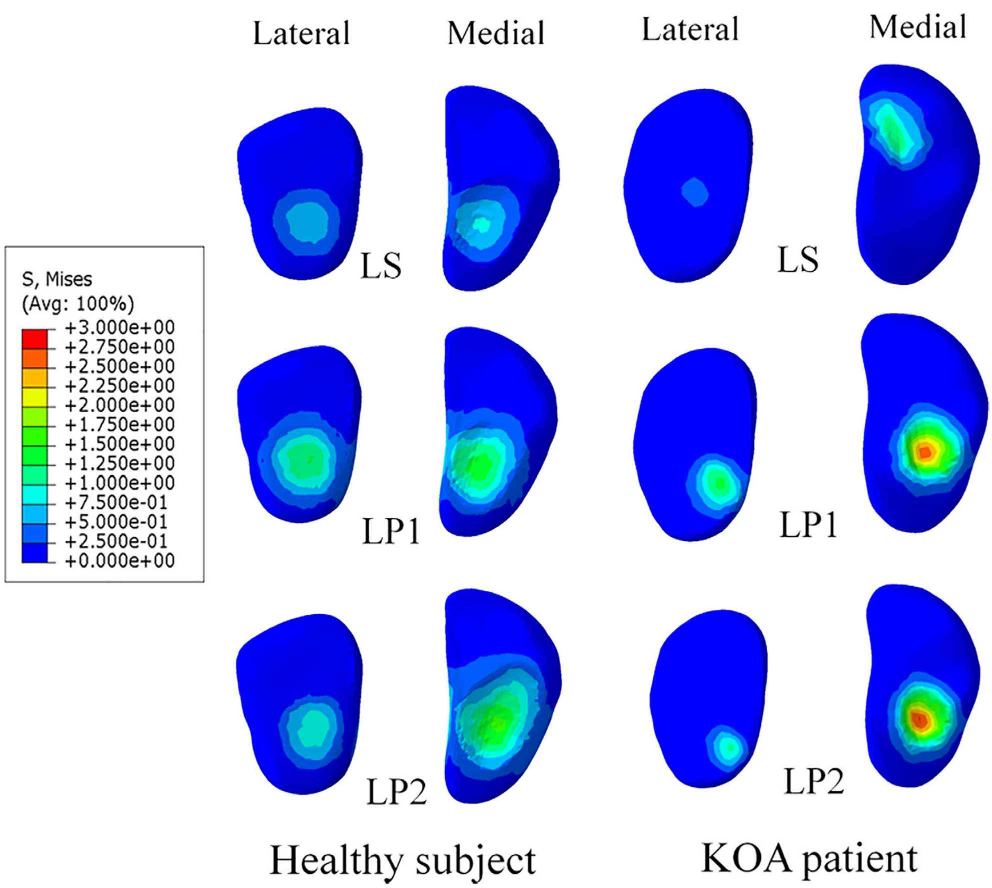

Fig. 2 Nephograms of von Mises stresses on tibial plateau for a healthy subject and KOA patient From top to bottom: static standing, first peak and the second peak of vertical GRF of the stance phase during walking. LS means the standing of the left knee, LP1 means the first peak of the left knee, and LP2 means the second peak of the left knee.

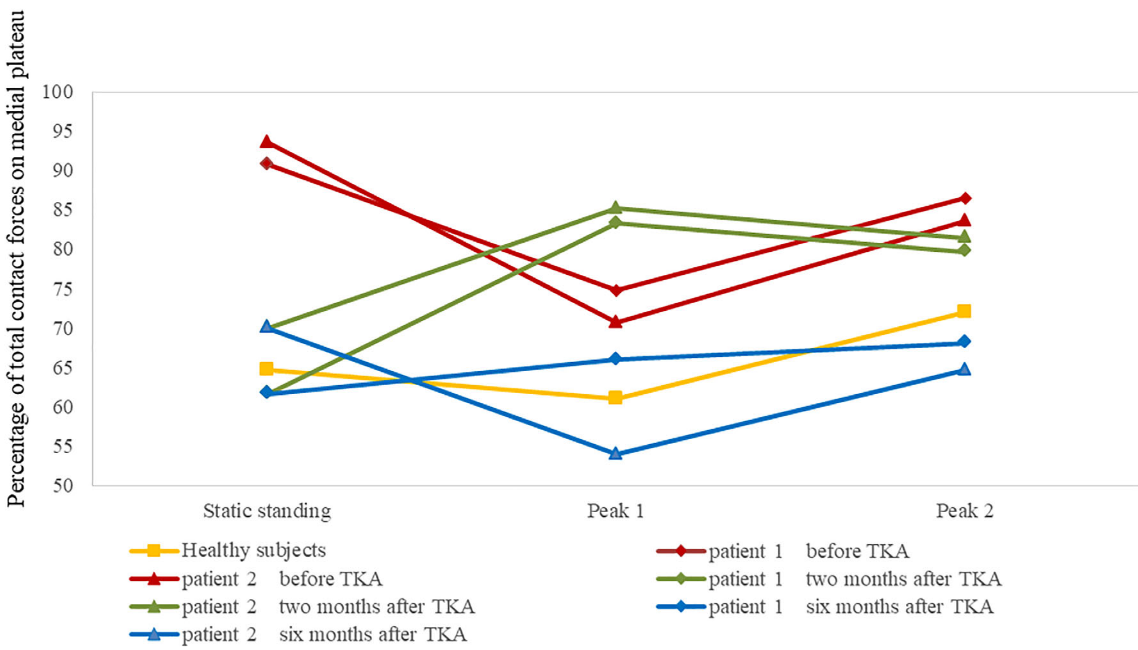

Fig. 3 The percentages of the total tibio-femoral contact forces on medial tibial plateaus.

TABLE 5 Gait parameters

Gait parameters	Healthy subjects	patient 1			patient 2		
		before TKA	2 month	6 month	before TKA	2 month	6 month
Gait cycle (s)	1.18 ± 0.06	1.4	1.76	1.21	0.99	1.19	0.97
Speed (m/s)	1.07 ± 0.28	0.74	0.31	0.65	1.03	0.63	1.07
Step length (m)	0.61 ± 0.12	0.53	0.24	0.38	0.48	0.42	0.54
Cadence (steps/min)	105.04 ± 7.49	84.25	64.32	97.57	122.58	100.43	124.7

Notes: Peak1: the moment of the first peak of ground reaction force.; Peak 2: the moment of the second peak of ground reaction force.; Total knee arthroplasty (TKA).

lateral distributions of knee contact stress from 2 to 6 months following TKA (Fig. 3).

The maximum von Mises stress after TKA was 8.71 MPa on the medial plateau and 6.77 MPa on the lateral plateau of the tibial polyethylene insert (Table 4). Two months after TKA, the maximum von Mises stress during walking was 9.02 MPa on the medial plateau and 4.88 MPa on the lateral plateau for patient 1, and 12.56 MPa on the medial plateau and 7.19 MPa on the lateral plateau for patient 2. Six months after TKA, the maximum von Mises stress on the tibial polyethylene insert was 12.84 MPa on the medial plateau and 7.86 MPa on the lateral plateau for patient 1, and 18.08 MPa on the medial plateau and 9.61 MPa on the lateral plateau for patient 2 (Table 4).

Improvements after TKA

For patients 1 and 2, the respective walking speeds were 0.74 and 1.03 m/s before surgery, 0.31 and 0.63 m/s at 2 months after TKA, and 0.65 and 1.07 m/s at 6 months after TKA. Similar patterns were found for the gait cycle, step length, and cadence. For the healthy subjects, the gait cycle, walking speed, step length, and cadence were 1.18 ± 0.06 s, 1.07 ± 0.28 m/s, 0.61 ± 0.12 m, and 105.04 ± 7.49 steps/min, respectively (Table 5).

Model Evaluation through Inverse Dynamic Analysis

The total contact forces of the knees during static standing calculated using the inverse dynamic method were 258.92 N for patient 1 and 242.74 N for patient 2 before TKA, while the forces from the FEA method were 267.51 N for patient 1 and 251.48 N for patient 2. The total contact force of healthy knees was 309.49 N by the inverse dynamic method and 322.40 N by the FEA model (Table 6). The respective knee forces at the first and second peaks of GRF during walking were 584.48 and 524.50 N for patient 1, and 568.87 and 529.98 N for patient 2 using the inverse dynamic method, and 600.56 and 566.58 N for patient 1, and 603.12 and 568.29 N for patient 2 using the FEA method. The respective average forces in the healthy knees at the first and second peaks of GRF during walking were 756.09 ± 52.03 and 753.74 ± 64.61 N using the inverse dynamic method, and 788.64 ± 51.19 and 808.57 ± 72.10 N using the FEA method.

The ratios of total knee contact forces between the FEA and inverse dynamic models were more than 0.96 during static standing and more than 0.90 at the first and second peaks of GRF in a gait cycle.

Discussion

FEA was effective in identifying the tibio-femoral contact forces of knee joints, as the results from the FEA models

TABLE 6 The total contact forces of knees by inverse dynamic method and FEA model method (N)

	Healthy subjects	patient 1			patient 2		
		before TKA	2 months	6 months	before TKA	2 months	6 months
Inverse dynamic methods (Static standing)	309.49 ± 2.02	258.92	242.74	242.74	242.74	258.92	258.92
FEA model (Static standing)	322.40 ± 4.40	267.51	251.48	251.48	251.48	267.51	267.51
(%)	95.83	96.68	96.4	96.4	96.4	96.68	96.68
Inverse dynamic methods (Peak 1)	756.09 ± 52.03	584.48	595.84	573.88	568.87	554.488	526.848
FEA model(Peak 1)	788.64 ± 51.19	600.56	646.543	627.752	603.12	610.227	572.67
(%)	95.69	97.25	91.49	90.61	93.98	89.95	91.3
Inverse dynamic methods (Peak 2)	753.74 ± 64.61	524.5	550.054	548.17	529.98	526.848	529.788
FEA model (Peak 2)	808.57 ± 72.10	566.58	600.325	605.389	568.29	565.4	576.94
(%)	92.73	91.98	90.86	89.56	92.77	92.68	91.1

Notes: Peak1: the moment of the first peak of ground reaction force.; Peak 2: the moment of the second peak of ground reaction force.; Total knee arthroplasty (TKA).

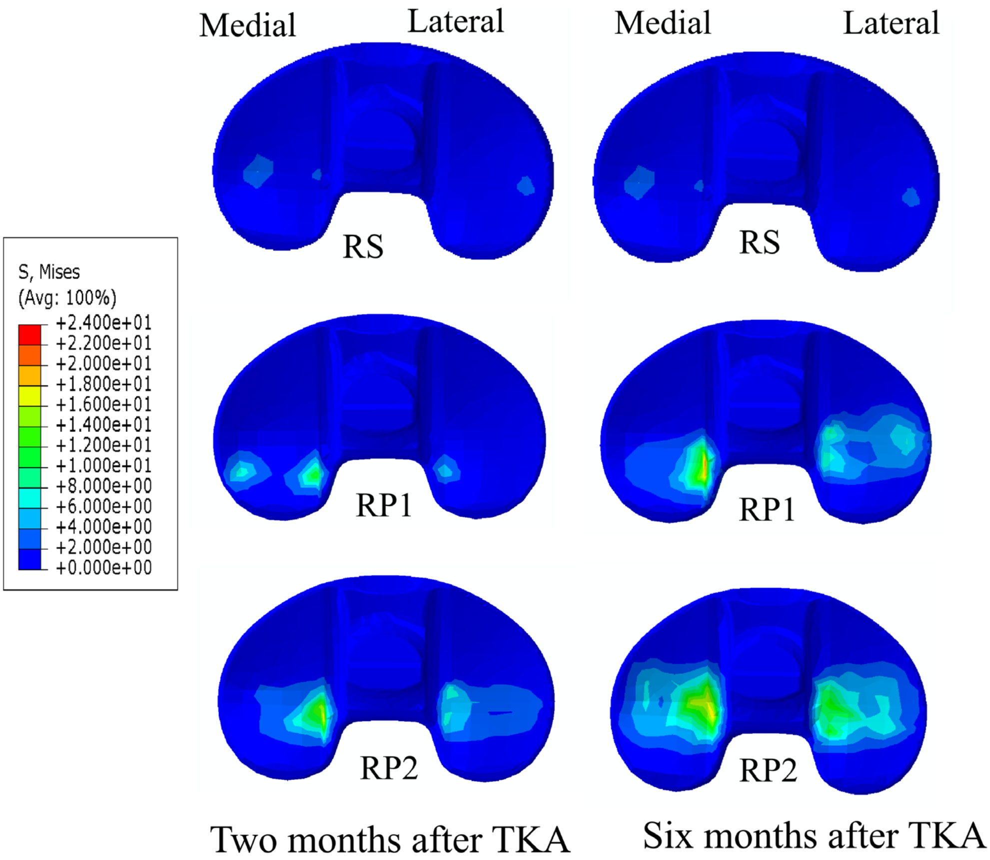

Fig. 4 Nephograms of von Mises stresses on the tibial polyethylene inserts two and six months after TKA. From top to bottom: static standing, first peak, and the second peak of vertical GRF during the stance phase of a gait cycle. RS means the standing of the right knee, RP1 means the first peak of the right knee, and RP2 means the second peak of the right knee. The load-bearing mode on the tibial polyethylene inserts following TKA was recovered to the mode in the tibial plateaus of healthy subjects.

were similar to those from the inverse dynamic analysis ($R^2 = 0.996$).

Load Pattern in Patients with KOA

At the first and second peaks of the GRFs during the stance phase of the gait cycle, the medial plateaus in knees with varus KOA exhibited much higher percentages of total contact forces and obvious stress concentrations compared with the healthy knees (Fig. 2). Furthermore, the increased contact forces and stresses on the medial plateau in the knees of patients with varus KOA, especially over long periods of time, might aggravate the wear of the tibial cartilage, accelerate the progression of KOA, and eventually lead to functional deficiencies of the knee. This is supported by our intraoperative observations of severe medial tibial cartilage damage in both patients. The cause of KOA is complex, and the abnormal loading pattern on the medial and lateral plateaus in the knee joint might contribute to the development of KOA.[31]

Multiple factors may affect the load-bearing modes on the tibial polyethylene inserts during walking. For patients with varus KOA, insufficient medial collateral ligament release leads to higher postoperative contact forces and stresses on the medial plateau, while excessive medial collateral ligament release leads to lower postoperative medial plateau contact forces and stresses. With the correction of lower limb alignment, the postoperative residual laxity or tension of the collateral ligament gradually diminishes with time after TKA.[32] The angle between the quadriceps load vector and the patellar tendon load vector (Q-angle) has a direct effect on tibio-femoral contact forces. Patients with KOA typically have a large Q-angle, which might cause an increased tibial internal rotation angle and potentially produce a torsional load on the tibio-femoral joint, and this can result in abnormal load distribution on the tibial plateau, contributing to the progression of KOA.

The abnormal mechanical performance also might be caused by the varus malalignment, which was diagnosed based on the radiographic HKA angles of 169.70° and 171.54° for patients 1 and 2, respectively. Perillo-Marcone and Taylor[33] suggested that even a small amount of varus malalignment dramatically increases the contact forces on the medial plateau. The neutral mechanical alignment was improved after TKA, as the HKA angles after surgery were 177.09° for patient 1 and 177.71° for patient 2 which were similar to the HKA angles of the healthy subjects (177.07° and 178.46°). The FEA results also showed that the load-bearing mode on the tibial polyethylene inserts following TKA was consistent with the load-bearing mode in the tibial plateaus of healthy subjects during static standing and at the first and second peaks of the stance phase of the gait at 6 months after TKA (Figs. 3, 4).

Adjusted Tibio-Femoral Contact Force Distribution after TKA

The tibio-femoral contact force distribution and gait parameters of patients with KOA adjusted gradually with recovery time. Two months after TKA, the percentages of total contact forces on the medial plateaus were still considerably higher in both patients at the first peak of the GRFs during the stance phase of the gait cycle and were nearly the same at the second GRF peak compared with before TKA. However, 6 months after TKA, the tibio-femoral contact force distribution between the medial and lateral plateaus was similar to that in healthy knees (Fig. 4); similar findings were reported in the previous studies.[6-9] The phenomenon might be explained by the marked residual quadriceps femoris weakness that often persists long period of time after surgery.[34,35]Mizner *et al.* reported that the strength of the quadriceps is decreased one month after TKA, but is significantly improved six months after TKA.[36] Lorentzen *et al.* also demonstrated that temporary isometric muscle strength decreases at 3 months after TKA, but increases at 6 months after TKA.[37] The maximum von Mises stress increased from 2 to 6 months after TKA, which might be due to the recovery of muscle strength, as muscles are significant contributors to the high joint forces that develop in the knee during walking.[38] The results of the present study indicate that the gait and the load-bearing mode on the medial and lateral plateaus had not reverted to normal two months after TKA due to insufficient time for soft tissue recovery. However, these variables may be gradually restored with time, as the respective HSS knee scores for patients 1 and 2 changed from 73 and 78 at 2 months after TKA to 85 and 89 at 6 months after TKA.

Tibio-Femoral Contact Force Distribution Correlates with Gait

The changes in the knee contact forces were likely expressed by alterations in gait. The walking speed, step length, and cadence were decreased 2 months after TKA, which is consistent with the results of a previous study that showed large locomotor deficits 2 months after TKA.[39] However, the walking speed, step length, and cadence were improved 6 months after TKA compared with 2 months after TKA. The improvements in the knee contact forces and stress distribution corresponded to the improvements in the gait and HSS knee score before and after TKA, which may indicate the important influence of knee contact forces on knee function and gait.

Limitations

There are some limitations in the present study. The knee joint relies on a variety of soft tissue structures, such as muscles, ligaments, and tendons, to maintain flexibility, stability, and strength. Therefore, the present results would be more convincing if the soft tissues around the knee joints were thoroughly investigated, although the postoperative residual laxity or tension of the collateral ligament gradually diminishes with time after TKA. As the subject-specific model may not be feasible for application in certain conditions,[40] it might be hard to investigate other gait phases. The results from two patients cannot be generalized to the entire population, and the 6-month follow-up after TKA might not be long enough. As the subject-specific model hindered the external generalizability of the findings,[40] studies with more subjects and longer follow-ups are warranted to conduct a long-term analysis of contact force changes after TKA.

Conclusion

FEA showed that the medial plateaus of knees with KOA bear the most of the total tibio-femoral contact forces during static standing and at the first/second peaks of GRFs during the stance phase of the gait cycle. For the patients with varus KOA, the unreasonable stress distribution restores the load-bearing mode on tibial polyethylene inserts six months after TKA. The load-bearing modes on the tibial polyethylene inserts, gait, and HSS knee scores of patients with KOA gradually improved after TKA, as the changes in the gait cycle, step length, cadence, and walking speed corresponded to the changes in tibio-femoral contact force distributions on the tibial polyethylene inserts and HSS knee scores.

Funding Information

This study was supported by the National Nature Science Foundation of China (Grant 31771018) and the School Nature Science Foundation of Capital Medical University (Grant PYZ 20156).

Authors' Contributions

Mingming Du finished finite element model construction and analysis, interpretation of results as well as draft manuscript preparation. Jun Sun contributed to study design, data collection, finite element model construction, analysis and interpretation of results, draft manuscript preparation, and revision of the manuscript. Yancheng Liu contributed to model analysis and interpretation of results, as well as revision of the manuscript. Yingpeng Wang participated in data collection, analysis and interpretation of results. Songhua Yan participated in study design, data analysis and interpretation of results. Jizhou Zeng is in charge of total knee arthroplasty surgery, analysis and interpretation of results as well as revision of the manuscript. Kuan Zhang is responsible for study conception and design, analysis and interpretation of results, draft manuscript preparation, and revision of the manuscript. All authors reviewed the results and approved the final version of the manuscript.

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