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Original Article

Analysis of different bicruciate-retaining tibial prosthesis design using a three dimension finite element model

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Abstract: The recent interest in bicruciate-retaining prostheses has aimed to address the need for an implant that can mimic a natural knee. Arguments have always existed about survivorship, including loosening and subsidence, as well as tibial preparation in bicruciate-retaining tibial prostheses. The aim of this study was to investigate the biomechanics of a new modular design and other bicruciate-retaining designs using a three-dimensional finite element model under different load conditions to discover which prosthesis was more suitable. We also evaluated related parameters (the third principal stress, shear stress, micromotion, and von Mises stresses) to compare the characteristics of different bicruciate-retaining designs. The biomechanics of the bicruciate-retaining tibial prosthesis can be influenced by the style of the designed prosthesis and gait loading. The new modular design showed stability and moderated the third principal stress, leading to less shear stress and stress shield, suggesting that this type of design can avoid knee prosthesis loosening and subsidence. Therefore, the new design may be used as a more suitable prosthesis for future bicruciate-retaining implant application.

Keywords: Bicruciate-retaining tibial prosthesis, new modular design, three dimensional finite element model, biomechanics, loosening, subsidence

Introduction

Total knee arthroplasty (TKA) is currently one of the most successful orthopedic procedures, with good long-term results [1, 2]. TKA is designed to relieve pain and restore knee function for patients with severe arthritis [3], but as many as 25% of patients report residual knee symptoms, after primary TKA [4]. One study reported that some North American patients had difficulty performing high knee flexion activities after TKA [5]. Therefore, surgeons are dedicated to designing prostheses that are more proper and surgical techniques for patients to experience better natural feeling in the knee, higher activity levels, and better satisfaction after TKA.

The above dissatisfaction may potentially be explained by the abnormal kinematics that affects muscle movement and proprioception due to sacrifice of the anterior cruciate ligament (ACL) during TKA. The bicruciate-retaining knee prosthesis was designed to preserve the physiological movement of the knee [1]. The bicruciate-retaining TKA implants more closely replicate normal knee kinematics than other designs and thus have the advantage of improved functional performance and similar range of motion to that of the normal knee [6]. Sabouret reported a 22-year follow-up study of TKA with retention of both cruciate ligaments and demonstrated that preservation of the ACL in patients who undergo TKA can provide improved function and adequate stability at long-term follow-up [7]. Townley studied the long-term results of bicruciate-retaining cemented TKA over 11 years, and they found that bicruciate-retaining TKA has low failure rates and provides excellent pain relief; 89% of patients in that study experienced good clinical results in terms of pain relief, motion, and activity [8]. Pritchett performed a study to test the prosthesis preference of patients who under-

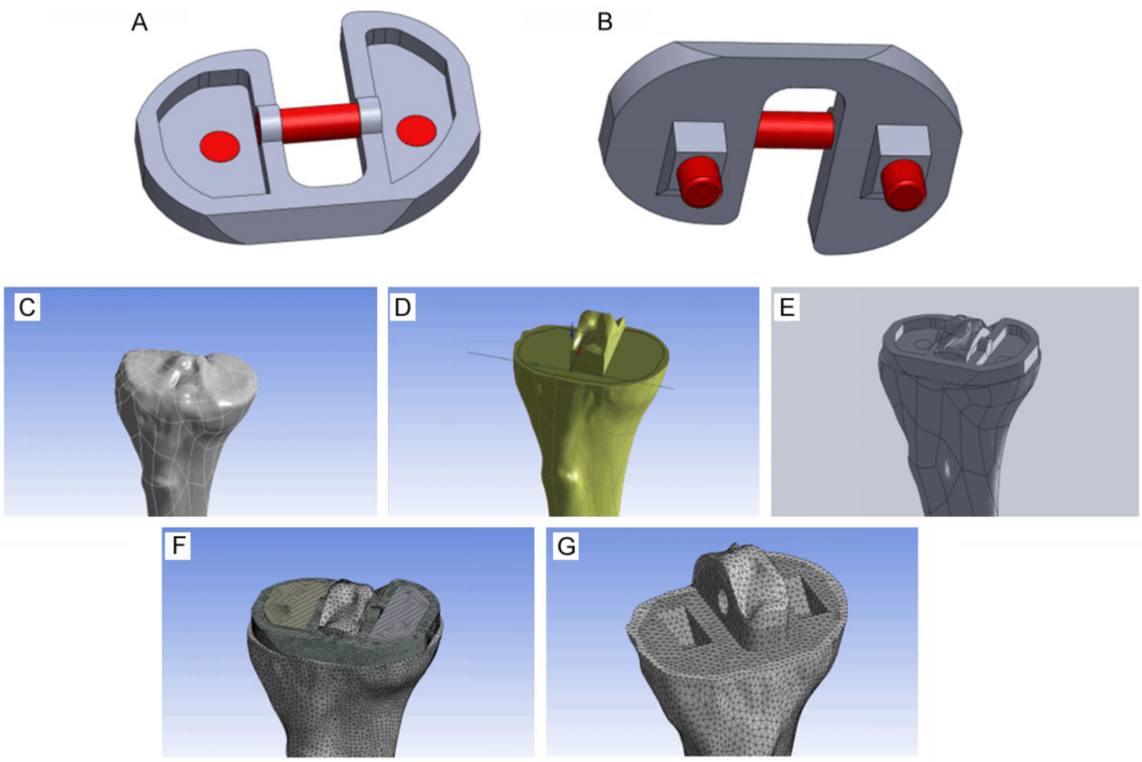


Figure 1. A new modular bicruciate-retaining tibial prosthesis and finite element models of the implanted bicruciate-retaining tibial prosthesis. A, B: A new modular bicruciate-retaining tibial prosthesis is a modified posterior cruciate retaining prosthesis. The joint surfaces were enhanced with a single transversal support (horizontal red column) located between the tibial spine, and two trapezoids and columns (vertical red column) beneath the lateral and medial joint surfaces. A vertical red column was fixed after the tibial baseplate was placed, so that the tibial baseplate was easily tilted in a certain direction; C: Preoperative tibia; D: Tibial cutting; E: Constructing the prosthesis and tibia; F, G: Finite element model of the implanted proximal tibia.

went bilateral, staged TKA with a bicruciate-retaining prosthesis in one knee and a posterior cruciate ligament (PCL) retainer in the other knee. The authors found that 70% of the patients preferred the bicruciate-retaining prosthesis [9]. Their follow-up study showed that bicruciate-retaining TKA provides satisfactory function and implant survivorship at 23 years' follow-up evaluation [10].

Since the advent of bicruciate-retaining TKA, a majority of the discussion has been focused on the design of bicruciate-retaining tibial prosthesis; therefore, the bicruciate-retaining TKA implant has not been widely used. In one bicruciate-retaining TKA design, the recess for the PCL retainer was extended anteriorly, but the anterior implant bridge was relatively narrow and it lacked strength [11]. Another bicruciate-retaining method used two unicondylar knee prostheses; however, unicondylar components were difficult to fix and orientate, and different levels of stress could lead to varied subsidence of separate compartments [12]. Arastu reported that unicompartmental TKA had a failure rate of 21% at a mean of 22 months after implantation; the causes were pain (44%) and component loosening (33%) [13]. In these designs, the central axial stem was discarded to allow retention of both cruciate ligaments; however, this modified design easily caused early loosening of the prosthesis [14]. Another design included a transversal support tibial plateau, which consisted of two individual joint surfaces that were enhanced by joint surface support and linked by a transversal support, providing good bone fixation [15]. However, in this design, the incision needed to be enlarged to implant the transversal support. Recent research has shown that a new Food and Drug Administration-approved bicruciate-retaining prosthesis has inferior survivorship, emphasizing the fact that tibial preparation in knees with bicruciate-retaining prostheses is more difficult

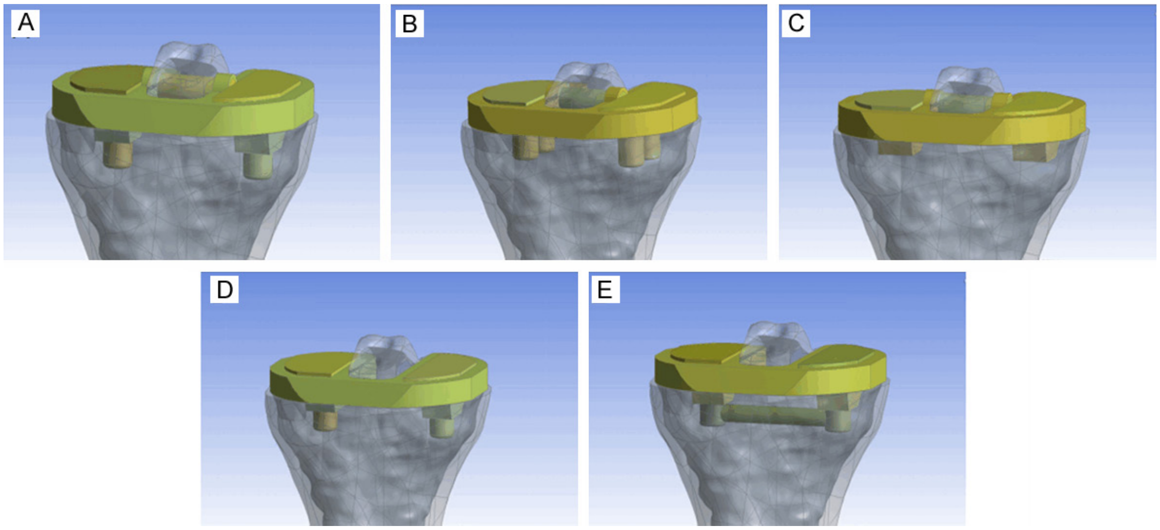


Figure 2. Finite element models of different types of bicruciate-retaining tibial prostheses. A: Model 1 (TS_{two}), which has two trapezoids and columns beneath the lateral and medial joint surface; B: Model 2 (TS_{four}), which has four columns; C: Model 3 ($TS_{trapezoid}$), which has no column; D: Model 4 (TSNo), which has no transversal support; E: Model 5 (TS_{colum}), in which transversal support is fixed on the two columns beneath the lateral and medial joint surfaces.

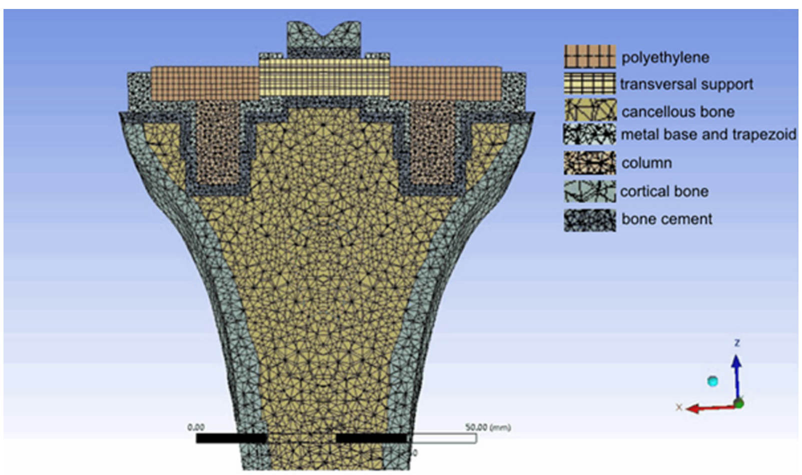


Figure 3. The interface of the prosthesis (including the metal base and trapezoid, transversal support, and column), bone cement, cortical bone, cancellous bone, and polyethylene.

[16]. These controversial findings raise concerns about the new bicruciate-retaining tibial prosthesis design.

In this study, we designed a new modular bicruciate-retaining tibial prosthesis by modifying the posterior cruciate-retaining prosthesis, in which the joint surfaces were enhanced by a single transversal support located between the tibial spine (**Figure 1A** and **1B**). The aim of this study was to investigate the biomechanics of different bicruciate-retaining designs using a three-dimensional finite element (FE) model to discover which prosthesis was more suitable.

Materials and methods

Model construction

FE models have been used to analyze TKA kinematics in normal and high flexion ranges [17]. An anatomically detailed, three-dimensional finite element model of the tibia was built from computed tomography images of the left tibia of a healthy adult volunteer (**Figure 1C**). The medial and lateral side of the proximal tibia was horizontally resected at 10 mm below the lateral articulating surface of the tibial plateau. In an effort to avoid damaging the ACL and PCL, we cut a vertical incision at the medial and lateral border of the total tibial eminence, and the anterior incision was located 10 mm behind the anterior-most tibial edge (**Figure 1D**). Different types of bicruciate-retaining tibial prostheses of the finite element models of the tibial component were based on cross-sections of a commercially available implant (Depuy, Warsaw, IN, USA).

Table 1. Loading conditions according to different gait styles [20]

Loading	Load condition	Load (× body weight)			Knee fexion angle (°)
		Medial	Laterial	Anteroposterior	
Generic	Single	2.1	0.9	0.5	0
Stair climbing	Single	2	1.5	0.5	30
HS	Sequential	0.45	0.6	0.1	0
CTO		0.83	0.83	0.08	15
MS		1.06	0.94	0.2	10
CHS		1.33	0.89	0.3	20
TO		0.5	0.6	0.26	30

Generic: single leg standing; HS: heel strike; CTO: contralateral toe-off; MS: mid stance; CHS: contralateral heel strike; TO: toe-off.

The tray and polyethylene insert sizes were dimensioned to provide maximum coverage of the resected surface, similar to clinical practice. The solid structures of the implant and tibial bone were constructed using the Solid Works 2012 program (**Figure 1E**) and were transferred to the ANSYS Workbench 13.0 program for analysis (**Figure 1F** and **1G**). The entire FE model consisted of approximately 41,000 linear tetrahedral elements, which varied according to the different types of bicruciate-retaining tibial prostheses, and the convergence tolerance was set at 1%.

Tibial prosthesis design

Five different types of bicruciate-retaining tibial prostheses were designed, as follows:

Model 1 (TS_{two}): This was the modified posterior cruciate-retaining prosthesis. The recess for the PCL was extended anteriorly, and the joint surfaces were enhanced with a single transversal support that was located between the tibial spine, as well as two trapezoids and columns beneath the lateral and medial joint surfaces (**Figure 2A**).

Model 2 (TS_{four}): Similar to Model 1, in Model 2, the two trapezoids and columns beneath the lateral and medial joint surface were replaced by four columns, which was similar to the conventional bicruciate-retaining tibial prosthesis (**Figure 2B**).

Model 3 ($TS_{trapezoid}$): Similar to Model 1, in Model 3, only the trapezoid structure located beneath the lateral and medial joint surface (**Figure 2C**).

Model 4 (TS_{No}): This model is an analog of Model 1 in which the transversal support that was located between the tibial spine was removed (**Figure 2D**).

Model 5 (TS_{colum}): Similar to Model 4, in Model 5, a single transversal support was fixed on the two columns beneath the lateral and medial joint surfaces, which is the concept of TTTP (**Figure 2E**) [15].

Material behavior and boundary conditions

The tibia and materials of each of the models used in this study have different mechanical and physical characteristics. These materials were modeled as linear elastic and isotropic, and the elasticity modulus and Poisson's ratios were obtained from the literature for cortical bone (elastic modulus of 8 GPa, Poisson's ratio of 0.3), cancellous bone (elastic modulus of 1.5 GPa, Poisson's ratio of 0.2) [18], metal base (elastic modulus of 112 GPa, Poisson's ratio of 0.34), bone cement (elastic modulus of 2 GPa, Poisson's ratio of 0.23), and polyethylene (elastic modulus of 1 GPa, Poisson's ratio of 0.3) [19]. The interfaces were modeled as bonded, where bone cement was applied. The cement mantle thickness was 2 mm around the tibial tray and stem. The interface were consisted of the prosthesis (including metal base, transversal support, and trapezoid column), bone cement, cortical bone, cancellous bone (**Figure 3**), and transversal support contacted the adjacent metal by friction, with a friction factor of 0.2.

Loading

To mimic the physiological biomechanics of the knee joint in daily activity, we loaded different axial load conditions and shear forces on the lateral and medial tibial plateau area according to different gait styles (**Table 1**) [20]. The body weight was set as a normal 70 kg. The load sites at the tibio-femoral contact were decided based on the angles of knee flexion [21]. The loads that were applied at the tibio-femoral contact points were distributed over areas that were 10 mm in diameter.

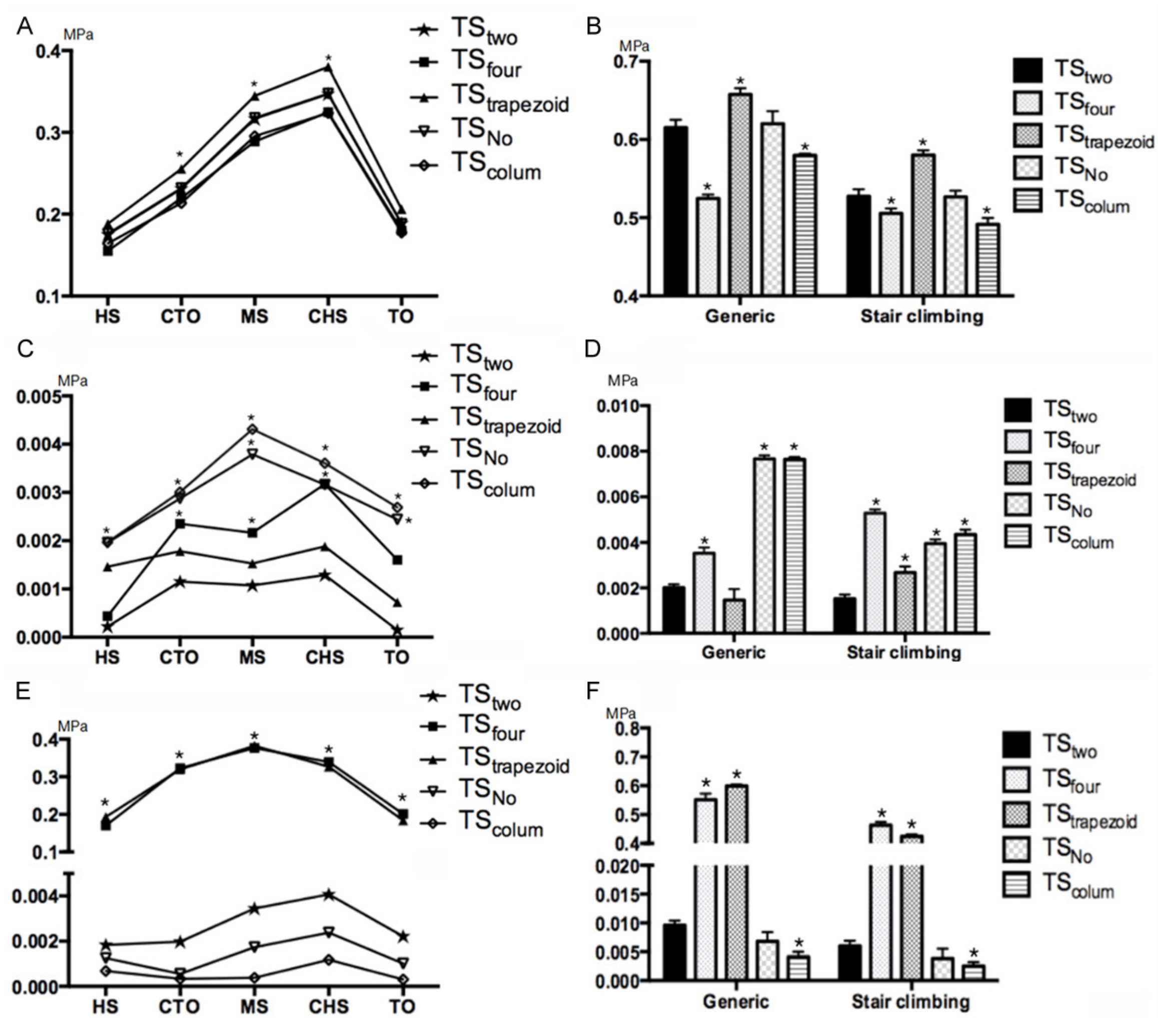


Figure 4. The third principal stress of the cancellous bone and shear stress distribution in the bone-implant system. A, B: The third principal stresses were the higher in Model 3 ($TS_{trapezoid}$) in normal gait styles and special gaits styles, while lowest in the Model 5 (TS_{colum}) or Model 2 (TS_{four}) in special gaits styles; C, D: The shear stresses in Model 1 (TS_{two}) showed the lowest level in tibial cancellous bone, except for the generic load condition, while almost highest in Model 5 (TS_{colum}) and Model 4 (TS_{four}), except for the stair climbing load condition; E, F: The shear stresses in Model 2 (TS_{four}) and Model 3 ($TS_{trapezoid}$) were obviously higher on the bone-cement interface than in other models. *: P<0.05 , compared to Model 1 (TS_{two}).

Statistical analysis

Data were analyzed with the use of SPSS 21.0 statistical software. Data are presented as the mean ± standard deviation, and Student's t test or a one-way ANOVA were used for comparisons between groups. A *p* value <0.05 was defined as statistically significant.

Results

The third principal stress on the cancellous bone

The third principal stress is an important predictor of aseptic loosening of the prosthesis. The distribution of the third principal stress on the tibial cancellous bone where the implant was inserted was evaluated for different bicruciate-retaining tibial prosthesis models. The stresses in different loading conditions are presented in **Figure 4A**. The third principal stresses are presented as parabolic variations in gait styles, and were the higher in Model 3 ($TS_{trapezoid}$). Similar results were found in some other special gaits, while lowest in the Model 5 (TS_{colum}) or Model 2 (TS_{four}) (**Figure 4B**).

Shear stress in cancellous bone and bone cement

The maximum shear stress for the cancellous bone interface and bone cement interface was evaluated to predict horizontal stress change

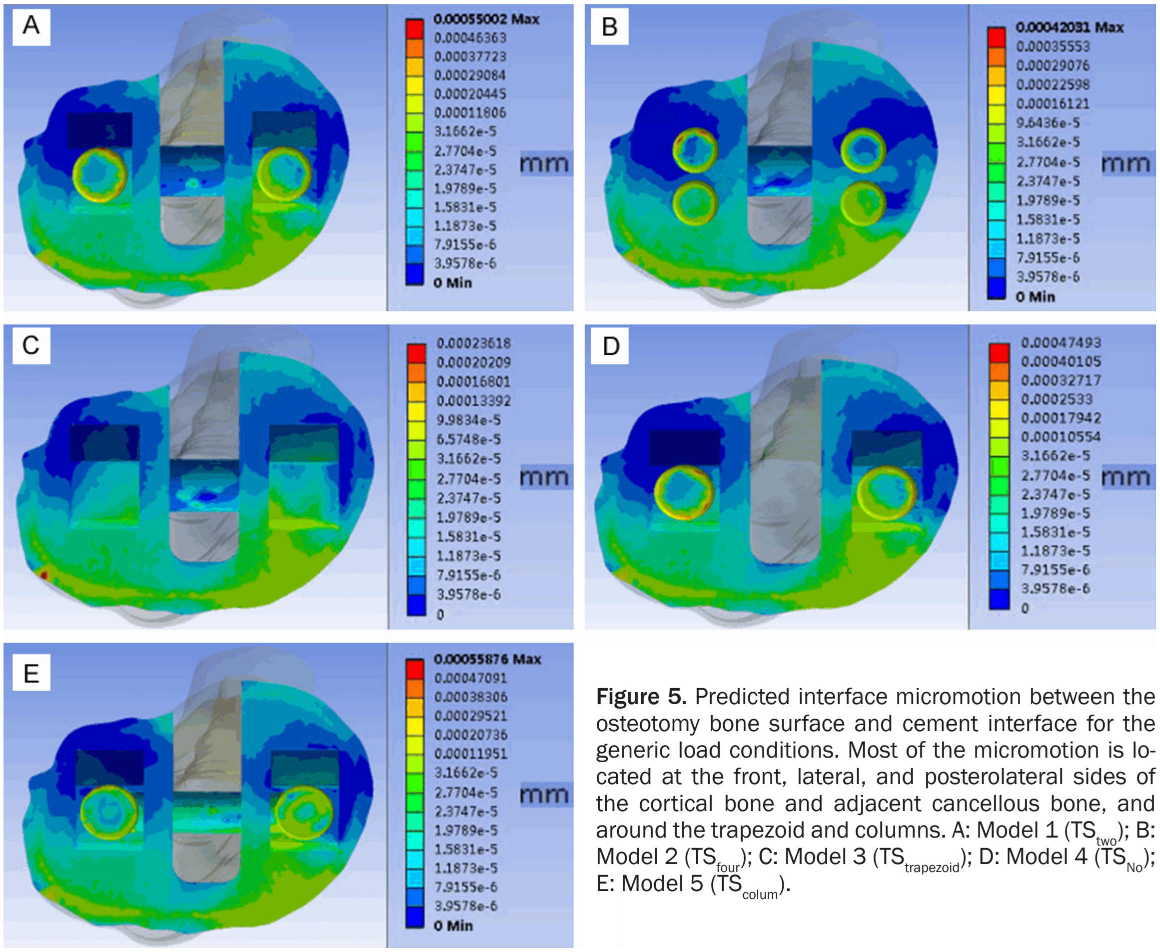


Figure 5. Predicted interface micromotion between the osteotomy bone surface and cement interface for the generic load conditions. Most of the micromotion is located at the front, lateral, and posterolateral sides of the cortical bone and adjacent cancellous bone, and around the trapezoid and columns. A: Model 1 (TS_{two}); B: Model 2 (TS_{four}); C: Model 3 ($TS_{trapezoid}$); D: Model 4 (TS_{No}); E: Model 5 (TS_{colum}).

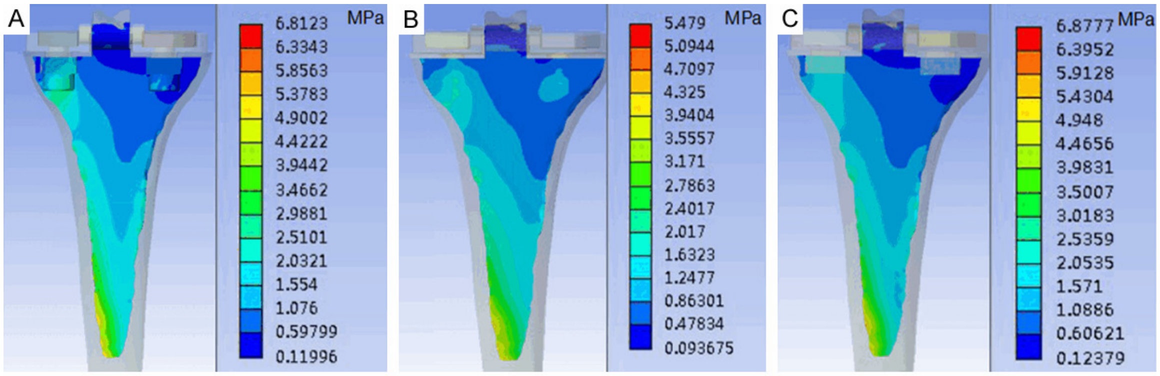
of the prosthesis, which was different from the vertical stress of the third principal stress. In the normal gait cycle, shear stress of CTO, MS and CHS was still higher than that of other load conditions (**Figure 4C**). The shear stresses in Model 1 (TS_{two}) showed the lowest level in tibial cancellous bone, except for the generic load condition, which was slightly higher than Model 3 ($TS_{trapezoid}$), while almost highest in Model 5 (TS_{colum}) and Model 4 (TS_{four}) both in normal gait and special gait, except for the stair climbing load condition (**Figure 4C** and **4D**). In contrast, the shear stresses in Model 2 (TS_{four}) and Model 3 ($TS_{trapezoid}$) were obviously higher on the bone-cement interface in both normal gait and special gait (**Figure 4E** and **4F**) than in other models.

The micromotion between the osteotomy bone surface and cement interface

The micromotion between the osteotomy bone surface and cement interface can allow the observer to view the stability of the bicruciate-retaining tibial prosthesis models. In case of vertical load, due to the bound state of the bone-cement interface, the micromotion between the osteotomy bone surface-cement interface is very small, with the largest as 0.0005 mm; most of the micromotion is located at the front, lateral, and posterolateral sides of the cortical bone and adjacent cancellous bone, and around the trapezoid and columns (**Figure 5A-E**). No significant difference was found among the designed tibial prosthesis models because they had the same bond interface (data not shown).

von Mises stresses of the cancellous bone

The distribution of von Mises stresses can display a stress shielding effect on cancellous bone after implantation of the prosthesis. The results showed that the von Mises stresses of the cancellous bone increased gradually proximally and distally to the tibial prosthesis. The



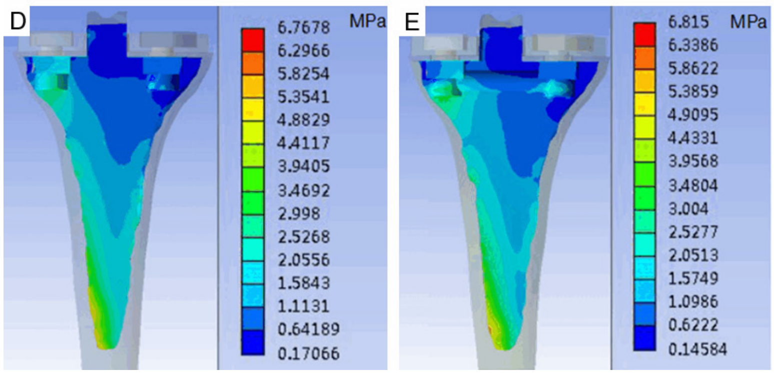
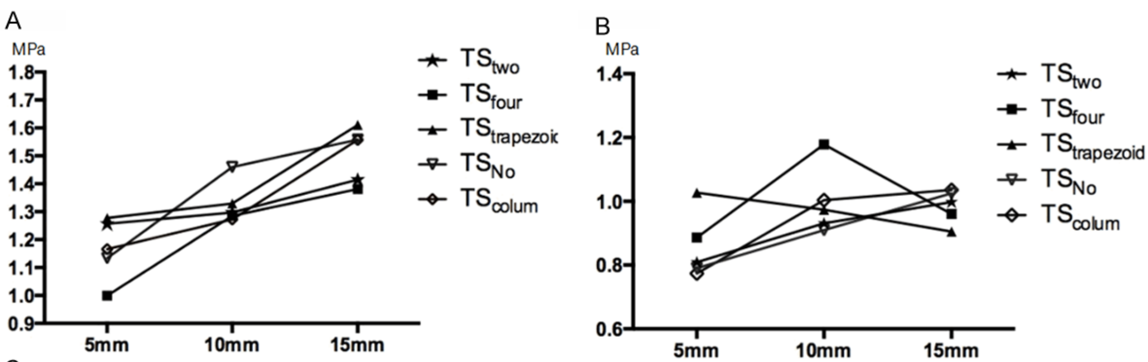


Figure 6. Von Mises stress distribution in the cancellous bone for the generic load condition. The von Mises stresses of the cancellous bone increased gradually proximally and distally to the tibial prosthesis, and the medial distribution of von Mises stresses in the cancellous bone was higher than lateral distribution, but the stress concentrated on the metal column. A: Model 1 (TS_{two}); B: Model 2 (TS_{four}); C: Model 3 ($TS_{trapezoid}$); D: Model 4 (TS_{No}); E: Model 5 (TS_{colum}).



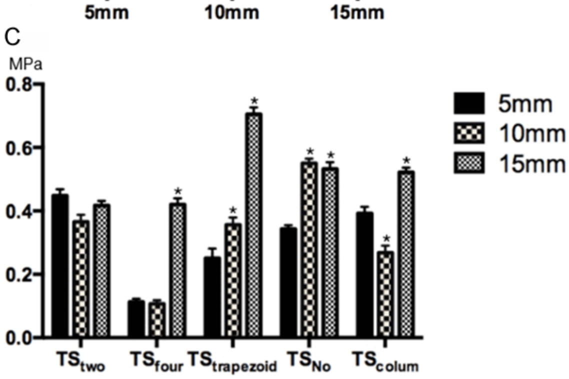


Figure 7. The variation of von Mises stresses on the medial side or lateral side of cancellous bone for the generic load conditions. A, B: Model 1 was more gradual than in other models on the medial or lateral sides; C: The difference between the medial and lateral sides of the von Mises stresses of cancellous bone in Model 1 was more stable than in other types of models under generic load conditions. *: $P<0.05$, compared to Model 1 (TS_{two}).

distribution of von Mises stresses in the cancellous bone varied under different gait loads, and the medial distribution of von Mises stresses in the cancellous bone was higher than lateral distribution, but the stress concentrated on the metal column (**Figure 6A-E**). Three selected loading points (5 mm, 10 mm, and 15 mm below the resected surface) were distributed between the edge of the tibial spine and metal column, where the von Mises stresses of the cancellous bone were recorded. There was no significant difference of variation of the von Mises stresses on cancellous bone among Models 1-5 at the normal gait between the medial and lateral sides, although both increased gradually from 5 mm to 15 mm (data not shown). The variation tendency of the von Mises stresses of cancellous bone in Model 1 was more gradual than in other models under generic load conditions both on the medial and lateral sides (**Figure 7A** and **7B**). The difference between the medial and lateral sides of the von Mises stresses of cancellous bone in Model 1 was more stable than in other types of models under generic load conditions (**Figure 7C**).

Discussion

We investigated the biomechanics of different bicruciate-retaining designs using a three-dimensional FE model to discover which type of prosthesis was the most suitable. Model 1 (TS_{two}) showed stability, moderated the third principal stresses, and led to less shear stresses and stress shielding, suggesting that this type of design may avoid loosening and subsidence of the knee prosthesis.

The recent interest in bicruciate-retaining prostheses has aimed to address the need for an implant that can mimic a natural knee during high activity levels. With the advent of TKA, discussions have arisen on the influence of the cruciate ligaments, especially that of the PCL [22]. However, the ACL is believed to play a more crucial role in the physiological movement of the knee than the PCL. TKA with a bicruciate-retaining prosthesis was shown to be surgically feasible; it can reduce antero-posterior laxity compared to cruciate-retaining TKA, and could improve knee stability without using conforming geometry [23]. Bicruciate-retaining prosthesis implants could provide improved functional properties. Superior proprioceptive function of bicruciate-retaining implants can be an important factor in implant selection [24]. Studies by Pritchett showed that patients who received bicruciate-retaining TKA implants have less bone loss, generated heat, and noise than patients with ACL-sacrificing TKA [25, 26]. However, arguments have always existed about complications including loosening and subsidence, as well as tibial preparation in bicruciate-retaining prosthesis; therefore, a new bicruciate-retaining tibial prosthesis design was created to solve these problems.

FE models in knee biomechanics are now a common way to investigate the effect of the prosthesis on load bearing and knee kinematics [27, 28]. Perillo-Marcone stated that FE modeling of an implanted proximal tibia showed the mechanical environment of the implanted tibia [29]. In this study, we used a three-dimensional finite element model to evaluate the biomechanical properties of the bicruciate-retaining tibial prosthesis models, and we mimicked the normal walking gait and special gait of patients under various stresses, including generic load conditions and stair climbing. The parameters that were related to stability and stress shielding were measured to evaluate the biomechanics of the different models.

Adequate prosthesis stability is the key factor to evaluate the mechanical quality of the prosthesis after TKA [30]. Instability can induce micromotion at the bone-prosthesis interface [31]. Micromotion may cause an unbalanced flexion and extension gap, leading to failure of the implant and a higher revision rate [32]. Therefore, the stability can be assessed using the micromotion that occurs in the bone-cement interface. Bone cement is used to solidify the prosthesis during TKA and the bonding of bone cement to the osteotomy bone surface and prosthesis interface is an essential step in performing TKA successfully [33]. Our results showed good postoperative stability of the implant; the largest micromotion between the osteotomy bone surface-cement interface was only 0.005 mm, which is similar to that observed in another study [34]. However, little difference was found among different models, which suggested that bone cement had a great influence on the mechanical stability compared with prosthesis design, indicating the importance of cement preparation and fixation.

One of the major causes of long-term failure in TKA is loosening of the tibial component [35]. The conventionally designed bicruciate-retaining tibial prostheses can usually lead to prosthesis loosening and subsidence. Because the bicruciate-retaining tibial prosthesis has less area in which to anchor, the pressure of the cancellous bone beneath the prosthesis increases, leading to early subsidence of the prosthesis. The radiolucent line of the prosthesis that is seen on X-ray images, which indicates loosening and rupture of the implant, usually appears beneath the base of the prosthesis [36]. In the current study, we detected stress on the cancellous bone under the prosthesis base, and we speculated on the possibility of prosthesis loosening under different load conditions. The third principal stress is an important factor of aseptic loosening of the prosthesis. We found that the third principal stress in Model 3 ($TS_{trapezoid}$) was the highest under different loads compared with that under other loads, and the lack of a column led to increased stress of the entire osteotomy bone surface, which initially could be transferred downward by the column. This was the same reason why the early design of bicruciate-retaining tibial prostheses without a center stem loosened easily. The third principal stress was similar in the two designs of bicruciate-retaining tibial prostheses with or without the transversal support that was located between the tibial spine, indicating that the transversal support between the tibial spine did not influence the third principal stress. Model 2 (TS_{four}) and Model 5 (TS_{colum}) had the lowest stress, because it was easier for the four columns or the combination of transversal support fixed on the two columns to transfer the vertical stress downward.

The third principal stress represents the vertical stress parameter of the prosthesis, while shear stress represents the horizontal parameter, which also predicts failure of the prosthesis [37]. Our results showed that the shear stresses in Model 4 (TS_{No}) and Model 5 (TS_{colum}) were the highest in tibial cancellous bone compared with other areas. This shows the importance of the transversal support, which is located between the tibial spine and can reduce the horizontal shear stress of the cancellous bone. The stress of Model 1 (TS_{four}) and Model 3 (TS_{colum}) was lower than that of Model 2 (TS_{four}), suggesting that the trapezoid structure can reduce shear stress. Cement loosening is the failure of the bond between an implant and bone in the absence of infection in patients who undergo TKA [38]. In this study, shear force of the bone cement was also detected. We found that the shear stresses in Model 2 (TS_{two}) and Model 3 (TS_{colum}) were obviously higher than in the other designs, indicating that the combined trapezoid structure and column can decrease the fatigue behavior rate of the bone cement.

The biomechanics of the knee joint are an important criterion for the design of an appropriate knee prosthesis, and TKA indeed changed the knee's biomechanics during walking [39]. TKA leads to the removal of normal stress from the proximal bone, which results in the reduction of load on the bone and bone density, according to Wolff's law. The reduction of the load on the proximal bone plays an important role in aseptic loosening in TKA, which is one of the main reasons for the revision the procedure [40]. In this study, we tested the load on the bone using different gaits, and the results showed that the von Mises stress distribution varied with the change of gait and increased with the increase of distance from the proximal position of the tibial prosthesis. All of the stress concentrated on the metal column of the prosthesis, which was similar to the mainstream design of knee prostheses. There was no significant difference among these bicruciate-retaining tibial prostheses under normal gait, while a significant difference among the designed tibial prostheses was noticed under generic load conditions. The variation of von Mises stresses in Model 1 (TS_{two}) between the medial and lateral or from proximal to distal was more average than in other models, leading to less stress shield and concentration.

This study has some limitations. First, the bone and soft tissue were assumed to be linear elastic material model coefficients, which could not modulate the exact biomechanical effect of bone and soft tissue [41]. However, all the designed prostheses were evaluated in the same conditions; therefore, this limitation is acceptable. Second, the friction between the metal and polyethylene materials was not studied. In fact, the locking mechanism of the metal and polyethylene materials had a small contribution to the overall outcome. Third, the FE analysis did not consider parameters such as race, gender, and age, which may affect the biomechanical results. Therefore, caution should be used when extrapolating the findings to a larger patient population.

In conclusion, the biomechanics of the bicruciate-retaining tibial prosthesis can be influenced by the style of the prosthesis and gait loading. The new design could be used as a prosthesis that is more suitable for future bicruciate-retaining implant application.

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Disclosure of conflict of interest

None.

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