Optimisation of the posterior stabilised tibial post for greater femoral rollback after total knee arthroplasty—a finite element analysis

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Abstract Femoral rollback after total knee arthroplasty (TKA) is necessary for flexion beyond 90–100°. Femoral rollback in posterior cruciate substituting TKA occurs as a result of the interaction between the femoral cam and tibial post. The geometric design of the cam post mechanism determines the kinematics of rollback. The purpose of this study is to optimise the design of the femoral cam-tibial post articulation through finite element analysis and suggest various design parameters that would optimise femoral rollback. Modifications to the tibial post geometry without changing the relative post position or slope are made. Results are characterised in terms femoral rollback and pressure distribution at the tibial post. Small design modifications to the tibial post are seen to produce large

changes in femoral rollback with relatively small accompanying increases in contact pressures at the tibial post.

Résumé Le rollback fémoral après prothèse totale du genou est nécessaire lorsque la flexion va au delà de 90 à 100°. Le rollback fémoral dans les prothèses postéro-stabilisées est le résultat de l'interaction entre la came fémorale et le plot tibial postérieur. La géométrie de la came détermine la cinématique de ce rollback. Le but de cette étude est d'optimiser le dessin de la came fémorale et de son articulation avec la butée tibiale postérieure. Il s'agit d'une étude par éléments finis. Des modifications du dessin de la butée tibiale postérieure, sans changer sa position ou sa pente ont été réalisés. Les résultats ont été définis en terme de rollback et de pression au niveau de la butée postérieure. De petites modifications du dessin de cette butée postérieure peuvent entraîner d'importantes modifications du rollback sans augmenter les pressions au niveau de la butée postérieure.

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Introduction

Maximising knee flexion after total knee arthroplasty (TKA) is important for normal function during activities such as climbing stairs and arising from a chair [10]. Flexion is particularly important in certain ethnic and religious groups where a high range of motion (ROM) is necessary for daily activities for activities such as prolonged kneeling and cross-legged sitting [6].

Flexion of the prosthetic knee requires that the femoral condyles clear the posterior rim of the polyethylene tibial insert [11]. Impingement of the femur on the insert will limit flexion [1]. Flexion can be improved by maintaining proper condylar offset, by decreasing the radius of

curvature of the femoral component in deep flexion and by maintaining femoral rollback during flexion [1, 11].

In the normal knee and in a posterior cruciate retaining knee proper function of the posterior cruciate ligament is necessary for rollback to occur [7, 8, 11]. In a cruciate substituting knee arthroplasty the posterior cruciate ligament is excised and rollback occurs as a result of a cam that engages in variable degrees of flexion [4, 11].

The normal knee exhibits femoral rollback with femoral external rotation (the screw home mechanism) [3, 3, 7, 11]. Rollback occurs as a function of the posterior cruciate ligament and the geometry of the tibial and femoral articulating surfaces. Rollback is increased laterally allowing the lateral condyle to clear the posterior tibia. The medial condyle rollback occurs to a lesser degree [9]. The differential rollback between the two creates external femoral rotation. The medial condyle is able to clear the tibial plateau because of a larger radius of curvature than the lateral condyle [11].

The posterior cruciate substituting prosthesis recreates rollback with engagement of a tibial spine femoral cam mechanism that engages in a variable degree of flexion depending on the manufacturer and design. Most modern designs of posterior cruciate substituting knee exhibit symmetrical rollback [11].

The cam/spine mechanism was originally introduced by Insall et al. in 1978 as a means of preventing posterior tibial subluxation in deep flexion and inducing femoral rollback [10].

Design considerations describing an optimal tibial spine-femoral cam articulation have yet to be elucidated. Modern tibial cam designs vary greatly between manufacturers. Differing incidences and magnitudes of posterior femoral rollback have been seen when comparing various fixed bearing posterior-stabilised TKA designs. The purpose of our study was to determine if changes in the tibial post articulating interface could optimise femoral rollback and tibial post contact pressures.

Materials and methods

The effects of changes in the geometric parameters of the tibial post on femoral rollback were studied in three different computer simulations. The dimensions of a Johnson and Johnson PFC Sigma Cruciate Substituting Femoral Component and tibial insert were used as standard design. Using this baseline design as reference, the tibial post independent sagittal plane design parameters were defined as shown in Fig. 1. The cam design of the posterior stabiliser depend on the curvature, height, thickness and the initial and end slopes of the engaging surfaces. To illustrate how these parameters influence the rollback we have taken

Fig. 1 Sagittal view of the posterior stabiliser tibia post and identification of the independent design parameters. The *dashed lines* represent the femoral and tibial condyles' profile and their corresponding contact point which tracks the rollback

a sagittal view of Depuy/J&J crucial substitute and identified these geometric parameters and their mathematical relations. The base of the cam is defined by x in Fig. 1 and the tip of the curvature which controls the height is defined by the extension a and the slope angle θ . The additional dependent design parameters which define the slopes to the curvature were calculated as shown in Appendix 1. Variations in the tibial post's geometry were made and their effect on femoral rollback calculated. Modifications in the tibial post's coronal plane or in the femoral cam component were not considered in the analysis.

Three-dimensional models of the femoral component and tibial insert were created using measurements from the J&J PFC Sigma prosthesis with a vernier caliper. The tibial post modifications were incorporated into the model creation. These components were then assembled for high

Fig. 2 FEM mesh of the femoral and tibial insert showing an engaged cam. The model is used to illustrate rollback and different designs of the tibial post

flexion angle in a design software programme called Pro-E (at the point where the tibial spine makes contact with the femoral cam creating rollback) and the corresponding solid model was imported into a popular finite element analysis programme called ANSYS. Quasi-static finite element analysis of the model was then performed. An initial mesh of the components with different designs of the tibial post were generated using special tetrahedral elements referred to as SOLID92 as shown in Fig. 2. Essentially the entire geometry is broken into elements which are connected through nodes and then ANSYS generates the necessary forces-displacements equations and computes the stress-strain under the conditions prescribed.

A non-linear contact model was developed to study the rollback mechanism and distribution of pressure on the interfaces of the components. Pressure values from experimental results were applied to the femoral component to induce rotation.

First analysis

As an initial analysis to investigate the relationship between tibial post geometry and femoral rollback, different tibial post designs were considered as shown in Table 1.

Table 1 Different tibial post design parameters for first experiment

Θ	φ	Ψ	X	a	R
15	65	22	2.83	1.6	0.55
20	63	15	2.98	0.95	0.55
25	60	19	2.87	1.06	0.5
30	65	13	2.73	1.21	0.45
35	62	16	2.65	1.43	0.45

Baseline J&J PFC Sigma tibial post dimensions listed in italics

Fig. 3 Cubic splines used to model the cam curvature of the tibial post articulating surface. Spline 1 (blue), spline 2 (green), spline 3 (red), spline 4 (grey), spline 5 (pink)

No changes were made to the geometry of the remainder of the tibial insert. All the tibial post parameters were derived from independent parameters (X , h , ψ , θ , and φ) as shown in Fig. 1.

Second analysis

As a second analysis, the curvature of the tibial post articulating surface was changed while keeping the remainder of the tibial post design parameters constant. The original J&J PFC Sigma tibial insert was used as the baseline design. Changes to the tibial post articulating surface were modelled as cubic splines. Five different cubic spline models were considered for analysis as shown in Fig. 3. To represent the curvature mathematically we opted for a spline where we can generate different curvatures based on the splines's coefficients and end conditions. The overall objective is to see how to select the optimum curve of the cam to obtain maximum rollback and minimum stress at the contact level between the insert and the femoral component.

The methods for spline generation are shown in Appendix 2 and can be explored further in reference [13].

Table 2 Design parameters used for tertiary analysis

Different design	Splines	θ	φ	Ψ	X	a	R
1	Spline 1	35	62	16	2.65	1.43	0.45
2	Spline 2	25	62	16	2.65	1.43	0.45
3	Spline 1	25	62	16	2.65	1.43	0.45
4	Spline 2	35	62	16	2.65	1.43	0.45

The selection of each spline corresponds to certain geometric values that are all computed which allow for the complete design of the posterior stabiliser cam. These cams are then tested for maximum rollback and stress at the contact level

Table 3 Results at the commencement of rollback for first analysis where the pressure distribution on the insert surface, on the spine of the cam and the femoral component are computed

Different design/parameter	Average pressure distribution on the tibial insert (kPa)	Pressure distribution on the tibial spine (kPa)	Max. pressure distribution on the tibial insert (kPa)	Posterior displacement of the femoral component (mm)
$\theta=15$	23.7	156.3	285.6	0.151
$\theta=20$	36.2	246.1	447.4	0.233
$\theta=25$	40.5	241.8	386.5	0.134
$\theta=30$	18.3	183.2	345.6	0.146
$\theta=35$	20.4	169.6	468.2	0.2148

These table data are generated for the curvature composed of the three radiuses

No changes were made to the geometry of the femoral cam or the remainder of the tibial insert.

Third analysis

For the final analysis, design parameters from the first and second analyses were combined and characterised according to posterior rollback, pressure distribution on the tibial post, average pressure distribution on the tibial insert and maximum pressure distribution on the tibial insert. Designs with θ angles of 25 and 35° were combined with splines 3 and 4. Design parameters are shown in Table 2.

Results

First analysis

The results from the initial experiment are shown in Table 3.

Because of the variation in the independent variables presented in this analysis, it is possible to make an association between the variables depicting the cam design and its relationship to femoral rollback or tibial post contact pressure. Generally however it can be seen that small changes in post design can cause large changes in post displacement of the femoral component at the time of rollback. Comparing the design indicated by $\theta=20^\circ$ with the original design, posterior displacement of the femoral component was increased 160%. Minor dimension modifications in the femoral post also effected pressure

distribution within the tibial post and the femoral condyle-tibial insert interface. Designs with the largest contact pressure at the tibial post did not necessarily produce the greatest amount of femoral posterior displacement.

Second analysis

In this experiment, changes to the tibial post's articulating surface were made while holding all other variables constant. Four separate tibial spines were used to model the tibial articulating surface. Splines 1 and 2 possessed a more acute curvature than splines 3 and 4. Results are shown in Table 4.

Splines with a more acute curvature produced a greater rollback than those possessing a gentler curve. Rollback was increased 10% with the most acute tibial spline (spline 1). This increase in rollback however was associated with a higher increase in contact pressure at the tibial post. Contact pressure was increased a total of 41.2 kPa or 22%. Conversely, more gentle curves (splines 3 and 4) were associated with a maximum reduction in femoral rollback of 4% and tibial post contact pressure of 10%.

Third analysis

In the final analysis, tibial post geometries from the first analysis (designs indicated by $\theta=25^\circ$ and $\theta=35^\circ$) and splines from the second analysis (splines 3 and 4) were combined, and the posterior displacement of the femoral component and contact pressures calculated. Results are shown in Table 5.

Table 4 In this analysis splines are tested for rollback and stress and the contact surface at the insert and femoral part as well as the spine surface of the cam

Results at the commencement of rollback for second analysis

Different design/spline	Average pressure distribution on the tibial insert (kPa)	Pressure distribution on the tibial post (kPa)	Max. pressure distribution on the tibial insert (kPa)	Posterior displacement of the femoral component (mm)
Original	18.3	183.2	345.6	0.146
Spline 1	15.3	224.3	481.3	0.16
Spline 2	18.1	207.1	422.6	0.157
Spline 3	24.2	171.5	297.3	0.145
Spline 4	20.4	165.2	312.5	0.14

Table 5 Results at the initial contact pressure resulting from proposed designs for rollback from the third analysis

	Average pressure distribution on the tibial insert (kPa)	Pressure distribution on the tibial post (kPa)	Max. pressure distribution on the tibial insert (kPa)	Posterior displacement of the femoral component (cm)
Design 1	20.43	169.71	297.48	0.163
Design 2	18.2	192.57	322.13	0.159
Design 3	21.7	215.34	310.61	0.157
Design 4	21.5	186.56	342.34	0.167

As seen in this experiment, designs with the higher θ angle tibial insert geometry ($\theta=35^\circ$) and more gentle tibial spline (spline 4) had the highest rollback. As compared to the original baseline design, femoral rollback was improved in all combined designs. The curve producing the greatest femoral rollback ($\theta=35^\circ$, spline 4) had an increase of 14% as compared to the baseline, with only an increased contact pressure at the tibial post of 0.02%. Interestingly, even the $\theta=20^\circ$ tibial insert geometry that originally had a decreased

femoral rollback compared to baseline in the first analysis had an even greater femoral rollback compared to the baseline design with the spline modifications.

Discussion

Small changes in tibial post geometry can make relatively large changes in femoral rollback at the time of femoral cam-tibial post interaction. In the current experiment relatively small changes in the tibial post geometry and changes in the curvature of the tibial post geometry were made to optimise the function of the cam post mechanism. A 14% increase in the femoral rollback position along with a 0.02% reduction in the contact pressure at the tibial post was achieved at commencement of rollback.

The current model was quasi-static in nature, and it only considered the posterior displacement of the femur at the beginning of femoral rollback (80° knee flexion). A thorough analysis over a wider range of flexion angles would need to be completed to determine if increases in ultimate knee flexion would result.

Component motion was only constrained by the inherent geometrical shape of femoral component and tibial articulating interface. Rollback was considered to be symmetrical medially and laterally. The effects of ligaments and dynamic stabilisers were not considered in this model, although they are known to effect rollback in vivo. Abnormal motions such as anterior paradoxical translation, and reverse axial patterns,

Fig. 4 Parametric modelling of the stabilising post which consists of identification of all the dependent and independent design parameters of the cam in terms of height, length, width and curvatures **Fig. 5** Curvature details of the stabilising post using three different radii. Variation of these radii leads to different slopes. The default design used this principle

along with the effects of component malalignment were not part of the current model.

Deep flexion activities such as squatting generate large posterior forces approximately ($58.3\text{--}67.8 \times \text{body weight}$) between 90 and 120° of flexion. Although our model did not specifically address the consequences of these forces in relation to the contact pressure occurring at the tibial post, it did attempt to quantify the tibial post contact pressure occurring secondary to component geometry. These contact pressures occurring at the post at 80° were found to be approximately 54–70% of the maximum contact pressure occurring at the principle femoral condyle-tibial insert articulation. It is likely that actual contact pressures occurring at the post are much larger than those found during this study, particularly in deep flexion. With the experimental model, it is not possible to speculate in vivo if the contact pressures at the post approach the yield point of ultra high molecular weight polyethylene (UHMWPE) (10–30 MPa).

Delp et al. were one of the first investigators to study posterior stabilised total knee kinematics in terms of changes in tibial post anterior posterior placement and tibial post height, via computer simulation [2, 5]. They characterised knee stability (from dislocation) as a function of the vertical distance from the superior tibial spine to the inferior femoral cam distance termed the dislocation safety factor [5]. In a second study using a simple two-dimensional model, they concluded that moving the tibial post location posterior on the tibial insert could produce greater femoral rollback and knee flexion [12]. Greater femoral rollback however was accompanied with compromised knee stability. Shifting the tibial post 5 mm posteriorly enabled rollback to commence at 55° and the femur to roll off the back of the tibia at 100° of knee flexion. Our model did not change the relative position of the tibial post in order to produce greater femoral rollback and hence should not suffer from early roll-off of the femoral condyle from the tibial plateau. The effects of greater rollback from changes in component geometry on increasing the propensity for the femoral cam to jump the tibial cam (or a decrease in the dislocation safety index) was not addressed in this study.

The current model allows quantification of femoral rollback and associated tibial post contact pressures associated with multiple changes in tibial post component geometry. The utility of this model was that it allowed multiple design parameters to be modified and their combined effect be measured prior to fabrication and testing. The model was applied to a single design of tibial post femoral cam design, but the methodology is applicable to designs with other geometry. Despite the model's limitations, it suggests that in tibial post geometry an

articulating degree of curvature can be used to improve rollback and optimise contact cam/post contact pressures (Fig. 4).

Appendix 1

Following Fig. 5 the dependent variables are derived from the independent parameters also known as the control variables (X , h , θ , ψ , and ϕ).

We define x as function of h and

$$x = h \left[\frac{1}{\tan \theta} - \sin 10 \right]$$

Furthermore we obtain θ and ϕ relation from:

$$\frac{L \sin \theta}{\sin \theta} - \frac{L \sin \theta}{\tan(\theta + \phi)} = \frac{f \sin(\theta + \phi)}{\tan \theta} - \frac{h}{\tan(\theta + \phi)}$$

L1 is found making use of two relations which define e which yield

$$L1 = \frac{x \sin \psi}{\sin \eta}$$

Appendix 2

Second analysis is based on the fact that the curvature is no longer confined to three radii and is replaced by a cubic spline of order 3.

We also define the slopes at the end points by ψ and ϕ as

$$90 - \left(\frac{dx}{dy} \right)_{y=0} = \psi$$

$$90 - \left(\frac{dx}{dy} \right)_{y=194} = \phi$$

First curve design

Coinciding with the original design (default design)

$$\theta = 30^\circ \quad \psi = 65^\circ \quad \phi = 14$$

The data points are changed such that

$$\psi_{\text{default}} = \psi_{\text{maximum}}$$

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