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Original research article

Finite element analysis of the tibial component alignment in a transverse plane in total knee arthroplasty

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Abstract

The research aims to analyze the tibial component rotation using the finite element method by resecting the tibia in a transverse plane at an angle between 1.5° (external rotation) and –1.5° (internal rotation). We used a three-dimensional scanner to obtain the tibia's geometrical model of a cadaveric specimen. We then exported the surfaces of the tibial geometrical model through the Computer-Aided Three-dimensional Interactive Application (CATIA), which is a Computer-Aided Design (CAD) program. The CAD program three-dimensionally shaped the tibial component, polyethylene, and cement. Our analysis determined that the maximum equivalent stress is obtained in the case of proximal tibial resection at –1.5° angle in a transverse plane (internal rotation) with a value of 12.75 MPa, which is also obtained for the polyethylene (7.693 MPa) and cement (6.6 MPa). The results have shown that detrimental effects begin to occur at –1.5°. We propose the use of this finite element method to simulate the positioning of the tibial component at different tibial resection angles to appreciate the optimal rotation.

Keywords: Finite element analysis; Rotational alignment; Tibial component; Total knee arthroplasty

Highlights:

- Finite element analysis is an important tool for simulating different angles of tibial resection.
- Tibial component malrotation begins to have an adverse effect at more than –1.5° in a transverse plane (internal rotation).
- Preoperative planning based on finite element analysis can improve the outcome of total knee arthroplasty.

Introduction

Total knee arthroplasty (TKA) is the most successful surgical technique used for the severe stage of knee osteoarthritis, with favourable long-term outcomes and significant improvement of the patient's quality of life. However, compared to total hip arthroplasty (7% rate of unsatisfied patients that underwent total hip arthroplasty – Okafor and Chen, 2019) the rate of unsatisfied patients following TKA is higher (between 4.8% and 20.5%) (Maier et al., 2019).

Many complications such as anterior knee pain, patellofemoral instability, joint stiffness, and polyethylene wear, result from the prosthetic components' malrotation, especially the tibial component (Rhee et al., 2018).

Tibial component malrotation is still an important issue, despite the multitude of anatomical landmarks used for positioning, as well as pre-, intra-, and post-operative imaging evaluation of the prosthetic components. Positioning the tibial component is as complex as positioning the femoral component because the tibia's geometry is highly variable. Lee et al. (2017) highlight that combined malrotation of the tibial and femoral component may determine anterior knee pain, and Aglietti et al. (2008) sustain that more negative consequences are determined by the combined malrotation of both prosthetic components such as flexion instability and stiffness, and abnormal gait patterns.

The anatomical landmarks of the rotation of the femoral component are: the transepicondylar axis (the axis between the lateral and the medial epicondyle – the lateral epicondyle is more easily identified during surgery after the apex of bony proeminence), the posterior condyle line (tangent line to the most posterior part of the femoral condyles), and the Whiteside line (connection of the center of the intercondylar notch and the lowest point of the trochlear groove anteriorly) (Castelli et al., 2016; Showronek et al., 2021). Compared with the tibial component, the femoral component has the advantage of having a "gold standard" landmark – which is the trans-

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epicondylar axis (Asano et al., 2005; Berger et al., 1993; Jang et al., 2019; Victor, 2009). Despite the "gold standard" landmark, the rotational alignment of the femoral component is also as much of a challenge as the rotation of the tibial component; still, in our study we preferred to choose the tibial component, largely because of the absence of a "gold standard" landmark due to the tibia's geometry.

In the current literature, tibial component rotation is a frequently approached topic. This is mainly because an anatomical landmark "gold standard" has not been found yet, and the malrotation of the tibial component is the main factor for the patient's dissatisfaction after TKA (Maier et al., 2019). Several anatomical landmarks have been proposed as reproducible and reliable for guiding the tibial component, including Akagi's line and the anterior tibial cortex (Hanada et al., 2019; Kim et al., 2017; Saffarini et al, 2019).

A new technique "Kingpin" uses the Whiteside line (also named transverse axis of the femoral component, which extends from the trochlear groove to the lateral edge of the posterior cruciate ligament; Babazadeh et al., 2009) and extends it distally for the positioning of the tibial component. This technique is considered an auxiliary method for the surgeon to achieve an optimal tibial component rotation (Arnaout and Holt, 2020). Positioning the tibial component using the extra-articular landmarks is not recommended due to the frequent errors in rotation that may occur (Ma et al., 2019).

The purpose of our experimental analysis is to simulate, using the finite element method, the positioning of the tibial component at certain angles. We will do this by cutting the tibia in transverse plane at an angle between 1.5° (representing external rotation from neutral positioning) and –1.5° (representing internal rotation from neutral positioning) to observe the tibial component's behaviour (particularly the rate of wear of the polyethylene). Through this method we are also able to determine the negative impact of malrotation on the outcome in TKA.

Materials and methods

We scanned the tibia's geometrical model of a cadaveric specimen (the tibia had no previous bone pathologies or deformities, and the mechanical properties of the tibia are described in Table 1), using a three-dimensional scanner, after we obtained cross sectional images of the tibia through computer tomography. To export the surfaces of the tibial geometrical model in Computer-Aided Design (CAD) program, we used the Computer-Aided Three-dimensional Interactive Application (CATIA) after the scan had been performed. After correcting geometrical inaccuracies, we used the Abaqus software for the finite element analysis. We also used the CAD program to three-dimensionally shape the tibial component, polyethylene and cement. Meshing in finite elements through the CAD program is necessary due to geometry. Afterwards the type of element, the material, and geometrical data used were attached (Danczyk and Suresh, 2012; Fries and Belytschko, 2010; Mac Donald, 2007). We took into consideration the longitudinal modulus of elasticity (measured in gigapascal – GPa) and Poisson Ratio as the most important material data.

Meshing is necessary to reduce the tibia's geometric complexity and the time for analysis. For our study, we used the "surface on surface" contact for interface condition, after importing and meshing all the component's elements. According to specialty literature, there are three phases of analysis through finite element – pre-processing, solving and post-processing. The pre-processing phase implies meshing, definition of materials and applying boundary conditions. It is important to mention the boundary conditions because they define the

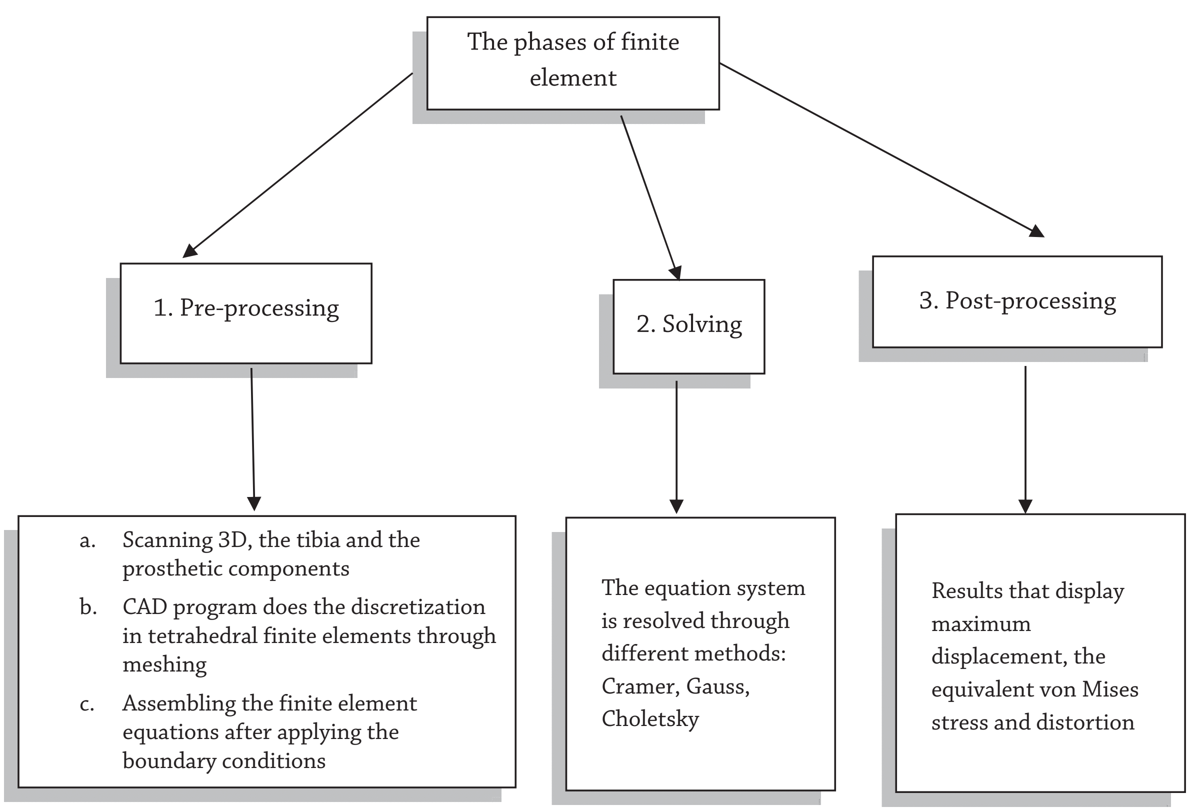

Table 1. Material data for tibia and prosthetic components in TKA

Component	Modulus (GPa)	Poisson ratio
Tibia	6	0.3
Polyethylene	10.9	0.46
Tibial component	113.8	0.265
Cement	14	0.1

Legend: GPa – gigapascal.

external forces exerted on the tibia and the prosthetic components. So, in our study we used a load of 1000 N in order to see how it affects the prosthetic components at different tibial cuts in transverse plane (–1.5° and 1.5°), this being sufficient to perform a successful calculation. After running all the phases, the last one allows us to calculate the maximum displacement of components (provides information about the geometric deflections of the tibia and the prosthetic components), the equivalent von Mises stress (allows to determine the mechanical durability of the bone and prosthetic components) and distortion. In order to ensure the accuracy of the calculations (the absence of standard error), we used the application of calculation verification – which estimates the numerical error associated with the discretization.

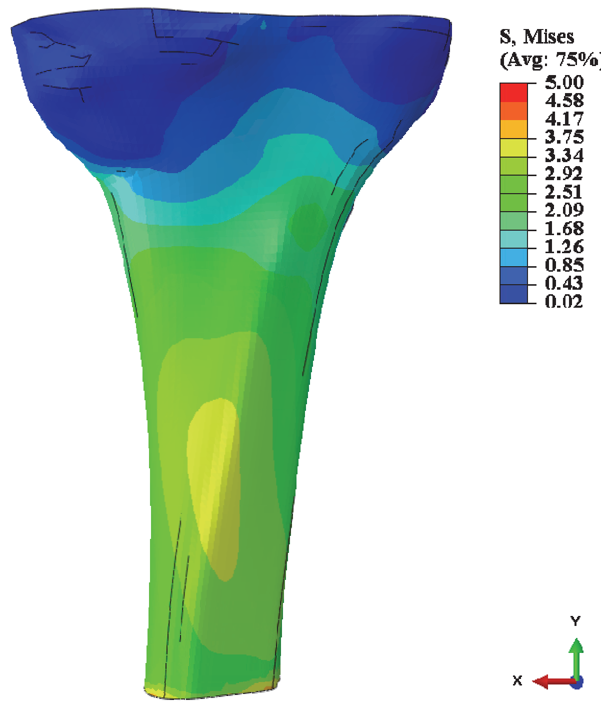

Fig. 1. Variation of the equivalent von Mises stress for tibia in case of proximal resection at 1.5° angle in transverse plane (external rotation) – frontal view

Results

In the transverse plane, the proximal tibial cut was made at a 1.5° (external rotation) and at –1.5° (internal rotation) determining the nodal displacement, equivalent stress and distortion at these values for the tibia. The equivalent von Misses stress and the main maximum distortion were calculated for the polyethylene, tibial component and cement (Tables 3–5).

The equivalent von Mises stress represents the maximum limit of the bone hardness, after which the bone breaks. The equivalent von Misses distortion represents the maximum capacity of a material to deform, and the nodal displacements show how the stress is spreading through the bone in the three directions of the coordinate axes (Table 2, Figs 1–2).

Table 2. Results obtained for the tibia

Analysis	Equivalent stress [MPa]	Equivalent distortion [mm]	Nodal displacement [mm]
Proximal tibial cut at 1.5° – transverse plane (external rotation)	5.00	0.001	0.069
Proximal tibial cut at –1.5° – transverse plane (internal rotation)	12.75	0.001	0.074

Table 3. Results obtained for the tibial component

Analysis	Equivalent stress [MPa]	Equivalent distortion [mm]
Proximal tibial cut at 1.5° – transverse plane (external rotation)	10	0.00015
Proximal tibial cut at –1.5° – transverse plane (internal rotation)	10	0.00015

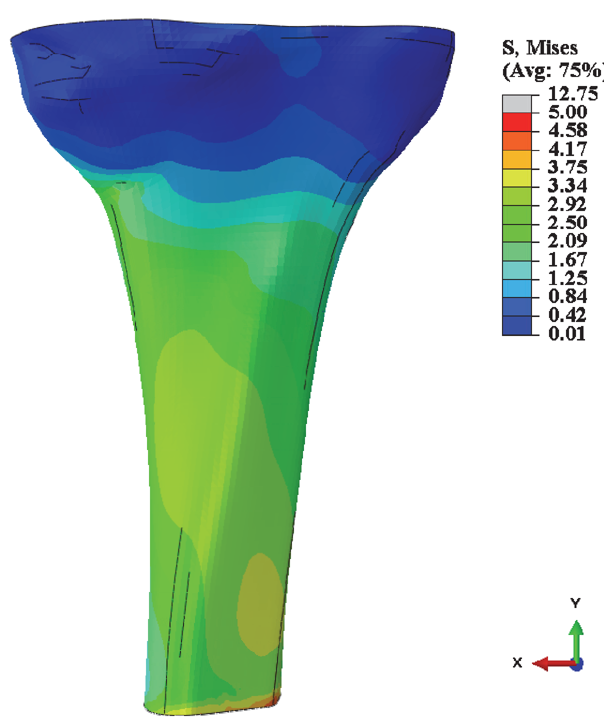

Fig. 2. Variation of the equivalent von Mises stress for tibia in case of proximal resection at –1.5° angle in transverse plane (internal rotation) – frontal view

Table 4. Results obtained for the polyethylene

Analysis	Equivalent stress [MPa]	Equivalent distortion [mm]
Proximal tibial cut at 1.5° – transverse plane (external rotation)	6.737	0.00057
Proximal tibial cut at −1.5° – transverse plane (internal rotation)	7.693	0.00067

Table 5. Results obtained for the cement

Analysis	Equivalent stress [MPa]	Equivalent distortion [mm]
Proximal tibial cut at 1.5° – transverse plane (external rotation)	3.1	0.00020
Proximal tibial cut at −1.5° – transverse plane (internal rotation)	6.6	0.00020

Our analysis determined that the maximum equivalent stress for the tibia, polyethylene and cement is obtained in the case of proximal tibial resection at −1.5° angle in transverse plane (internal rotation). Regarding the tibial component, the equivalent stress had the same value for both studied angles in the transverse plane.

Discussion

The rotation of the tibial component in TKA is still a debatable subject and it is important because malrotation determines joint instability, tibiofemoral and patellofemoral kinematic issues and thus affects the clinical outcome (Seo et al., 2015).

Previous studies have proven the importance of finite element in the orthopaedic field and have guided the surgeons to better position the tibial component in the sagittal and frontal planes. Still, the optimal positioning of the tibial component has not been defined in the rotational plane, thus resulting in higher revision rates (Sahu and Kaviti, 2016; Wernecke et al., 2016).

Dong et al. (2020) used the finite element method to simulate the effect of different angles in the three planes (frontal, sagittal and axial) to determine accurate positioning of the tibial component simultaneously in the three planes. They chose to simulate the external rotation of the tibial component at 3°, 4° and 5° in transverse plane. They determined that the best positioning in transverse plane is 4° external rotation associated with 0° in frontal plane and 1° in sagittal plane. Although our study did not simultaneously simulate the angles in all the three planes, our results also determined that the external rotation of the tibial component at 1.5° is better than internal rotation at −1.5°.

Yamamura et al. (2020) compared conventional patient-specific instrumentation and a newly designed patient-specific instrumentation and found that the new design improved the tibial component rotation. However, while the positioning in axial plane was improved, the internal malrotation >3° still caused complications.

Watanabe et al. (2014) found that anterior knee pain is associated with a 6.2° internal rotation of the tibial component. And Abdelnasser et al. (2020) explained that the internal malrotation of the tibial component causes a post-operative deficit in lower limb extension. They also found that patellar subluxation was determined by an internal rotation of the tibial component at a value between 3° and 8°, and the patellar luxation occured at a value starting at 7°.

Ammantullah et al. (2018) suggested that malrotation of the tibial component occurs more frequently in the case of pre-existing deformations or inadequate tibial resection. One study shows that a 10° flexion contracture and a 15° varus deformity determine internal malrotation of 2.6° (Watanabe et al., 2014), suggesting that the supposition of Ammantulah et al. (2018) is accurate.

Babazadeh et al. (2019) found that an internal malrotation of the tibial component of more than 6° was associated with anterior knee pain. Likewise, they asserted that it is difficult to define the optimal rotation for the tibial component in order to prevent short or long-term post-operative complications.

Referring to anatomical landmarks, Nedopil et al. (2016) included four reference lines (between the most medial and lateral portion of the tibial plateau, between the medial one-third of the tubercle and the center of the posterior cruciate ligament insertion, between the medial border of the tibia and posterior cruciate ligament, between the projection of the anterior cortex and the posterior cruciate ligament) that determined a variation of the tibial component rotation from −44° internal rotation to 46° external rotation, thus suggesting that these lines cannot be used as landmarks. Their study also suggested that a variation from −11° internal rotation to 12° external rotation does not affect pain scores, which does not exclude the possibility that such variations may affect the TKA outcome and long-term tibial component survival.

Osano et al. (2014) concluded that the internal rotation of the tibial component determined an increased stress level on the polyethylene. They also demonstrated an increase of 15% of the maximum von Mises stress in case of internal rotation, which is consistent with our findings.

The consequences of tibial component internal rotation have been debated and discussed in other papers (Liu et al., 2020; Nam et al., 2020; Planckaert et al., 2018), and even though the literature data imply different resection angles that determine internal rotation of the tibial component, the particularity of our study lies in the fact that our analysis used the finite element method, which allowed us to determine the minimum value threshold that determines micro changes of the tibia, cement and polyethylene without causing symptoms.

The results obtained in our study demonstrate that the proximal tibial cut at −1.5° (internal rotation) in a transverse plane compared to 1.5° (external rotation) loads the tibia, the polyethylene and the cement with greater stress. This suggests that it is better to position the tibial component in external rotation, in order to reduce the risks of loosening and polyethylene wear.

One limitation of our study is the fact that we did not compare the results for the cadaveric tibia with the patients' tibia (that implies a dynamic analysis, which could probably change the boundary conditions). At the same time, the possibility of using different resection angles to obtain results that are comparable with the literature values also implies a dynamic analysis. These limitations also represent future research directions we intend to carry out.

Another limitation of the study is the absence of deformities or other pathologies of the cadaveric tibia. At the same time, the individual variability could not be taken into consideration because the meshed tibia was created based on a single cadaveric specimen.

Currently, to the best our knowledge, it has not been claimed or demonstrated in literature that variations in the rotation of the tibial component in transverse plane of ± 1.5° are meaningful or relevant. Our analysis argues that even such a small difference in rotation can have a significant impact. In the future, the finite element method may improve clinical results by becoming a useful tool in the preoperative planning of TKA.

Conclusions

In our experimental study, we demonstrated that the tibial resection at –1.5° angle in the transverse plane (internal rotation of the tibial component) represents the minimum threshold at which the tibial component malrotation begins to cause unfavorable consequences.

Using the finite element to adjust the rotation of the tibial component can help obtain an ideal alignment, which is associated with reduced risk of complications and a longer prosthesis survival. Our findings are consistent with the literature data and have led us to recommend the creation of a preoperative planning.

We propose using the finite element method to simulate the positioning of the tibial component at different tibial resection angles, in order to achieve optimal rotation.

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Availability of data and materials
Data and materials are available from the corresponding author on reasonable request.

Ethical aspects and conflict of interests
The authors have no conflict of interests to declare.

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