A finite element analysis for predicting outcomes of cemented total knee arthroplasty

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Abstract. The study was designed to assess the validity of a finite element analysis for predicting the behavior of cemented knee implant used in total knee arthroplasty (TKA), for different mechanical loads, and correlation with clinical outcomes of this procedure. We conducted computational simulations using finite element analysis of two situations: i) The ideal prosthetic component positioning; and ii) variable varus tibial malposition, but with a balanced knee. A total of 80 cemented TKAs performed on 70 patients were divided into two groups. Patients from one group required secondary asymmetric tibial recut for balancing the prosthetic knee and patients from the other group, did not. In regards to the results, we observed no differences upon analysis of the postoperative results of the Knee Society Score (KSS), the angle between the femur and tibia, the range of motion and frontal laxity between groups. The finite element analysis showed that in a 3˚ varus inclination of the joint interline, but with a balanced knee, the maximum contact stress, measured on the tibial plateau surface, increased by 11% compared to the value of mechanical alignment. In conclusion, analysis of the computational model using finite elements showed predictable results of cemented TKA for the different situations of mechanical loads.

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Introduction

Finite element analysis can be used to calculate the tensile stress on a polyethylene tibial insert and von Mises stress. Polyethylene (PE) wear leads to a process known as 'particle disease' a factor of failure of the procedure. Total knee arthroplasty (TKA) has become a routine intervention for treating late stage osteoarthritis worldwide. Its success, in terms of function and survivorship, costs, days of hospitalization, depends on several factors, including component alignment and ligament balance (1). The ideal conditions for success of TKA are still a matter of debate in the literature. On the one hand, most researchers agree that, for better survivorship, the overall alignment should be neutral or slightly valgus and the tibial component must be positioned at a right angle to the tibial mechanical axis (2,3). On the other hand, there are studies which have demonstrated no difference in terms of survival between groups of neutrally aligned and other then neutrally aligned knees after TKA (4). These authors argue that the mechanical axis goal of $0\pm3˚$ is not enough to predict the durability of modern TKA implants (4). Furthermore, an additional issue of TKA is post-surgery patient satisfaction. Studies report that patient satisfaction ranges between 75 and 92%, even in the case of knees with neutral alignment of components. For example, a systematic review of studies on post-TKA patient satisfaction published between 2000 and 2012 showed only 85% satisfaction (5). The new concept of kinematic knee alignment arose as a response to the issues discussed above. Kinematic knee alignment aims to improve the functionality of the patient knee and to control pain, with minimal surgical involvement, centered on ligament balance (6). Despite the widespread view that neutral alignment is a condition for TKA success, kinematic knee alignment does not always ensure neutral overall alignment and tibial alignment. These findings highlight the combined importance of both alignment and ligament balance for TKA outcomes. In some cases, especially in severe varus knees, standard

bone cuts and safety ligament releases may not be enough for balancing the TKA. In such cases, secondary asymmetric tibial resection may be necessary to achieve balance, although overall alignment may not remain neutral. Good knowledge of contact pressures and pressure areas in TKA is the key to success for the knee implant. It has been shown that higher contact stress on the tibial bearing component is associated with more severe damage in the tibial components (6). The present study assessed the validity of a finite element analysis for predicting behavior over time of a cemented knee implant used in TKA, for different mechanical loads, and the correlation with clinical outcomes of this procedure.

Patients and methods

Our study took place between 2008 and 2015. A total of 80 TKAs were performed on 70 patients. The patients were split in two groups. Whereas in group 1 of 50 TKAs, secondary asymmetric tibial recut was not necessary, group 2 of 30 TKAs, needed secondary asymmetric tibial recut for balancing. Out of the 70 patients, the sex ratio was 45:25 in favor of women. At the moment of TKA, the mean age of the patients was 65.5. The mean body mass index (BMI) was 24.9 kg/m^2. Group 1 consists of 25 female and 18 male patients; mean age 62.5 years, mean BMI 26 kg/m^2. Regarding group 2, it included 27 patients, of which 20 were female and 7 men. Participants in group 2 had a mean age of 61.4 years and a mean BMI of 23.2 kg/m^2. All surgical procedures were performed by the same senior surgeon. For all cases, the same type of posterior-stabilized cemented knee prosthesis (Zimmer-Nexgen) was utilized. All osteophytes were removed. Next, medial ligament release was performed, using a subperiosteal osteotome. For the patients in group 1, these actions alone led to a balanced knee, thus we did not need further procedures. For the patients in group 2, a further asymmetrical tibial coronal recut was needed, because of the tightness in flexion and extension of the medial compartment. The surgeon removed an extra slice of bone, 2-mm thickness, from the medial tibial plateau. After this artifice, the knee became balanced, with equal extension and flexion gaps. Recovery began immediately after surgery, with alternating placement of the knee in the flexion and extension positions. Postoperative control was conducted at 6 weeks, 3 months, 6 months, and 1 year periods, and then, once yearly. The mean follow-up period for the patients was 5 years (±3 years). The range of motion, stability to varus-valgus stress and Knee Society Score (KSS) (7) were noted for all patients, preoperatively and during each postoperative visit. Standing standard AP and a lateral view X-ray exam of the knee was conducted preoperatively and postoperatively. We also conducted computational simulations using finite element analysis of two situations: i) The ideal prosthetic component positioning, corresponding to group 1 of patients, and ii) the 3°, 5° and 8° of varus tibial malposition, but with a balanced knee, corresponding to patients in group 2. Malposition in varus for the tibial component results from extensive surgical removal from the medial part and little removal from the lateral part of the tibial plateau. The *in vivo* kinematics tests for the knee, have been achieved using SIMI Motion (SIMI Reality Motion Systems GmbH), a performance system for image acquisition and image analysis. The image acquisition was achieved with two video cameras, high speed, in two planes at a 90°angle. The metal implants were made of cobalt chromium molybdenum alloy (CoCrMo). The femoral component wasentirely made of CoCrMo alloy. The tibial component consisted of two parts. One was made of CoCrMo alloy, and the other of PE. The elastic modulus of the material (polyethylene) was established at 1,016 MPa, and the Poisson constant considered 0.46. The modulus of elasticity was obtained by the ratio between stress per area unit and the consecutive deformation.

Statistical analysis. SPSS software 20 (IBM Corp.) was used for statistical analysis. P<0.05 was assigned to indicate statistical significance. The results are expressed as the value of the standard deviation ± the arithmetic mean for continuous quantitative variables. Quantitative variables were expressed as proportions. The independent t-test was performed to determine statistical significance. We considered the results to be statistically significant if the P-values concerning the two groups were <0.05, with a 95% confidence interval.

Results

We found no statistically significant differences between the group 1 and 2 regarding demographic characteristics: Age, sex, height and weight. In addition, we noted no differences in terms of postoperative evolution of KSS, frontal laxity and range of motion (Table I).

However, we did observe a statistically significant difference between the groups, regarding the positioning of the tibial component. The mean angle between the tibial component and the tibial mechanical axis was 1±3.5° of varus for group 1, and respectively 3±3.5° of varus for group 2 (P<0.001). We did not need any revision for any of the operated knees at the final follow-up period. The mean follow-up interval was 6 years. The results of the finite element analysis are summarized in Table II.

We also measured the stress around the tibial post for 3°, 5° and 8° of tibial varus malalignment (Fig. 1).

For 3°, the maximum contact pressure (13.7 MPa) was around the base of the tibial post, especially on the lateral side. Towards the tip of the post there was a decrease in pressure: 5.4 MPa on the lateral side (L) and 4 MPa on the medial (M) side. For 5°, the maximum contact pressure increased to 17.5 MPa around the post base. At the top of the post, the contact pressure was 8 MPa placed on the lateral part and 3.5 MPa on the medial part. For 8°, the maximum contact pressure increased to 22.5 MPa around the post base. At the top of the post, the contact pressure was 6.5 MPa on the medial side of the tibial plateau and 14.1 MPa on the lateral side.

Discussion

If the contact pressure areas are known, it is possible to provide the potential wear of polyethylene (PE). The higher the contact pressure on the tibial component, the more severe the damage to the implant may be, due to particle disease (6). Polyethylene is a polymer which contains CH_2-chains (8,9). For orthopedic implants, a type of this polymer is used, ultra-high molecular weight (UHMWPE). The elastic modulus of PE diminishes

Table I. Postoperative outcomes.

Score	Group 1 (P<0.001)		Group 2 (P<0.001)	
	Preoperative	Postoperative	Preoperative	Postoperative
Knee society score	25.15±12.1	96.3±5.6	20.45±10.1	92.15±12.1
Range of motion	76.4±24.3°	110.3±9.7°	70.5±20.8°	100.4±20.3°
Frontal laxity	8.81±2.8°	1.34±1.2°	10.5±4.8°	1.7±1.4°

Table II. Finite element analysis.

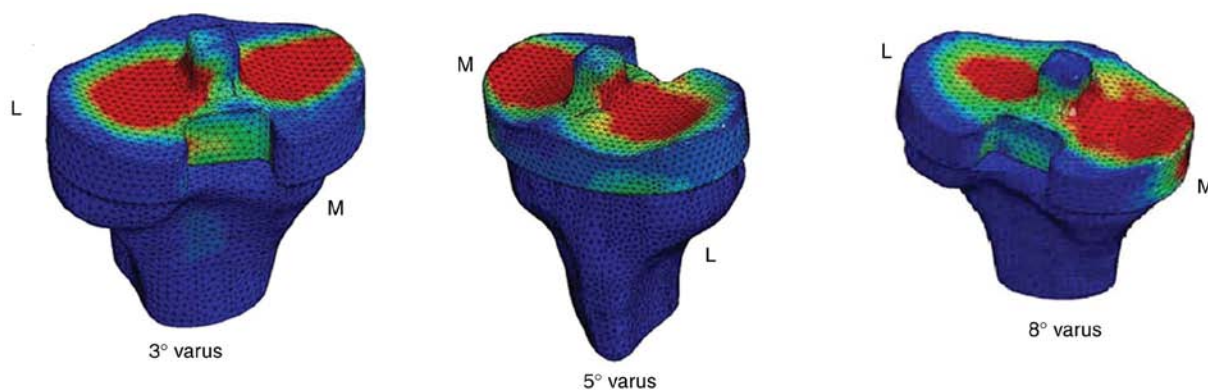| Alignment	Maximum contact pressure (megapascal)	Mean contact pressure-medial condyle (megapascal)	Mean contact pressure-lateral condyle (megapascal)
Mechanical	10.90	6.00	6.00
3° of varus	12.10	6.26	5.00
5° of varus	16.30	14.00	7.00
8° of varus	18.30	16.00	9.00

Figure 1. Stress around the tibial post. L, lateral side; M, medial side.

with tension. PE is a viscous-elastic implant, having the potential of plastic deformation in addition to wear. Beside wear, creep and plastic deformation may occur in PE fatigue. Long polymer chains of PE can slide over each other, resulting in creeping (10). Creep is responsible for delaminating, but decreases over time (10). The wear of PE results in particle debris between 0.2 to 10 μm which results in phagocytosis by macrophages. The macrophages activate other mediators responsible for osteolysis such as tumor necrosis factor (TNF) α, interleukin (IL)-1, and IL-6, or act like osteoclasts with direct bone resorption (10). A proper position of the implant is crucial for prosthetic joint load distribution, wear and survival of the prosthesis (6). The best placement of the prosthetic knee implant components remains uncertain. The disagreement among orthopedic surgeons is magnified by the important number of patients displeased with TKA. Most surgeons have concluded that a good alignment provides the best chances for survivorship of TKA (6). Mechanical best alignment represents the condition in which both angles between the femoral cut and the mechanical axis of the femur, respectively, between the tibial cut and the mechanical axis

of the tibia have 90° (11). However, some authors show that a femoral component placed in a 7° valgus position, with the tibial plateau perpendicular to the long axis of the tibia, ensures an equal distribution of forces between the medial and the lateral sides and in consequence, assuring the best chances for survivorship (12). Howell *et al* considers that kinematic knee alignment is provided by aligning the transverse femoral component axis with the primary transverse axis in the femur about which the tibia makes movement of flexion and extension. The authors also consider, regarding the tibial component, that the longitudinal tibia axis should make a 90° angle with the transverse femoral axis, about which flexion and extension of the tibia take place (13). For this purpose, the femoral cut should be made 1°-2° more valgus, while the tibial cut should be made 1°-2° varus, compared to the mechanically aligned TKA (14). Surgeons who support this approach claim that the restoration of mechanical alignment becomes improper in patients with constitutional alignment in varus or valgus and could cause increased tension in the collateral ligaments (15). They also argue that patients whose previous alignment is restored, may have better clinical and functional

status than patients whose alignment is set to neutral (16). Irrespective of the operatory technique for TKA, an important problem for surgeons is represented by technical details. For example, instrument errors are of great consequence in this respect. For the femoral distal cut, precision depends on the intramedullar rod engaging the isthmus of the medullar canal for realign the anatomical axis. The precision of placement is influenced by the rod length and thickness, the diameter of the medullar canal, and by the placement of the entry hole for the intramedullar guides (13,14). Therefore, surgeons aiming for mechanical alignment must be aware that instruments and the location of the entry holes could lead to large errors. The goal of our TKAs in both groups was to obtain mechanical alignment. With regard to tibial component alignment, we observed a significant difference between the two groups. In group 1, there was a neutral alignment (1±3.5°), while in group 2 it was in principle in the varus position (3±3.5°). The vast majority of patients in group 2 constituted extreme situations, because of additional asymmetric tibial varus cut. The finite element analysis showed that in a 3° varus inclination of the interline, but with a balanced knee, the maximum contact pressure measured at the surface of tibial plateau increased by 11% compared to the value of mechanical alignment. At 8° of inclination the maximum contact stress intensified by 68%, even for a balanced knee. For 3° of varus the distribution of forces was uniform on both tibial condyles, and the mean medial contact stress was 1.26 MPa higher than the lateral contact stress. At 8° of varus, we observed a medial displacement of the contact patch, and the mean medial contact stress was 7 MPa higher than lateral stress. There are very few studies regarding post-cam stress of posterior-stabilized knee prosthesis. Pulosky *et al* investigated tibial post wear of certain types of knee prosthesis and found increased wear of the posterior part of the tibial post (17). Huang *et al* found a maximum von Mises contact stress of 21.2 MPa at 60° flexion and 27.6 MPa at 150° flexion (18). Koh *et al* researched post-cam design via finite element analysis to study the most normal-like knee mechanics (19). Amyand's hernia was a curious association in one case (20). Our study showed that for 3° of varus inclination of the articular interline the maximum contact pressure was localized around the base of the tibial post, especially on the lateral side (13.7 MPa). As the inclination increased, the stress increased, also at the top of the post, thus leading to shearing and bending forces around the lateral and the medial aspect of the surface. These forces added to those from the posterior component of the post during flexion and contributed to tibial post wear.

In conclusion, polyethylene has a special abrasive resistance, shows low friction forces, high impact resistance, good chemical resistance and high energy absorption in contact with CoCrMo alloy. Still these advantages are also dependent on multiple factors such as surgical technique or implant positioning. The study findings support our technique for balancing severe varus knee and demonstrated that a computational model can be a useful tool for predicting clinical outcomes. If more than 3° of varus in the tibia in the coronal plane, more stress will be sent in the post-cam and on the surface of the implant. Still further studies are necessary to completely evaluate the loadings, regarding complex 3D motion of the prosthetic knee and not only by varus-valgus stress.

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