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Computational study on the effect of malalignment of the tibial component on the biomechanics of total knee arthroplasty

A FINITE ELEMENT ANALYSIS

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Objectives

Malalignment of the tibial component could influence the long-term survival of a total knee arthroplasty (TKA). The object of this study was to investigate the biomechanical effect of varus and valgus malalignment on the tibial component under stance-phase gait cycle loading conditions.

Methods

Validated finite element models for varus and valgus malalignment by 3° and 5° were developed to evaluate the effect of malalignment on the tibial component in TKA. Maximum contact stress and contact area on a polyethylene insert, maximum contact stress on patellar button and the collateral ligament force were investigated.

Results

There was greater total contact stress in the varus alignment than in the valgus, with more marked difference on the medial side. An increase in ligament force was clearly demonstrated, especially in the valgus alignment and force exerted on the medial collateral ligament also increased.

Conclusion

These results highlight the importance of accurate surgical reconstruction of the coronal tibial alignment of the knee joint. Varus and valgus alignments will influence wear and ligament stability, respectively in TKA.

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Article focus

■ This study investigated the biomechanical consequences of coronal tibial component malalignment during simulated stance-phase gait-loading in a total knee arthroplasty model.

■ The maximum contact stresses and contact areas on the medial and lateral sides of the polyethylene insert and the effect on maximum contact stress on the patellar button as well as the collateral ligament forces were evaluated with respect to varus and valgus malalignment.

Key messages

■ There was greater total contact stress in the varus malalignment than in the valgus malalignment.

■ Changes in ligament force was clearly demonstrated with malalignment. In the valgus malalignment the force exerted on the medial collateral ligament increased by the greatest margin.

Strengths and limitations

■ Strengths: reproducible analysis of knee biomechanics under varus and valgus loading during simulated stance-phase gait condition.

- Limitations: only the intact model was validated and the computational model was developed using data from only one young male subject.

Introduction

The primary aims of total knee arthroplasty (TKA) are to restore normal knee joint function and alleviate pain. Maintenance of the coronal alignment in TKA results in good long-term functional outcomes for patients.[1] A retrospective analysis of 820 revision TKAs found that malposition and malalignment were the seventh most common reason for revision.[2] In addition, coronal malalignment of the tibial component in TKA may result in increased wear of the polyethylene (PE) insert, ligament instability, loosening and future revision surgery.[3,4] Even with experienced surgeons performing the surgery, coronal malalignment is present in approximately 28% of patients.[5] Despite the improvements in surgical instruments and techniques, as well as implant designs, revisions are directly associated with malpositioning of the components.[5] In addition, wear evaluation of retrieved PE inserts has shown that a varus malalignment of as little as 3° may result in accelerated wear, even with ideal mechanical alignment.[6] Fang et al[7] reported that valgus knees failed because of ligament instability. A previous study evaluated studies that examined the influence of coronal alignment upon the performance of TKA, consolidating the importance of proper alignment.[8-10]

Finite element (FE) analysis is a method of assessing the loading through the prosthesis in TKA. It is considered to be more of a qualitative comparative tool than a quantitative method in biomechanical analysis. A number of FE studies have evaluated the effect of malalignment in TKA: Perillo-Marcone et al[4] studied the effect of tibial plateau orientation on cancellous bone stress, Liau et al[11] studied the effect of malalignment on stress within the PE insert of total knee prostheses and Thompson et al[12] studied the biomechanical effects of malalignment of the TKA components using a computational simulation. However, most previous computational studies have investigated aseptic loosening and contact stress within the tibial component as a consequence of malalignment.[4,13-15] The bone resection for the tibial component is perpendicular to the long axis of the tibia. Malpositioning of the tibial component can occur in a slightly slanted cut such that too much or too little bone is removed laterally and medially, respectively. Differences in tibial coronal alignment of between 3° to 5° can occur clinically, therefore warranting an investigation into its biomechanical effect.[16,17]

This study investigates the effect of stance-phase gait and varus and valgus alignments of 3° and 5° upon implant loading mechanics. The maximum contact stresses and contact areas on the medial and lateral sides of PE insert, and maximum contact stress on the patellar button as well as the forces generated within the collateral ligament were evaluated with respect to varus and valgus alignment.

Materials and Methods

A 3D FE knee model was developed on the basis of images from CT and MRI scans of a healthy 35-year-old male subject.[18-20]

The contours of the bony structures (femur, tibia, fibula and patella) and soft tissue (ligaments and menisci) were reconstructed from CT and MR images, respectively. This computational knee joint model has been established and validated in previous studies.[18,21]

The reconstructed CT and MRI models were combined with the anatomical alignment of each model using the commercial software Rapidform (version 2006; 3D Systems Korea Inc., Seoul, South Korea).[18,21] The bony structures were modelled as rigid bodies.[22] All major ligaments were modelled with non-linear, tension-only spring elements and ligament wrapping (ligament that is modelled with a linear line can penetrate bone, however it is not practical in anatomy, therefore we used wrapping).[23,24]

The force-displacement relationship based on the functional bundles in actual ligament anatomy is given as follows:[25]

$$f(\varepsilon) = \begin{cases} \dfrac{k\varepsilon^2}{4\varepsilon_1}, & 0 \leq \varepsilon \leq 2\varepsilon_1 \\ k(\varepsilon - \varepsilon_1), & \varepsilon > 2\varepsilon_1 \\ 0, & \varepsilon < 0 \end{cases}$$

$$\varepsilon = \frac{l - l_0}{l_0}$$

$$l_0 = \frac{l_r}{\varepsilon_r + 1}$$

where $f(\varepsilon)$ is the current force, k is the stiffness, ε is the strain, and ε_1 is assumed to be constant at 0.03. The ligament bundle slack length, l_0, can be calculated by the reference bundle length, l_r, and the reference strain, ε_r, in the upright reference position (Table I).

The femoral component and tibial component were fully bonded to the femoral and tibial bone models, respectively. Contact conditions (where the two objects where in contact but may come apart under loading) were applied between the PE insert and the femoral component in the TKA. The coefficient of friction between the PE insert and metal was chosen to be 0.04 for consistency with previous explicit FE models.[21,26] Contact was defined using a penalty-based method with a weighting factor.

Table I. Properties in ligaments[19]

Ligament	Stiffness (N)	Reference strain	Slack length (mm)
LCL	4000	0.06	57.97
aMCL	2500	-0.02	86.54
iMCL	3000	0.04	84.72
pMCL	2500	0.05	51.10
PFL	4000	0.06	43.54
OPL	2000	0.07	80.21
lCAP	2500	0.06	55.59
mCAP	2500	0.08	60.13
ALS	2000	0.06	31.69
aCM	2000	-0.27	37.53
pCM	4500	-0.06	34.48

LCL, lateral collateral ligament; aMCL, anterior bundle of medial collateral ligament; iMCL, intermediate bundle of the superficial medial collateral ligament; pMCL, posterior bundle of medial collateral ligament; PFL, popliteo-fibular ligament; OPL, oblique popliteal ligament; lCAP, lateral posterior capsule; mCAP, medial posterior capsule; ALS, antero-lateral structures; aCM, anterior deep medial collateral ligament; pCM, posterior deep medial collateral ligament

As a result, contact forces were defined as a function of the penetration distance of the master into the slave surface (aka the femoral component with a high stiffness cannot penetrate the PE insert with low stiffness due to contact). The weight factor was chosen to allow the master surface (femoral component) to have a greater effect on the calculated contact penetration.[27]

The materials of the femoral component, PE insert and tibial component were, cobalt-chromium alloy (CoCr), ultra-high molecular-weight-polyethylene (UHMWPE) and titanium alloy (Ti6Al4V). The material properties, in terms of Young's modulus and Poisson's ratio, were as follows: CoCr: E = 195 Giga Pascal (GPa), v = 0.3; UHMWPE: E = 685 Mega Pascal, v = 0.47; Ti6Al4V: E = 110 GPa, v = 0.3.[26,28,29]

The simulated TKA component positioning was performed by two experienced surgeons (D-SS and O-RK). A neutral-position FE model was developed according to the following surgical preferences: default alignment for the femoral component rotation was parallel to the trans-epicondylar axis, the femoral component coronal alignment was perpendicular to the mechanical axis or the femoral component sagittal alignment was with 3° flexion and a 9.5 mm distal medial resection. The positions of the tibial components were altered with respect to the neutral position to investigate the following four malalignment cases: neutral, 3° and 5° varus and valgus (Fig. 1).

To evaluate the effect of varus and valgus alignments upon the tibial component of the TKA model, a stance-phase gait cycle condition was applied. The computational analysis was performed with anteroposterior force applied to the femur with respect to the compressive load applied to the hip.[19,27,30] A proportional-integral-derivative controller was incorporated into the computational model to allow for the control of the quadriceps in a manner similar to that of previous studies.[31] The control system was used
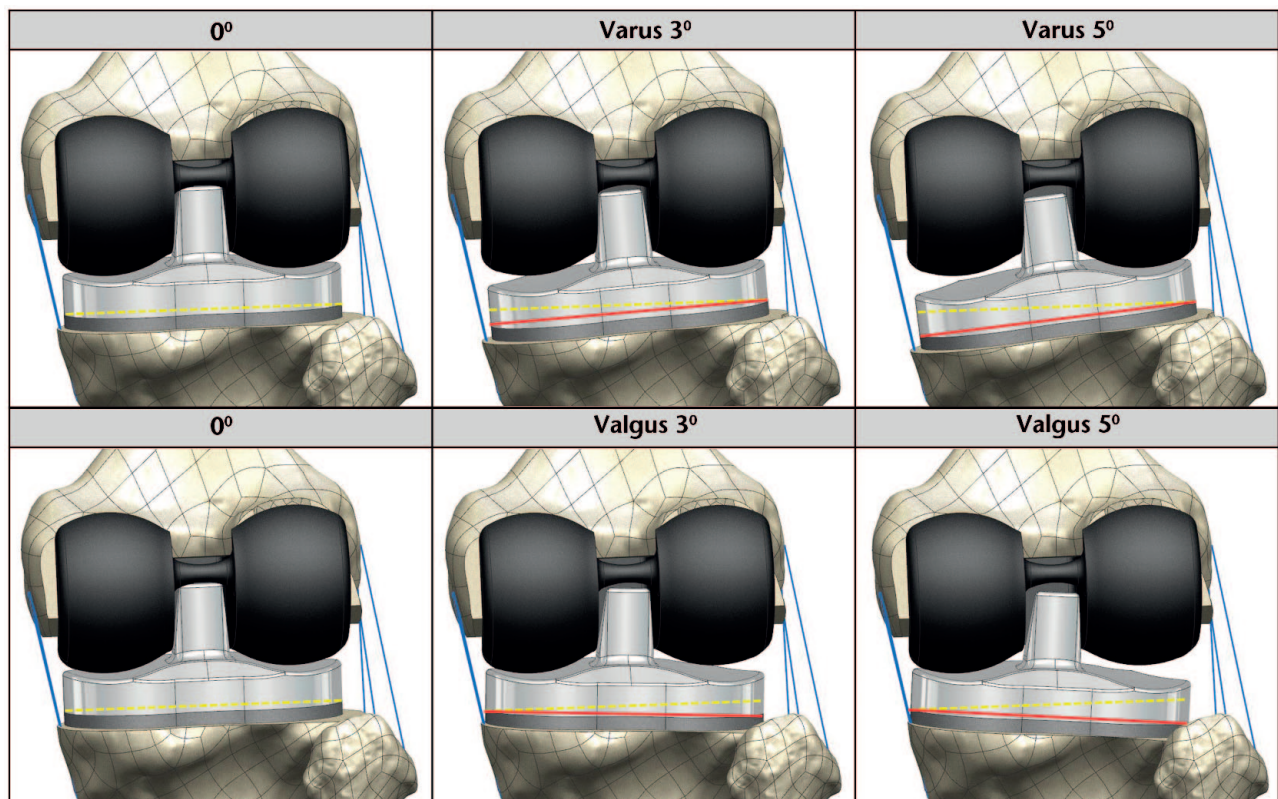
Fig. 1

Schematic of finite element model in neutral position and varus-valgus malalignment conditions.
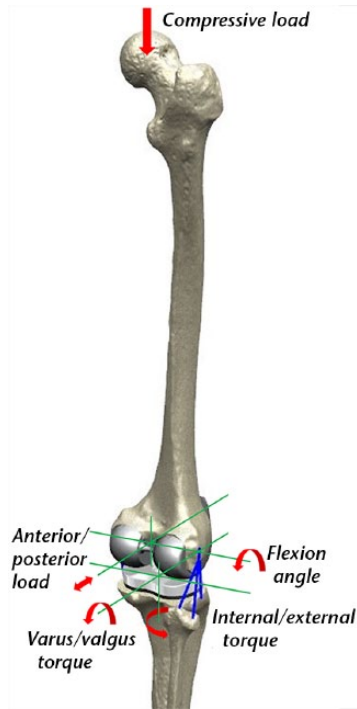
Fig. 2

Loading condition for finite element model used in this study.

to calculate the instantaneous quadriceps displacement required to match a target flexion profile.[31] Internal-external rotation and varus-valgus torques were applied to the tibia (Fig. 2).[19,27,30]

The FE model was analysed using the ABAQUS Explicit software (version 6.11; Simulia, Providence, Rhode Island). The results for maximum contact stress on the PE insert were calculated and the patellar button pressure and collateral ligament forces were evaluated in both varus and valgus malalignment conditions.

Results
Effects of malalignment upon the maximum contact stress and contact area on the PE insert and maximum contact stress on the patellar button. Figure 3 shows the maximum contact stress on the PE inserts in the neutral position and the malalignment FE models during the stance-phase gait cycle. The peak medial contact stress increased by 24.0% and 35.0% at varus alignments of the PE insert of 3° and 5°, respectively. However, an opposite trend was shown in the valgus alignment. The maximum medial contact stress decreased by 37.2% and 50.7% with valgus alignments of the PE insert of 3° and 5°, respectively, while the lateral maximum contact stress increased by 13.3% and 16.9%, respectively. The lateral maximum contact stress decreased by 17.4% and 27.3% with varus alignments of the PE insert of 3° and 5°, respectively. Figure 4 shows the maximum contact stress distribution on the PE inserts in the neutral position and malalignment FE models.

The medial contact area increased by 0.9% and 1.9% and the lateral contact area increased by 0.2 % and 2.5 % under varus alignments of 3° and 5° compared with the neutral alignment model (Fig. 3).

Patellar button maximum contact stress in the neutral position and malalignment are shown in Figure 5 during the stance-phase gait cycle condition. In both varus and valgus alignments, there was negligible difference, with less than 3% change in the patellar button pressure compared with that in the neutral position. Figure 6 shows the maximum contact stress distribution on the patellar button in the neutral position and malalignment FE models.

Effects of malalignment on collateral ligament forces. Figure 7 shows the ligament forces in the medial collateral ligament (MCL), lateral collateral ligament (LCL), popliteofibular ligament (PFL) and anterior lateral structure (ALS) in the neutral position and under malalignment conditions. The ligament forces on the MCL increased by 20.6% and 38.3% in valgus alignments of 3° and 5°, respectively. However, the ligament forces on the MCL decreased by 85.6% and 93.8% in varus alignments of 3° and 5°, respectively.

The ligament forces on LCL, PFL and ALS increased in both varus and valgus alignments. However, the amounts of increase were the greatest at a varus alignment of 5°, as the ligament forces on LCL, PFL and ALS increased by 16.5%, 10.1% and 2.2%, respectively. Under the 5° valgus alignment, the ligament force on LCL, PFL and ASL increased but only by 13.7 %, 4.3 % and 1.0 % on LCL, PFL and ALS, respectively.

Discussion
The function and long-term outcomes of TKA are dependent on factors associated with the patient, implant and surgeon. One key surgeon dependent factor is the use of appropriately sized components and the preservation of the knee joint alignment. Malalignment of the tibial component in TKA is associated with several important clinical complications. In many follow-up studies, the follow-up radiographic data shows that the wear on the PE insert is strongly associated with the varus alignment of knee joint and/or excessive femoral-tibial component subluxation.[32,33] Varus and valgus malalignment leads to high wear in the medial compartment and failure due to ligament instability, respectively.[7] Therefore, the increase in contact stress in the PE insert and collateral ligament forces under a malalignment conditions are of importance clinically. Previous studies have focused on the evaluation of contact stress in a PE insert, stress and strain within the bony structures, or tibial component loosening.[4,11,13,14] Evaluation of the contact stress on a PE insert, patellar button and ligament forces on a knee joint with respect to malalignment during a stance-phase gait loading conditions has not been reported before.
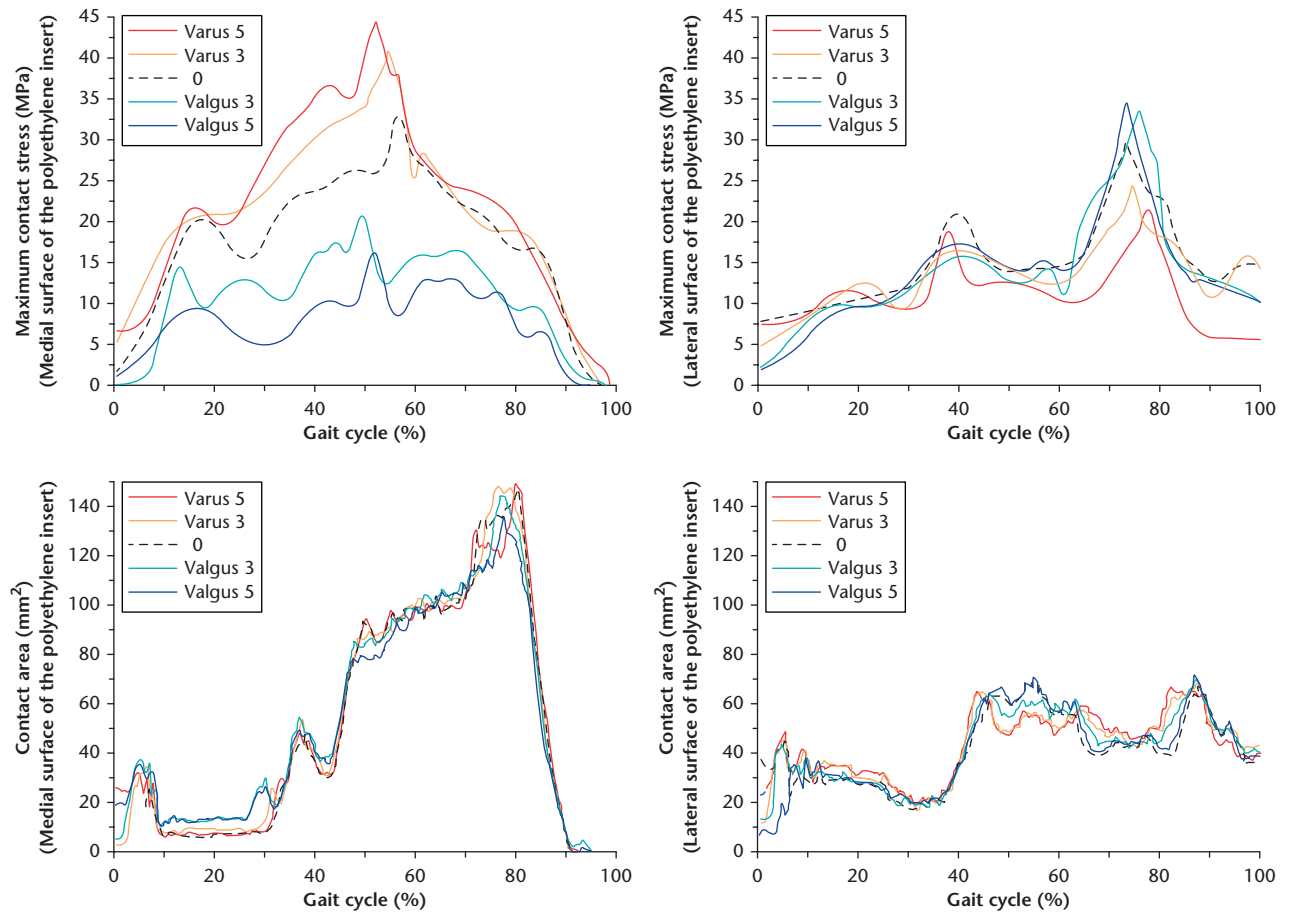
Fig. 3

Effects of the malalignment on the tibial component in total knee arthroplasty with respect to maximum contact stress and contact area on the polyethylene insert in varus and valgus conditions.
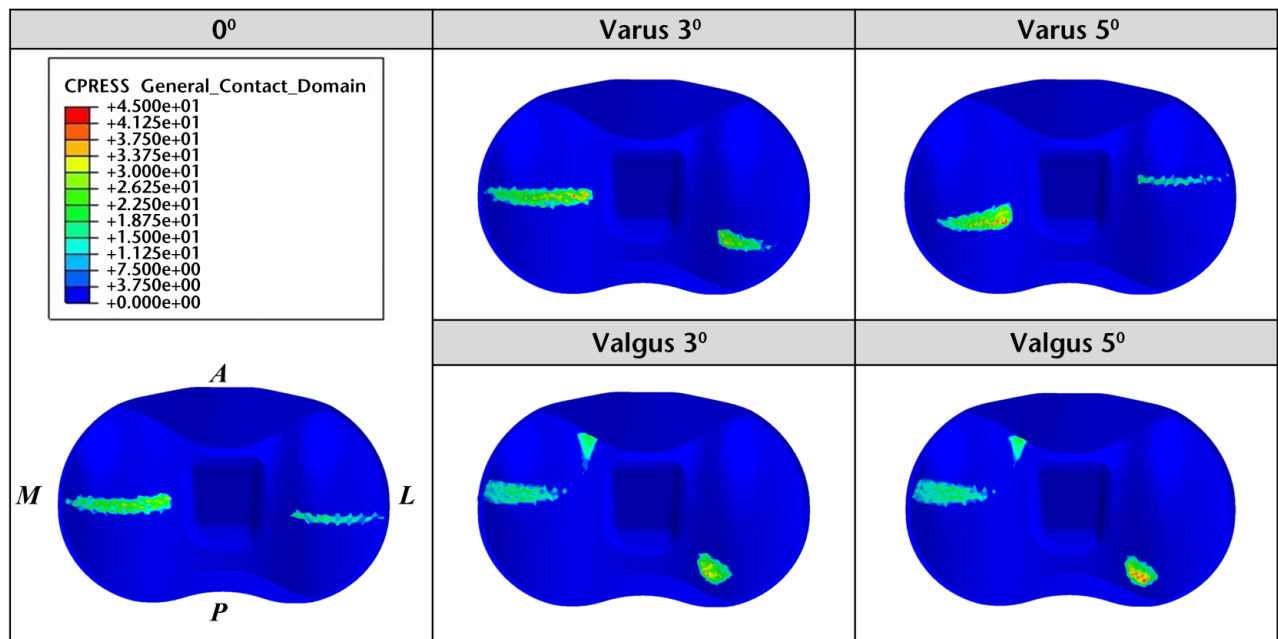

Fig. 4

Comparison of maximum contact stress distribution on the polyethylene insert with respect to varus and valgus malalignments.
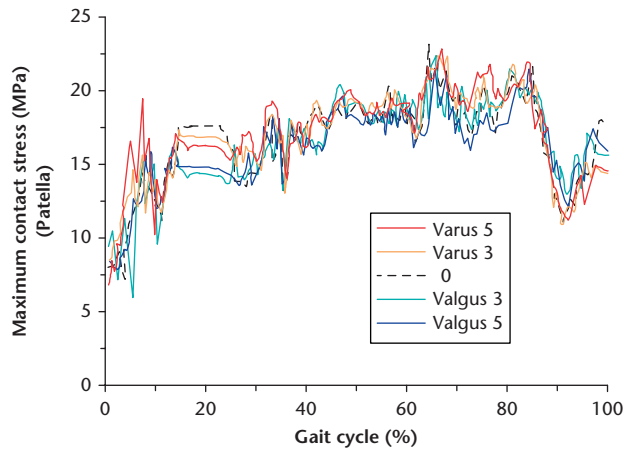
Fig. 5

Comparison of patellar button peak contact stress with varus and valgus malalignments during the stance-phase gait cycle.

This study investigated several biomechanical parameters when improper coronal tibial component alignment was simulated and also during simulated stance-phase gait. Our hypothesis was that varus malalignment increased the maximum contact stress on the medial side of the PE insert and that valgus malalignment would lead to ligament instability in TKA. Our findings of an increased maximum contact stress with varus alignment were consistent with the results of previous studies.[11,32] Recently,

Nishikawa et al[34] reported that improved designs reduced wear in TKA with varus malalignment. However, our study found peak contact stress on the medial and lateral sides increased as the varus and valgus alignment angles increased, respectively. Our results are similar to those of Chen et al[33]

Werner et al[17] found that 96% of load shifts to the medial compartment with 5° varus malalignment of the tibial component under static loading in the fully extended knee joint. Our study has similarly shown a shift to force to the medial side of the knee with varus malalignment throughout the simulated stance-phase gait cycle, though we only measured peak stress. Of interest was the increase in the maximum medial contact stress with varus malalignment which was greater than that of the change in maximum lateral contact stress in the valgus alignment.

Our results support the observations that wear on a medial side of a PE insert may be accelerated with varus malalignment.[6] Patellar button peak contact stress did not change significantly with malalignment of the tibial component. It is more likely to be affected by malrotation of the femoral component. The results for patellar button pressure and contact area were similar to previous studies.[33,35]

Bryant et al[35] also reported that the lateral compartment contact area increased with an increasing valgus
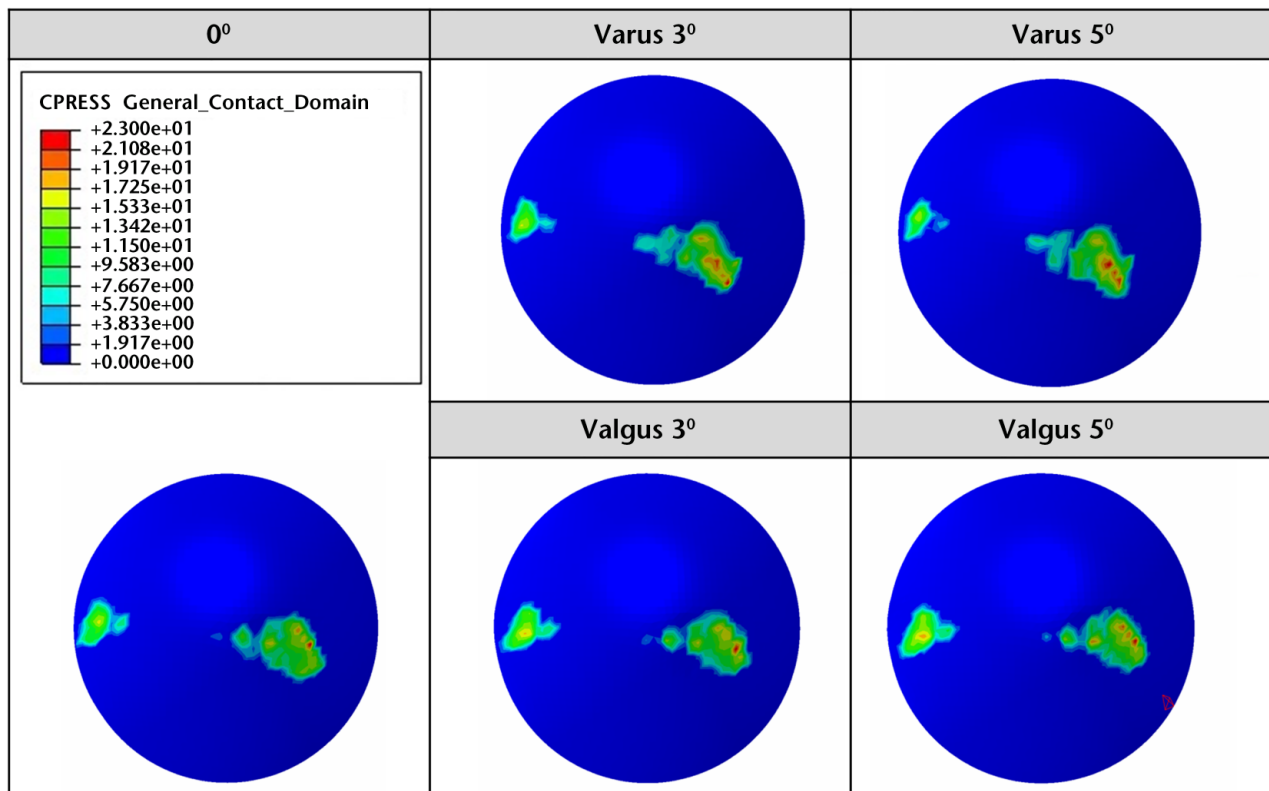

Fig. 6

Comparison of maximum contact stress distribution on patellar button with respect to varus and valgus malalignment.
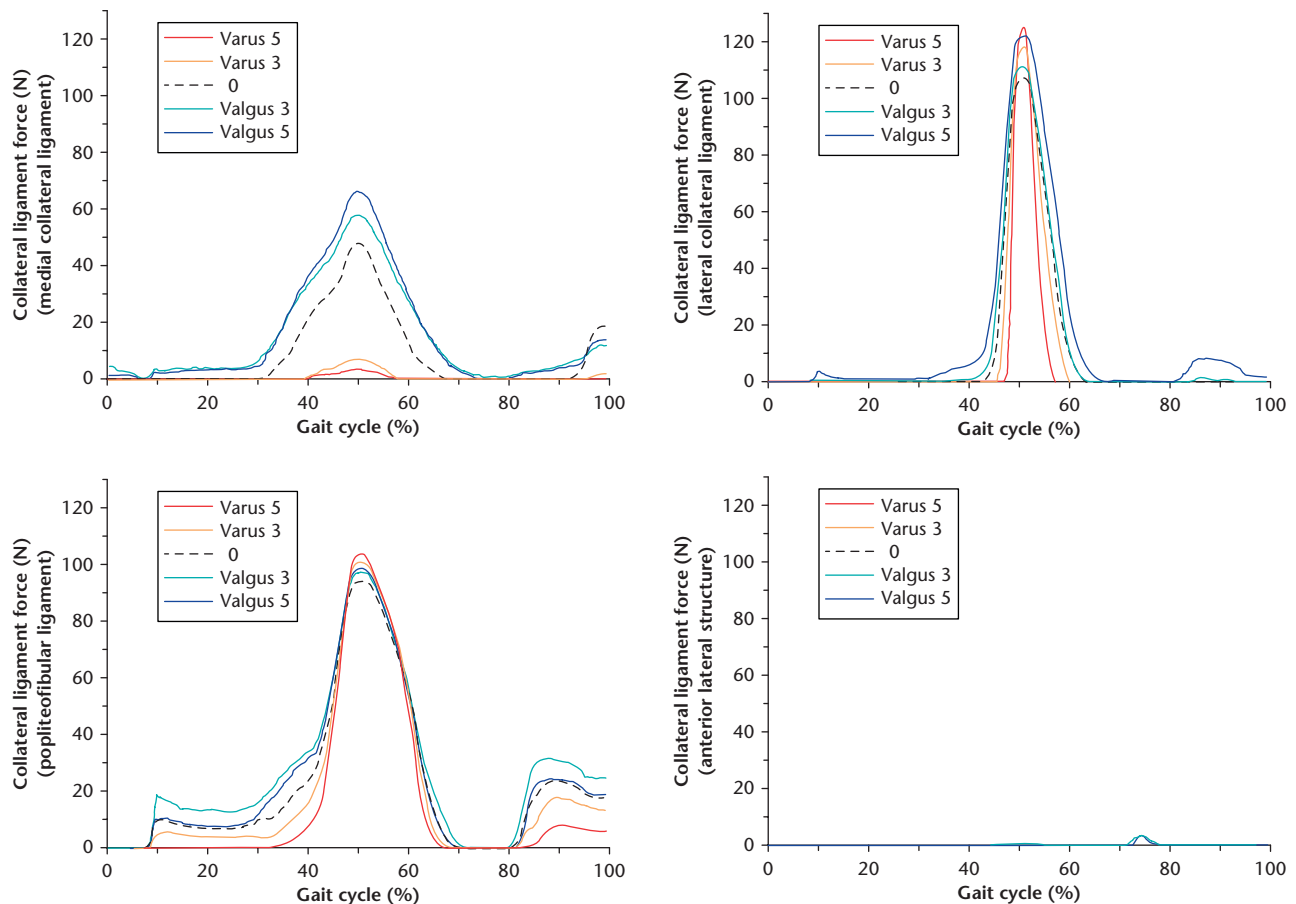
Fig. 7

Effects of the malalignment on the tibial components in total knee arthroplasty with respect to collateral ligament force in varus and valgus conditions.

alignment angle. The larger the contact area on the PE insert, the smaller the contact stress on the tibial component, in neutral alignment conditions. With varus alignment, the wider contact area on the medial side could potentially decrease the contact stress as a consequence of the mechanical malalignment. Malalignment should have some effect on the forces transmitted through the collateral ligaments during stance-phase gait. We observed that forces transmitted through the lateral collateral ligament and the other lateral constraints were greatest with varus malalignment but also changed with valgus alignment in our simulation.

Varus and valgus malalignment had less effect on the forces transmitted through the lateral sided structures than the medial structures where the greatest changes were noted

The change in medial collateral ligament forces caused by valgus malalignment is clearly likely to have some effect on the outcome of a TKA. Our observations were similar to the increase in the ligament force in the MCL found using using a cadaver model.[35]

Our results support the restoration of a neutral mechanical axis with accurate implant positioning is as critical requirements for successful TKA.

There are several limitations in this study. First, only the intact model (without TKA) was validated. Secondly, the computational model was developed using data from only a young male subject. Using more subjects with a wider age profile would improve the validity of the results. Thirdly, the balance of all collateral ligaments was assumed to be accurate in our FE model, residual ligament imbalance could have potentially influenced the results. Finally, this study used a linear model for the PE that provided an overestimation in the local stress on PE under plasticisation. However, the purpose of this study was to perform a comparative study using the identical model and approach in all configurations. Thus, it highlights the best and the worst configurations.

In conclusion, the maximum contact stresses and the contact areas on a PE insert along with ligament forces exerted through the collateral ligaments were evaluated with respect to varus and valgus alignments under a simulated stance-phase gait cycle loading condition. The greatest stress was found in the medial side of the PE insert with varus malalignment and the likely failure of a TKA due to ligament failure in valgus malalignment owing to the increase in the medial ligament force was observed. There was no apparent effect upon the patellar

button maximum contact stress, regardless of the varus and valgus malalignments.

References

1. **Huijbregts HJ, Khan RJ, Fick DP, et al.** Component alignment and clinical outcome following total knee arthroplasty: a randomised controlled trial comparing an intramedullary alignment system with patient-specific instrumentation. *Bone Joint J* 2016;98-B:1043.1049.

2. **D alury DF, Pomeroy DL, Gorab RS, Adams MJ.** Why are total knee arthroplasties being revised? *J Arthroplasty* 2013;28(suppl):120-121.

3. **D'Lima DD, Hermida JC, Chen PC, Colwell CW Jr.** Polyethylene wear and variations in knee kinematics. *Clin Orthop Relat Res* 2001;392:124-130.

4. **Perillo-Marcone A, Barrett DS, Taylor M.** The importance of tibial alignment: finite element analysis of tibial malalignment. *J Arthroplasty* 2000;15:1020-1027.

5. **Ng VY, DeClaire JH, Berend KR, Gulick BC, Lombardi AV Jr.** Improved accuracy of alignment with patient-specific positioning guides compared with manual instrumentation in TKA. *Clin Orthop Relat Res* 2012;470:99-107.

6. **Srivastava A, Lee GY, Steklov N, et al.** Effect of tibial component varus on wear in total knee arthroplasty. *Knee* 2012;19:560-563.

7. **Fang DM, Ritter MA, Davis KE.** Coronal alignment in total knee arthroplasty: just how important is it? *J Arthroplasty* 2009;24(suppl):39-43.

8. **Bargren JH, Blaha JD, Freeman MA.** Alignment in total knee arthroplasty. Correlated biomechanical and clinical observations. *Clin Orthop Relat Res* 1983;173:178-183.

9. **Jeffery RS, Morris RW, Denham RA.** Coronal alignment after total knee replacement. *J Bone Joint Surg [Br]* 1991;73-B:709-714.

10. **Tew M, Waugh W.** Tibiofemoral alignment and the results of knee replacement. *J Bone Joint Surg [Br]* 1985;67-B:551-556.

11. **Liau JJ, Cheng CK, Huang CH, Lo WH.** The effect of malalignment on stresses in polyethylene component of total knee prostheses–a finite element analysis. *Clin Biomech* 2002;17:140-146.

12. **Thompson JA, Hast MW, Granger JF, Piazza SJ, Siston RA.** Biomechanical effects of total knee arthroplasty component malrotation: a computational simulation. *J Orthop Res* 2011;29:969-975.

13. **Perillo-Marcone A, Taylor M.** Effect of varus/valgus malalignment on bone strains in the proximal tibia after TKR: an explicit finite element study. *J Biomech Eng* 2007;129:1-11.

14. **Kusz D, Wojciechowski P, Cielinski LS, et al.** Stress distribution around a TKR implant: are lab results consistent with observational studies? *Acta Bioeng Biomech* 2008;10:21-26.

15. **Small SR, Rogge RD, Malinzak RA.** Micromotion at the tibial plateau in primary and revision total knee arthroplasty: fixed versus rotating platform designs. *Bone Joint Res* 2016;5:122-129.

16. **Ritter MA, Faris PM, Keating EM, Meding JB.** Postoperative alignment of total knee replacement. Its effect on survival. *Clin Orthop Relat Res* 1994;299:153-156.

17. **Werner FW, Ayers DC, Maletsky LP, Rullkoetter PJ.** The effect of valgus/varus malalignment on load distribution in total knee replacements. *J Biomech* 2005;38:349-355.

18. **Kim YS, Kang KT, Son J, et al.** Graft extrusion related to the position of allograft in lateral meniscal allograft transplantation: biomechanical comparison between parapatellar and transpatellar approaches using finite element analysis. *Arthroscopy* 2015;31:2380-2391.e2.

19. **Kang KT, Koh YG, Son J, et al.** Measuring the effect of femoral malrotation on knee joint biomechanics for total knee arthroplasty using computational simulation. *Bone Joint Res* 2016;5:552-559.

20. **Kang KT, Kim SH, Son J, et al.** Probabilistic evaluation of the material properties of the in vivo subject-specific articular surface using a computational model. *J Biomed Mater Res B Appl Biomater* 2017;105:1390-1400.

21. **Kwon OR, Kang KT, Son J, et al.** Biomechanical comparison of fixed- and mobile-bearing for unicompartmental knee arthroplasty using finite element analysis. *J Orthop Res* 2014;32:338-345.

22. **Peña E, Calvo B, Martinez MA, Palanca D, Doblaré M.** Why lateral meniscectomy is more dangerous than medial meniscectomy. A finite element study. *J Orthop Res* 2006;24:1001-1010.

23. **Mesfar W, Shirazi-Adl A.** Biomechanics of the knee joint in flexion under various quadriceps forces. *Knee* 2005;12:424-434.

24. **Takeda Y, Xerogeanes JW, Livesay GA, Fu FH, Woo SL.** Biomechanical function of the human anterior cruciate ligament. *Arthroscopy* 1994;10:140-147.

25. **Blankevoort L, Huiskes R.** Validation of a three-dimensional model of the knee. *J Biomech* 1996;29:955-961.

26. **Godest AC, Beaugonin M, Haug E, Taylor M, Gregson PJ.** Simulation of a knee joint replacement during a gait cycle using explicit finite element analysis. *J Biomech* 2002;35:267-275.

27. **Halloran JP, Clary CW, Maletsky LP, et al.** Verification of predicted knee replacement kinematics during simulated gait in the Kansas knee simulator. *J Biomech Eng* 2010;132:081010.

28. **Pegg EC, Walter J, Mellon SJ, et al.** Evaluation of factors affecting tibial bone strain after unicompartmental knee replacement. *J Orthop Res* 2013;31:821-828.

29. **Innocenti B, Truyens E, Labey L, et al.** Can medio-lateral baseplate position and load sharing induce asymptomatic local bone resorption of the proximal tibia? A finite element study. *J Orthop Surg Res* 2009;4:26.

30. **Kutzner I, Heinlein B, Graichen F, et al.** Loading of the knee joint during activities of daily living measured in vivo in five subjects. *J Biomech* 2010;43:2164-2173.

31. **Kang KT, Koh YG, Jung M, et al.** The effects of posterior cruciate ligament deficiency on posterolateral corner structures under gait- and squat-loading conditions: A computational knee model. *Bone Joint Res* 2017;6:31-42.

32. **Huang CH, Yang CY, Cheng CK.** Fracture of the femoral component associated with polyethylene wear and osteolysis after total knee arthroplasty. *J Arthroplasty* 1999;14:375-379.

33. **Chen Z, Wang L, Liu Y, et al.** Effect of component mal-rotation on knee loading in total knee arthroplasty using multi-body dynamics modeling under a simulated walking gait. *J Orthop Res* 2015;33:1287-1296.

34. **Nishikawa K, Okazaki K, Matsuda S, et al.** Improved design decreases wear in total knee arthroplasty with varus malalignment. *Knee Surg Sports Traumatol Arthrosc* 2014;22:2635-2640.

35. **Bryant BJ, Tilan JU, McGarry MH, et al.** The biomechanical effect of increased valgus on total knee arthroplasty: a cadaveric study. *J Arthroplasty* 2014;29:722-726.