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Computational analysis of tibial slope adjustment with fixed-bearing medial unicompartmental knee arthroplasty in ACL- and PCL-deficient models

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Aims

A functional anterior cruciate ligament (ACL) or posterior cruciate ligament (PCL) has been assumed to be required for patients undergoing unicompartmental knee arthroplasty (UKA). However, this assumption has not been thoroughly tested. Therefore, this study aimed to assess the biomechanical effects exerted by cruciate ligament-deficient knees with medial UKAs regarding different posterior tibial slopes.

Methods

ACL- or PCL-deficient models with posterior tibial slopes of 1°, 3°, 5°, 7°, and 9° were developed and compared to intact models. The kinematics and contact stresses on the tibiofemoral joint were evaluated under gait cycle loading conditions.

Results

Anterior translation increased in ACL-deficient UKA cases compared with intact models. In contrast, posterior translation increased in PCL-deficient UKA cases compared with intact models. As the posterior tibial slope increased, anterior translation of ACL-deficient UKA increased significantly in the stance phase, and posterior translation of PCL-deficient UKA increased significantly in the swing phase. Furthermore, as the posterior tibial slope increased, contact stress on the other compartment increased in cruciate ligament-deficient UKAs compared with intact UKAs.

Conclusion

Fixed-bearing medial UKA is a viable treatment option for patients with cruciate ligament deficiency, providing a less invasive procedure and allowing patient-specific kinematics to adjust posterior tibial slope. Patient selection is important, and while AP kinematics can be compensated for by posterior tibial slope adjustment, rotational stability is a prerequisite for this approach. ACL- or PCL-deficient UKA that adjusts the posterior tibial slope might be an alternative treatment option for a skilled surgeon.

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Keywords: Unicompartmental knee arthroplasty, Cruciate ligament, Tibial slope, Finite element method

Article focus

- The effect of tibial slope on the stability of medial unicompartmental knee arthroplasty (UKA) in anterior cruciate ligament (ACL)-deficient or posterior cruciate ligament (PCL)-deficient knees.

Key messages

- The cruciate ligament has the functionally important role of restricting anteroposterior (AP) translation in the medial UKA. In ACL-deficient or PCL-deficient UKAs, the proper posterior tibial slope provides kinematic stability.

Strengths and limitations

- This study showed that levelling of the posterior tibial slope has a significant

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effect on AP kinematics and contact stress in ACL-deficient or PCL-deficient UKAs.

- This study did not compare the actual clinical data for AP translation and contact stress.

Introduction

Isolated unicompartmental osteoarthritis (OA) of the knee joint is a common ailment. There are various operative treatments available, including high tibial osteotomy (HTO), total knee arthroplasty (TKA), and unicompartmental knee arthroplasty (UKA), which are prescribed according to the patient's activity level and age.[1] In particular, UKA is commonly prescribed for the treatment of isolated medial compartmental OA of the knee, and is effective as a less invasive surgical approach.[2] Generally, the ideal patient for medial UKA is a medial unicompartmental knee OA patient with an intact cruciate ligament.[3] The effectiveness of UKA as a method of managing medial and lateral compartment knee OA in a cruciate ligament deficient patient is controversial.[4] The UKA procedure is restrictive and requires precision. If not done correctly, patient pain and a requirement for UKA revision may be the result.[5] UKA is contraindicated in patients with cruciate ligament deficiency because of the possibility of resulting abnormal knee kinematics. Additionally, UKA is related to aseptic loosening of the tibial component and other surgical failures.[6,7] Kozinn and Scott[7] reported that cruciate ligament deficiency should be treated as a relative contraindication for fixed-bearing UKA. In addition, a major theoretical concern of UKA procedures for anterior cruciate ligament (ACL)-deficient patients is increased translation, which is likely to cause premature polyethylene wear.[8] UKA with accompanying ACL reconstruction has been suggested as a treatment method for medial compartment arthritis in ACL-deficient patients.[6] ACL reconstruction with UKA is a technically demanding procedure, and can cause damage to the medial tibial bone stock and complicate rehabilitation.[4] Previous studies on the effects of tibial slope on knee stability have been conducted.[9,10] As the tibial slope increases in UKA, the anteroposterior (AP) tibiofemoral (TF) translation and subsequent risk of ACL injuries can increase.[11] Many previous studies focused on the posterior tibial slope in ACL-deficient UKA patients.[4,11-13] Hernigou and Deschamps[11] suggested that a posterior tibial slope of > 7° should be avoided, particularly if ACL deficiencies remain after the UKA procedure. Suero et al[4] demonstrated that UKA with a posterior tibial slope decreased AP TF sagittal plane translation to levels similar to those of an intact knee.

However, those researchers focused only on TF kinematics and did not consider the contact stresses on the other compartment. The use of finite element (FE) analysis enables the evaluation of the biomechanical effects of ACL deficiency in UKA and posterior tibial slopes on contact stress. Accurate in silico evaluations are an important tool for clinical assessment.[14] In addition to performing these evaluations, we researched the effects of posterior tibial slope in posterior cruciate ligament (PCL)-deficient patients in a previous study.[15] However, no studies have compared the effects in ACL-deficient and PCL-deficient knee models.

Therefore, this study aimed to assess the biomechanical effects of ACL-deficient knees in relation to various posterior tibial slopes in medial UKA surgery. We hypothesized that posterior tibial slope adjustment decreases the AP translation and contact stress on the other compartment in ACL-deficient or PCL-deficient UKA patients.

Methods

Development of fixed-bearing UKA model. In this study, an existing 3D non-linear FE model for knee joints was developed, using MRI and CT images taken from a female subject (Subject 5: age 26 years, height 163 cm, mass 65 kg) and four male subjects (Subject 1: age 36 years, height 178 cm, mass 75 kg; Subject 2: age 34 years, height 173 cm, mass 83 kg; Subject 3: age 32 years, height 182 cm, mass 79 kg; Subject 4: age 34 years, height 173 cm, mass 71 kg) with normal knee conditions (mechanical femoral tibial angle: varus 1°).[16,17]

The medial and lateral proximal tibial angles of the intact model were within the normal range (normal knee: 87.4° and 88.1°, respectively). This computational knee joint model was validated in our previous studies by Kang et al[16-18] (Figure 1). The bony structures were designed as rigid bodies. The models for cartilage and menisci were designed as isotropic and transversely isotropic materials, respectively, using eight-node hexahedral elements (see Table I).[19,20] All of the major ligaments were designed using hyperelastic rubber-like materials, representing non-linear stress-strain relationships.[21,22] Implant type was a fixed-bearing UKA (Zimmer Biomet, USA) that was implanted in the medial side of the intact knee. The bone models were imported and adequately trimmed, positioned, and meshed with the rigid elements using surgical techniques.[23] Considering the dimensions of the femur and tibia, we selected prosthesis sizes of six and five of the femoral component and tibial baseplate. The prostheses were then aligned according to the mechanical axis and positioned at the medial edge of the tibia. The neutral alignment of the tibial baseplate was set as being at a square (0°) inclination in the coronal plane with a 5° posterior slope. The rotation axis of the knee was set parallel to the lateral edge of the tibial baseplate that penetrates the femoral component peg's centre. To create UKA models, we reproduced a neutral femoral component distal cut parallel to the tibial cut, and perpendicular to the mechanical axis of the femur. Also six different models, the ACL-deficient model, PCL-deficient model, and posterior tibial slope (1°, 3°, 5°, 7°, and 9°), were included in this scenario.[16,23,24] The femoral component and tibial baseplate were designed as linear elastic isotropic materials, and the polyethylene (PE) component was designed as elastoplastic material. The femoral component, tibial baseplate, and PE insert were made of a cobalt-chromium alloy (CoCr) material,

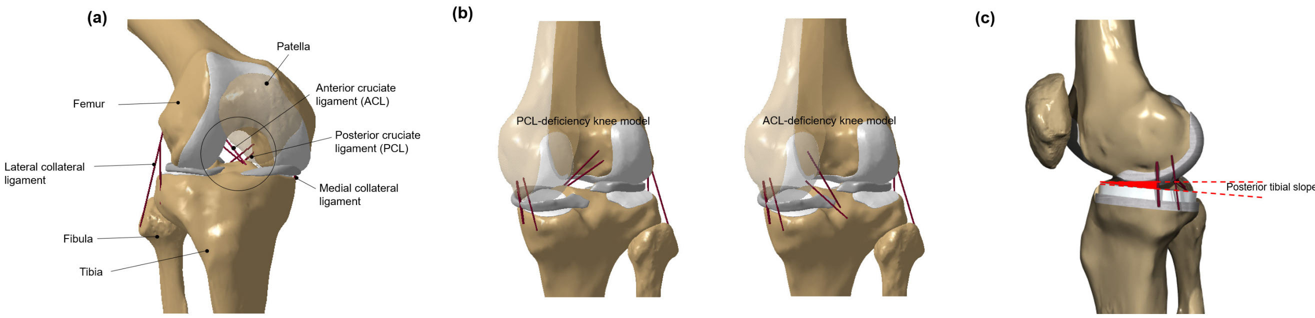

Fig. 1

Finite element models in analysis for a) intact, b) anterior cruciate ligament (ACL) deficiency and posterior cruciate ligament (PCL) deficiency, and c) unicompartmental knee arthroplasty (UKA) model.

Table I. Material properties of the articular cartilage and menisci.

Model	Properties	Measurements
Cartilage	Linearly elastic, isotropic	E = 15 MPa
		v = 0.475
Menisci	Linearly elastic, transversely isotropic	E_θ = 150 MPa, $E_r = E_z$ = 20 MPa
		v_{rz} = 0.2, $v_{r\theta} = vz_{z\theta}$ = 0.3, $G_{r\theta} = Gz_{z\theta}$ = 57.7 MPa

Table II. Material properties of implant.

Material	Young's modulus (MPa)	Poisson's ratio
CoCr	220,000	0.30
UHMWPE	685	0.47
Ti6Al4V	110,000	0.30

CoCr, cobalt-chromium alloy; Ti6Al4V, titanium alloy; UHMWPE, ultra-high molecular weight polyethylene.

a titanium alloy (Ti6Al4V), and an ultra-high molecular weight polyethylene (UHMWPE) material, respectively (see Table II). The coefficient between metal and PE was set to 0.04.[24]

The FE simulation was conducted under three load conditions, the load used in the model validation experiment, and the predicted daily activity loading scenarios. Under the first loading condition, we applied 1,150 N axial loading to the model and acquired contact stress results. These results were compared to those of a previously published FE knee joint study.[19] In addition, the UKA models were performed with flexion angles of 0°, 30°, 60°, and 90° using passive flexion simulation for the purpose of the validation. Anterior and posterior drawer loads (130 N) were applied to the tibia at the knee centre in a similar manner to that used in a previous experimental study.[25] The third loading condition, gait cycle loading, was applied to evaluation of knee joint mechanics. We applied an AP force to the femur according to the International Organization for Standardization (ISO) gait cycle. This is based on the compressive load applied to the hip by constrained femoral internal-external (IE) rotations, free medial-lateral translations, and knee flexion, based on quadriceps loads and a combination of the vertical hip.[26] Therefore, a TF joint with six degrees of freedom was developed.[27,28] The computational model incorporated a proportional-integral-derivative controller to control the quadriceps in a similar manner to that used in our previous study.[29] The control system was used with the aim of evaluating the instantaneous displacement of the quadriceps muscles. This reproduces the target flexion profiles used in the experiments. In addition, torques of varus-valgus and IE were applied to the tibia with the restraint of the tibial degrees of freedom. The FE analysis was performed using ABAQUS software (version 6.11; Simulia, USA). The primary outcome measure was AP translation under gait cycle loading conditions. Through these results, the kinematics of UKA models were assessed. The kinematics were analyzed based on Grood and Suntay's definition of a joint coordinate system.[30] The secondary outcome was a calculation of the contact stress on articular cartilage. The resulting values of the ACL-deficient, PCL-deficient, and intact UKA models were compared in this study.

Statistical analysis. For statistical analysis, this study was conducted by dividing single cycles of gait loading conditions into 11 timepoints. The corresponding simulation result of the knee was compared under the same phases of the cycle as the calculated kinematic data. In order to compare results obtained under the intact knee condition and ligament deficient status conditions, non-parametric repeated measures Friedman tests and post-hoc comparisons were performed using a Wilcoxon signed-rank test with Holm correction. In this study, we used SPSS for Windows for statistical analyses (version 20.0.0; IBM, USA). We set $p < 0.05$ as the significance level for all comparisons.

Results

For validation of the intact models, the results of the contact stress on the menisci were compared with another FE study.[19] The contact stresses in the medial

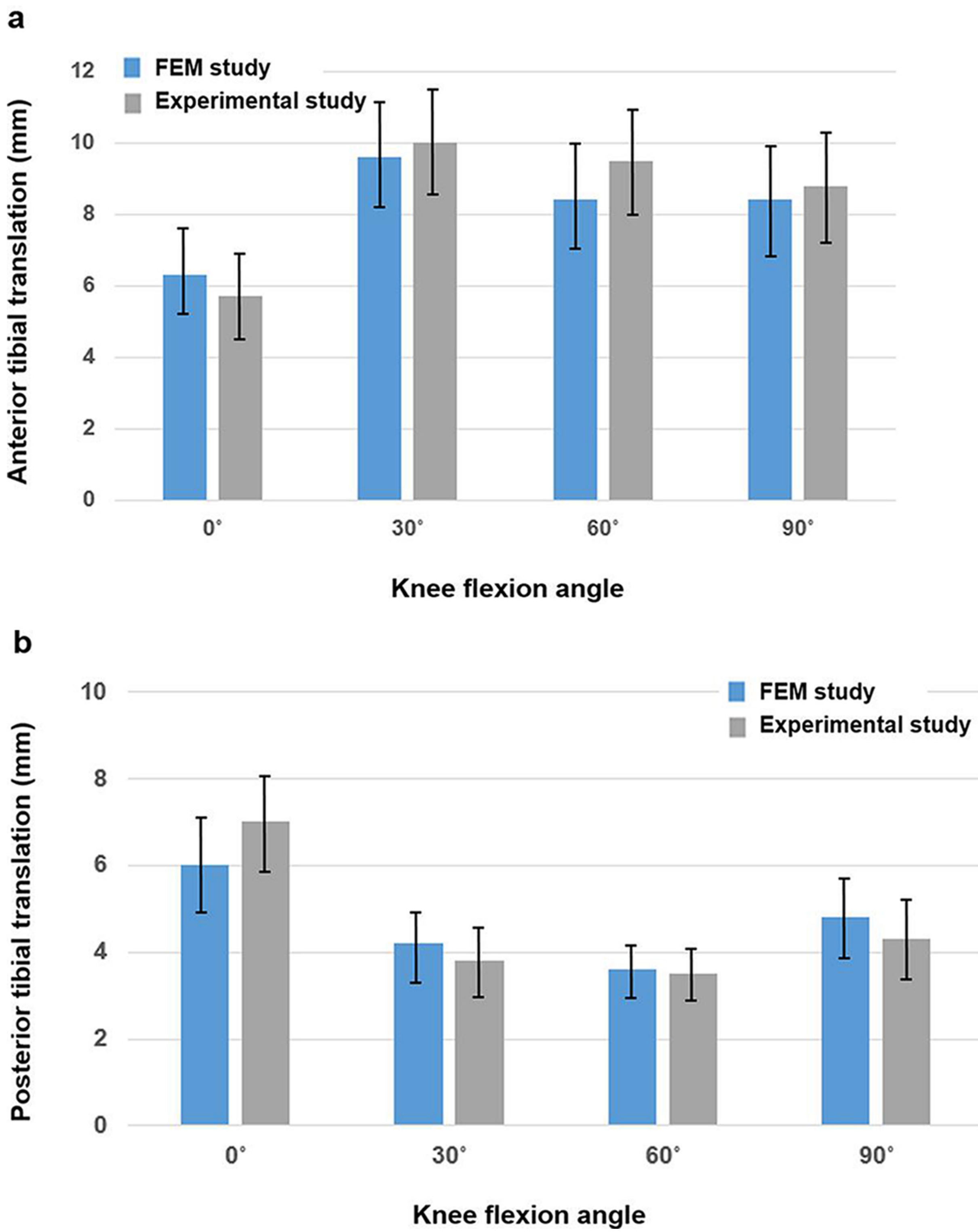

Fig. 2

Comparison of a) anterior tibial translation and b) posterior tibial translation for current finite element method (FEM) studies and the experimental studies by Suggs et al.[25]

and lateral menisci, under an axial load of 1,150 N, were 3.1 MPa and 1.53 MPa, respectively, which is within 4% (on average) of the corresponding contact stresses of 2.9 MPa and 1.45 MPa used in Peña et al's[19] study. These minor differences in results may be due to the geometrical distraction of the thickness of the meniscus and the cartilage between different studies. By showing general consistency between the value reported in the literature

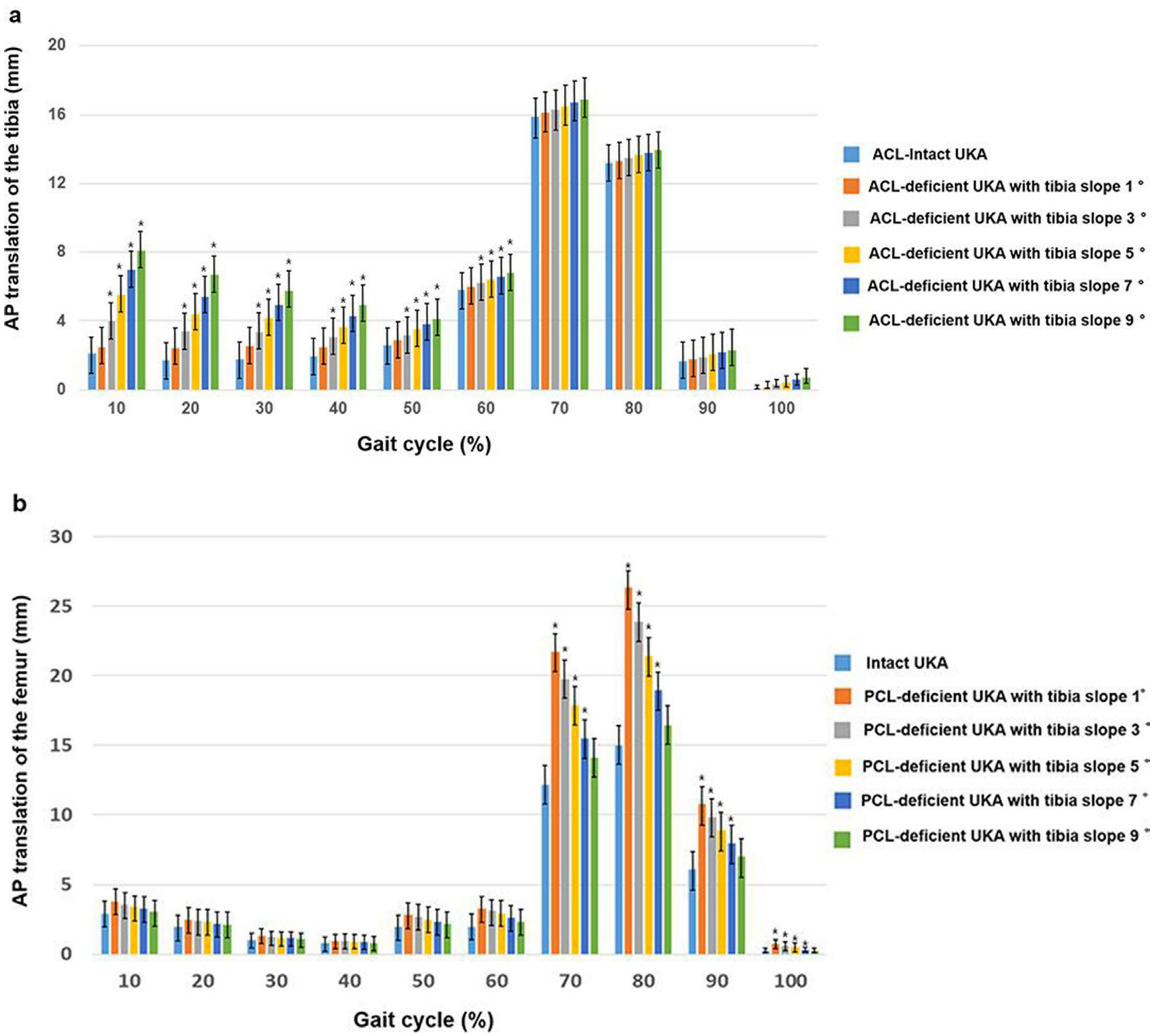

Fig. 3

Comparison of the anteroposterior (AP) translation between the intact unicompartmental knee arthroplasty (UKA) model and a) anterior cruciate ligament (ACL)-deficient UKA or b) posterior cruciate ligament (PCL)-deficient UKA, with respect to different posterior tibial slopes under gait cycle loading condition (*p < 0.05; Friedman test).

and our validation results, however, ours has been proven to be a dependable FE model.

For validation, the data in this study were compared with the data in a previous study.[25] In the 130 N anterior drawer test, the anterior tibial translations in the UKA models were 6.1 mm, 9.9 mm, 8.7 mm, and 8.5 mm (on average), while those in the posterior drawer test were 5.8 mm, 4.3 mm, 3.8 mm, and 4.9 mm (on average) at 0°, 30°, 60°, and 90° of knee flexion, respectively (Figure 2). These results are consistent with those of Suggs et al's[25] experimental studies gauged within the same range of values, under anterior and posterior drawer loadings.

Figure 3 shows AP translations in ACL-deficient, PCL-deficient, and standard UKA models, concerning different posterior tibial slopes. Anterior translation, for the same posterior tibial slope, significantly increased in the ACL-deficient model compared to an ACL-intact model in the stance phase of gait. This trend was clearly visible during gait cycle loading conditions, and the effects were largest in the mid-flexion region. The difference in anterior translation, between the ACL-deficient model and ACL-intact model, reached a maximum of 6 mm in the case of a 9° posterior tibial slope. However, anterior translation showed a decrease as the posterior tibial slope decreased. In contrast, the posterior translation of the PCL decreased as the posterior slope increased. In particular, we found that posterior translation significantly increased compared to the intact knee in the swing phase

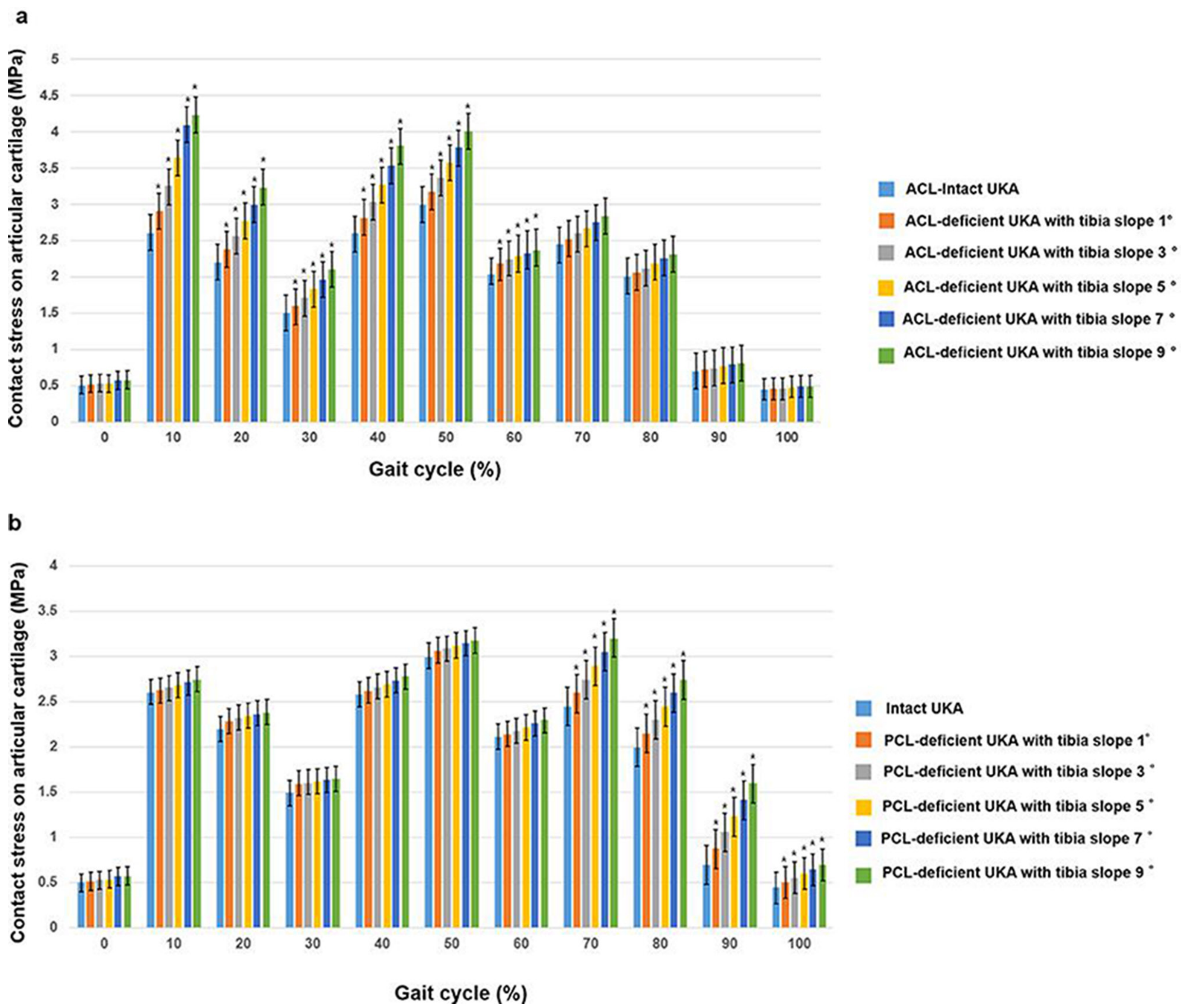

Fig. 4

Comparison of the contact stress on articular cartilage between the intact unicompartmental knee arthroplasty (UKA) model and a) anterior cruciate ligament (ACL)-deficient UKA or b) posterior cruciate ligament (PCL)-deficient UKA, with respect to different posterior tibial slopes under gait cycle loading condition (*$p < 0.05$; Friedman test).

of gait. We demonstrated the results of the contact stress on the other compartment in Figure 4. The results of ACL-deficient UKA, PCL-deficient UKA, and standard UKA models were compared with respect to different posterior tibial slopes. Both ACL-deficiency and PCL-deficiency significantly increased the contact stress exerted on the articular cartilage, compared to the intact model. This increase became more noticeable as the posterior tibial slope was increased in the stance phase of ACL-deficiency and swing phase of PCL-deficiency. The contact stress result of the articular cartilage, for the ACL-deficient UKA model with a 9° posterior tibial slope, was significantly increased by up to 63% (on average) of the value found in the ACL-intact UKA model. In the case of PCL-deficiency, the stress significantly increased by up to 30% (on average) compared to intact PCL-deficient models.

Discussion

The most important finding of this study was that ACL deficiency significantly increased anterior translation and contact stress on the other compartment in UKA during stance phase compared to the intact UKA. In addition, PCL deficiency significantly increased posterior translation and contact stress on the other compartment in UKA during swing phase compared to the intact UKA.

We have shown that levelling of the posterior tibial slope in a fixed-bearing medial ACL deficient UKA can control the aberrant anterior translations observed under gait cycle loading conditions. Additionally, as the posterior tibial slope increased, the contact stress of the other compartment increased, subsequently increasing the overall risk of progressive OA.

However, the opposite trend was shown in PCL-deficient UKA. To the best of our knowledge, this is the first investigation aimed at evaluating the biomechanical effects of posterior tibial slope alterations on the contact stress on the other compartment in ACL- or PCL-deficient UKA models.

A functional ACL plays an integral role in the success of UKA.[6,7,25,31] A previous study that investigated 103 mobile-bearing UKA cases found that the failure rate was significantly higher for knees with a deficient ACL compared to those with an intact one.[31] In a study of 301 mobile-bearing UKA cases, Goodfellow and O'Connor[6] showed that the six-year survival rate was 95% for knees with an intact ACL, while the rate for knees with deficient or damaged ACLs was only 81%. In contrast, Boissonneault et al[32] and Plancher et al[33] discovered that there was no significant difference in clinical outcomes between medial UKA with and without deficient ACL over a minimum follow-up period of 2.9 years. Moreover, Suter et al[34] showed that there were no differences between conventional medial UKA and medial UKA with deficient ACL in kinetics and kinematics, including knee joint movements. An intact ACL is important for successful meniscal-bearing UKA, but the role of the ACL in fixed-bearing UKA remains uncertain.[13,35]

The cruciate ligament is important for stabilizing knee motion. In previous studies, investigators have researched the influence of ACL and PCL deficiency on knee kinematics under various activity conditions. Cromie et al[36] studied knee kinematics under ACL and PCL deficiency, and showed that eliminating the ACL and PCL introduced abnormal anterior femoral translation, doubling the amount compared to the intact knee. Furthermore, our previous study indicated that the PCL is crucial to restraining AP translation, by showing a significant difference in the amount of translation between the PCL deficiency and the intact knee in UKA.[15] Defrate et al[37] demonstrated that ACL deficiency alters AP translation, and the difference between the translation of the ACL-deficient knee and the intact knee was more pronounced near full extension. In particular, the ACL has the functionally important role of restricting anterior tibial translations in the medial UKA. Consequently, any ACL or PCL deficiency leads to failures resulting from changes in knee biomechanics. Similar trends have been found in various biomechanical studies.[4,12,38] A previous study showed that anterior tibial translations during the Lachman test decreased by approximately 5 mm with an 8° posterior tibial slope.[4] However, no variation in slope altered the pivot shift kinematics in ACL-deficient knees.[4] Adulkasem et al[12] showed that UKA in ACL-deficient knees is challenging because a variation of posterior tibial slope, compared to ACL-intact knees, is about twice the degree of knee translation. However, the results from the aforementioned studies correspond to static loading conditions. Recently, Zumbrunn et al[38] compared ten UKA patients and eight ACL-deficient patients. ACL-deficient patients had reduced tibial slopes to compensate for the instability that results from the deficient ACL under dynamic loading conditions.[38] Their study showed that, in spite of the posterior femoral shift resulting from ACL deficiency, the two groups exhibited similar kinematic waveforms. This indicates that the reduction of the posterior tibial slope may partially compensate for the function of ACL. However, the small sample size was a weakness of their study.[38] The computational simulation has advantages in evaluating the effects of the posterior tibial slope on ACL-deficient or PCL-deficient UKA in the same person because the simulation eliminates the influences of other variables such as bony geometry, component size, ligament properties, height, and weight.[17] Interesting findings were obtained regarding the contact stress on the other compartment. Contact stress on the other compartment significantly increased with deficient ACL or PCL, and the effects became more noticeable as the posterior tibial slope was increased. Previous studies have proved that the posterior tibial slope is important for accurate knee arthroplasty.[35,36,38] A previous study by Kang et al[39] indicated that posterior TF translation significantly increased as posterior tibial slope increased. The translation of posterior TF is crucial in knee arthroplasty, as a higher degree of flexion is allowed before a TF impingement occurs.[39] In addition, a more posterior TF contact point at hyperflexion improves the quadriceps moment and is related to improved International Knee Society Function scores in knee arthroplasty.[39]

Additionally, Weber et al[40] demonstrated that translation between the prosthesis and the inlay was reduced due to an increased posterior tibial slope in the analyzed mobile-bearing UKA results, which reduced backside wear. The same trend was also found in their fixed-bearing UKA study.[41] We recently found that, in fixed-bearing UKA, the contact stress on the other compartment increased as the posterior tibial slope increased.[42] The contact stress on the tibial insert differed from that on the other compartment and generally increased as the posterior tibial slope decreased in fixed-bearing UKA.[42] A similar trend was found in this study. As the posterior tibial slope is increased the contact stress on the other compartment is also increased. This result was expected, as increased posterior tibial slope causes greater anterior translation, leading to an increase of contact stress on the other compartment. In addition, differences in contact stress were found most frequently during the stance phase because contact stress is affected by axial force.[17]

Restoration of the tibial slope angle and the native articular joint line is the treatment aim of UKA. However, the modification of the tibial slope is notable in the stability loss of ACL-deficient or PCL-deficient subjects' knees. Increasing posterior tibial slope has been recommended to increase knee flexion and femoral rollback, and improve stress distribution at the tibial component-bone interface.[12] A previous biomechanical study showed that levelling of the tibial slope did not assist the restoration of rotational stability, but that it did contribute to successfully restoring anterior stability.[4] This implies that treatment with UKA and posterior tibial slope levelling may not be ideal for young, medial OA patients secondary to ACL injury in whom reduction of rotational instability is the main aim of treatment. In contrast, the levelling procedure of the posterior tibial slope is a rational option to cure ACL insufficiency in older adults with medial OA due to lower functional demands. There was no difference in failure modes between UKA with or without ACL.

These results support our hypothesis that fixed-bearing UKA represents a feasible treatment option for patients with ACL or PCL deficiency, allowing patient-specific kinematics to adjust posterior tibial slope and offering a less invasive procedure. Patient choice is crucial and, while AP kinematics can be compensated for by adjusting posterior tibial slope, rotational stability is a prerequisite for this approach.[38] Additionally, an interesting finding was that in ACL-deficient UKA, significantly different AP kinematics and contact stress were seen in the stance phase of the gait cycle, while in PCL-deficient UKA, significantly different AP kinematics and contact stress were seen in swing phase of the gait cycle compared to intact UKA. The reason for these findings is the roles of the ACL and PCL. ACL deficiency has been theorized to occur due to a common mechanism of injury involving excessive internal rotation (IR) torque and anterior translation during low flexion angle.[43] In addition, PCL deficiency resists external tibial rotation and posterior tibial translation during high flexion angle.[44,45] However, further research is needed to explore the results of this study.

This study had several limitations. First, we assumed that the bony structures were rigid. Second, the lateral compartment was considered only as an elastic material except for the anisotropic and viscoelastic effects. Third, our results only correspond to fixed-bearing UKA. The biomechanical effects are different between fixed- and mobile-bearing UKAs.[46] Finally, the simulation of this study only applied gait cycle conditions. To expand this research, the effects of various loading conditions such as squatting, stair climbing/descending, and chair rising/sitting need to be assessed in future studies.

In conclusion, our data suggest that a functional ACL and PCL are required to ensure normal stability. ACL or PCL deficiency may be a predictor of poor UKA outcomes. Therefore, poor outcomes can be predicted in medial ACL- or PCL-deficient UKA. However, the anterior and other compartment stability may reduce the overall risk of progressive OA by adjusting the posterior tibial slope. ACL-deficient or PCL-deficient UKA with posterior tibial slope adjustment could be an alternative treatment option to TKA if performed by a skilled surgeon.

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