Changes in tibial insert design can alter mid-flexion anteroposterior stability and stress distributions in mechanically aligned total knee arthroplasty

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INTRODUCTION:

Modern total knee arthroplasty (TKA) is a surgical procedure that can achieve stable postoperative outcomes in knee osteoarthritis, but about 20% of patients remain unsatisfied after TKA. Causes include residual knee pain, range of motion limitation, joint instability, and aseptic loosening. However, despite new tibial insert designs that aim to improve patient satisfaction, it is uncertain whether the expected effects are achieved. In addition, few studies have demonstrated differences in clinical outcome between different implant design. To clarify these issues, it is important to investigate knee biomechanics in TKA. The purpose of this study was to develop a new musculoskeletal computer simulation using finite element analysis (FEA) to simultaneously investigate knee kinematics and stress distribution in post-TKA models and thus closely reproduce the details of the knee.

METHODS:

A musculoskeletal computer simulation using computed tomography (CT) data of a volunteer was developed to analyze knee biomechanics during squat (0°–120°) (Fig. 1). Kinematic comparison after mechanically aligned TKA with more than 2 years of follow-up between in vivo and simulated kinematics was performed using a 2D–3D registration technique. The hip–knee–ankle angle maintained a neutral alignment and posterior tibial slope was 3°. We compared biomechanical changes between posterior cruciate ligament (PCL)-retaining (CR)-TKA and CR-TKA without anterolateral (AL)-PCL, because the AL-PCL can be damaged during tibial bone resection. If the PCL were damaged intraoperatively, the surgeon would use a cruciate-sacrificing (CS) tibial insert with high anterior lip or PCL-substituting (PS) components with a post-cam mechanism. The femoral components had a single radius of curvature design. The AP movement (mm) at the facet centers or contact points of the medial and lateral femoral condyles against the tibial insert and peak equivalent stresses (MPa) on the tibial insert. The equivalent stresses (MPa) in the femur within 1 mm below the femoral component or in the tibia within 1 mm around the keel of the tibial component were also measured as indicators of the stress concentrations between respective bones and components.

RESULTS:

The CR model showed little femoral anterior movement during mid-flexion, and then suitable medial pivot motion and roll-back of the femoral component (Figs. 1 and 2). The CR model without the AL-PCL showed relatively larger femoral anterior movement than the CR model with an intact PCL, and also had attenuated medial pivot motion and roll-back. In the CS model, the femoral component moved anteriorly until the high anterior lip of the tibial insert exerted an effect, and it then rolled back, though the femoral component did not directly contact the anterior lip. The PS model exhibited the same type of anterior femoral movement as the CS model during mid-flexion. However, the PS femoral component was forcibly rolled back when the post-cam mechanism was active at knee flexion of 60° or more. Regarding to equivalent stresses on the tibial insert, the PS model due to its post-cam mechanism exhibited higher equivalent stress on the tibial insert throughout squat than the other TKA models (Figs. 1 and 2). In the CR model, the TF contact stress increased at mid-flexion because increased PCL tension caused femoral roll-back. The TF contact stress in the CS model increased significantly during deep knee flexion. In addition, during knee flexion, the stress of the bone element below the femoral component as the femoral cut surface was higher in the PS model than in the other models (Fig. 3). On the other hand, the stress concentration around the keel of the tibial component was higher in the CS model than in the other models.

DISCUSSION AND CONCLUSION: This study using a new musculoskeletal computer simulation based on FEA revealed that simply by changing the type of tibial insert can alter not only mid-flexion anteroposterior instability, but also high stress distribution, even with the same femoral component design in the same knee. The CR design showed good knee kinematics with little paradoxical femoral anterior movement, and it also reduced stresses on bone-component interfaces, probably because the PCL dispersed the stress between the femur and tibia. However, CR-TKA with partial PCL damage caused femoral anterior movement during mid-flexion. After PCL dysfunction, switching to a CS tibial insert with a high anterior lip could not reduce the mid-flexion instability. In addition, stress around the keel of the tibial component increased, possibly because excessive femoral AP movement caused stress on the tibial keel in the AP direction. In contrast, the change to the PS components resulted in mechanical femoral roll-back against the tibia, but also increased stress distribution on the tibial polyethylene. Moreover, the stress on the bone-component interface of the PS femoral component increased, possibly due to the post-cam mechanism. There is a close relationship between the tibial insert design and the mid-flexion anteroposterior instability or high stress distribution.

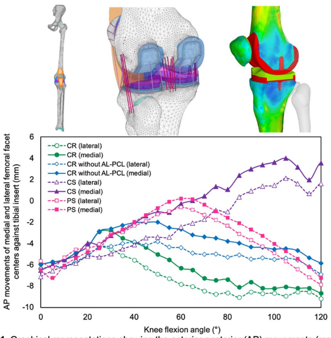

Fig. 1. Graphical representations showing the anterior-posterior (AP) movements (mm) of the facet centers of the lateral and medial femoral condyles against the tibial insert during squat in each total knee arthroplasty design based on the new musculoskeletal computer simulation using finite element analysis. CR: posterior cruciate ligament (PCL)-retaining, CS: cruciate-sacrificing, PS: PCL-substituting, AL: anterolateral.

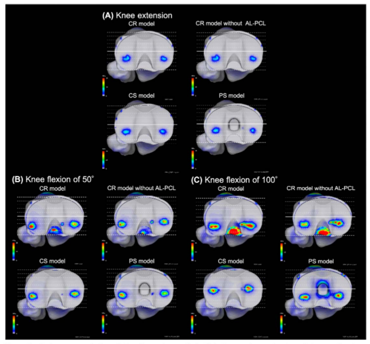

Fig. 2. Schemas of the lateral and medial tibiofemoral contact points and stress distributions in each total knee arthroplasty design at knee extension (A), knee flexion of 50° (B) and knee flexion of 100° (C). CR: posterior cruciate ligament (PCL)-retaining, CS: cruciate-sacrificing, PS: PCL-substituting, AL: anterolateral.

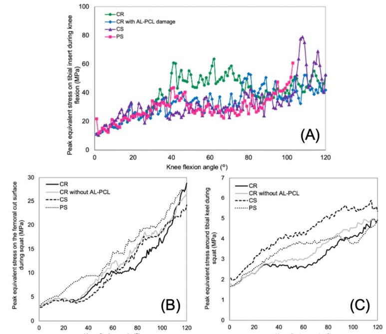

Fig. 3. Graphical representations showing peak equivalent stresses on the tibial insert (A) and femoral cut surface (B) and around the keel of the tibial component (C) in each total knee arthroplasty design during squat. CR: posterior cruciate ligament (PCL)-retaining, CS: cruciate-sacrificing, PS: PCL-substituting, AL: anterolateral.