Factors Influencing TKR Joint Mechanics in the Varus Knee

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Introduction: Varus alignment of the lower limb after total knee arthroplasty serves to distribute the compressive force across the tibiofemoral (TF) joint more medially. Altering the load distribution from a neutral alignment loading condition has a corresponding effect on the kinematics of the joint; offloading the lateral compartment will reduce the constraint on that side and facilitate greater TF motion. In the implanted knee, surgical decisions, such as component alignment and ligament release, play an important role in determining the overall mechanics of the joint, however, the influence of these decisions on resulting TF joint mechanics has not been directly quantified. The objective of the current study was to determine the effect of four parameters, including femoral component internal-external (I-E) alignment, posterior slope of the tibial insert, posterior cruciate ligament (PCL) tension, and medial-lateral (M-L) ligament balance, on TF load, M-L load distribution and kinematics in a varus knee implanted with cruciate-retaining (CR) fixed-bearing (FB) total knee replacement (TKR) components.

Understanding the impact and importance of each of these surgical variables will guide clinical decisions in patients with alignment which deviates from neutral mechanical alignment.

Methods: A finite element (FE) model of the lower limb was developed in Abaqus Explicit (SIMULIA, Providence, RI). The model included femoral, tibial and patellar bones. TF soft-tissues represented in the model included the medial and lateral collateral ligaments (MCL, LCL), represented as 2D fiber-reinforced membranes, and the posterior cruciate ligament (PCL), represented as a 3D anisotropic hyperelastic continuum with a single fiber direction. The patellar ligament, quadriceps muscle (divided into four bundles) and hamstrings muscle (divided into four bundles) were also included in the model (Figure 1). The hip-knee-ankle (HKA) angle of the model was 7° varus, and virtually implanted with CR-FB TKR components (Figure 1). External loads, derived from telemetric patient data \cite{1} were applied at the hip (vertical load), quadriceps, hamstrings (muscle loads) and ankle (I-E torque and flexion-extension torque) to simulate a stepdown activity \cite{2}. This activity was chosen as a high-demand (large compressive force, large anterior-posterior (A-P) shear force) activity which patients often associate with joint instability.

A design-of-experiments (DOE) was performed whereby four factors (femoral component I-E alignment, insert posterior slope, PCL tension, M-L ligament tension balance) were perturbed and the stepdown simulation repeated under each set of conditions. Femoral I-E alignment was evaluated at three levels: neutral (0°), 5° external rotation, and 10° external rotation. Insert posterior slope was evaluated at three levels: 0°, 3° and 7° of posterior slope. PCL tension was evaluated at three levels: nominal (as per published data \cite{3}), tight and slack (no PCL present). M-L ligament balance was evaluated at two levels: balanced MCL-LCL tension (50:50) at the start of the cycle, and tight MCL with slack LCL tension (70:30) at the start of the cycle. This resulted in a DOE analysis which encompassed 54 simulations with consistent external loading conditions.
**Results:** Varus alignment resulted in the majority of the compressive load (>60%) being applied to the medial condyle for most of the cycle. In most simulations, lift-off of the lateral condyle was evident towards the end of the simulation as the lower limb was being off-loaded. External rotation of the femoral component served to increase the load applied to the lateral condyle (Figure 2). Increased posterior slope served to shift M-L force distribution more medially, although differences due to posterior slope alignment were eliminated in the presence of a tight PCL. External rotation of the femoral component also resulted in a larger total compressive force on the TF joint, as more quadriceps force was required to maintain a consistent flexion profile across simulations.

The most notable factor in influencing TF A-P motion was insert posterior slope, with increased slope resulting in more posterior shift of the femur relative to the tibia (Figure 3). Femoral I-E alignment also played a role, with increased external rotation resulting in posterior shift of the femur. A slack PCL served to shift the femur more anterior. At the levels evaluated, MCL-LCL ligament balance had little effect on A-P translation. Femoral I-E alignment had the greatest influence on T-F I-E rotation, as external rotation of the femoral component resulted in a larger I-E range of motion (ROM). Increased posterior slope resulted in a small amount of internal rotation of the femur.

**Discussion:** Varus knee alignment inherently serves to offload the lateral compartment of the joint. In high-demand activities, where patients are particularly vulnerable to incidences of knee instability it is important to understand the effect of surgical decisions on joint stability and motion. This study helps to elucidate controllable surgical factors which influence stability and load distribution in the varus knee.

**Significance:** This study demonstrated that AP joint stability and kinematics are significantly influenced by slope of the tibial insert, and that to maintain stability, particular attention should be paid to appropriately tensioning the PCL when introducing a more natural posterior tibial slope. Femoral IE rotation in the varus knee impacts the M-L load distribution, contact mechanics, and IE rotation of the joint.
Figure 1: Lower limb model with a varus knee during a dynamic stepdown activity, shown in coronal (top) and sagittal (bottom) views during the cycle.
Figure 2: Ratio of medial condyle force to total compressive force on the insert with variation in external femoral alignment and insert posterior slope with a tight (left) and slack (right) PCL. Inserts show mediolateral load distribution mid-cycle (35° flexion) for neutral, 5° external and 10° external femoral component alignment.

Figure 3: A-P translation of the femur with variation in external femoral alignment and insert posterior slope with a tight (left) and slack (right) PCL. Inserts show femoral position mid-cycle (35° flexion) for 0° and 7° of posterior slope of the insert.