Management of Flexion-Extension Gap Inequality in TKA: A Computer Simulation Study

+[1]Piazza, S J; [1]Hast, MW; [2]Walker, CD; [3]Hanssen, AD
+[1]The Pennsylvania State University, University Park, PA, [2]Stryker Orthopaedics, Mahwah, NJ, [3]Mayo Clinic, Rochester, MN
Senior author piazza@psu.edu

INTRODUCTION

Equalizing the flexion and extension gaps is a technical challenge commonly faced in total knee arthroplasty (TKA). When the flexion gap is greater than the extension gap, as is often the case in revision TKA, the surgeon can address this problem by increasing the size of the femoral component. Because the anteroposterior dimension of the femoral component increases with increasing size, the posterior condyles of a larger implant may fill the flexion gap without overfilling the extension gap. If a discrepancy between the flexion and extension gaps persists after introduction of a larger femoral component, it may be necessary to increase the thickness of the tibial insert to fill the flexion gap and move the femoral component proximally to adjust the extension gap. These measures have the potential to disrupt the mechanics of the extensor mechanism because of (1) changes in the joint line that follow from increasing insert thickness; and (2) differences in the anterior geometry between femoral implants of different sizes. The purpose of this study is to use a computer simulation to investigate changes in extensor mechanics that result from femoral component upsizing and joint line elevation performed to correct varying degrees of flexion-extension gap inequality.

METHODS

A forward-dynamic simulation of a loaded knee flexion performed in an 'Oxford Rig' was used to study different methods of addressing inequalities between the flexion and extension gaps. A model was developed with four segments (pelvis stage, femur, patella, and tibia) and 12 degrees of freedom (DOF), including two DOF between the pelvis stage and the femur at the hip, three DOF between the tibia and ground at the ankle, and six DOF between the femur and the patella. The remaining DOF permitted the pelvis stage to slide on vertical rails with respect to the ground. This configuration has been shown to permit six DOF between the femur and tibia [1]. The equations of motion for the model were developed and integrated using SIMM/Dynamics Pipeline (MusculoGraphics, Inc.) and SD/FAST (PTC).

Each simulation consisted of a slow knee flexion that progressed from approximately 20° to 125° in 10 s under quadriceps force control. A modified version of a previously published proportional-derivative controller [2] was used to determine the quadriceps force required to lower the pelvis stage at a constant downward velocity. This quadriceps force was applied to the femur and patella using a single actuator with attachment points that approximated those of the vastus intermedius. The patellar ligament, lateral and medial collateral ligaments, and posterior capsule were represented by collections of tensile spring elements with quadratic force-extension relations. Contact between the femoral component and the tibial or patellar components was modeled using an elastic foundation approach in which the penetration of discrete spring nodes (on the patellar and tibial components) into the femoral component surface was penalized by the application of normal contact force. Contact forces were computed using a damped spring model with stiffness and damping constants based on the properties of polyethylene [3], and contact friction was not modeled.

Simulations of the flexion and extension gap tests were also run in order to determine implant placements. Simulations were run with the default implant (Triathlon TS, size 3) and no additional laxity, and with the slack lengths of both collateral ligaments increased by 3 mm, 6 mm, and 9 mm. These changes had the effect of increasing the flexion gap but not the extension gap, as the posterior capsule integrity was not modified. This gap inequality was addressed by increasing the size of the femoral component to size 4 or by increasing the insert thickness (raising the joint line). When the collateral laxity was increased by 6 mm or 9 mm, it was not possible to equalize the gaps through upsizing alone, and the joint line was also elevated in these cases. Once the implants were placed, Oxford Rig flexion simulations were run and extensor mechanics were assessed by examining the quadriceps force required to perform the identical flexion motions, which is an indicator of extensor mechanism efficiency.

RESULTS

The quadriceps forces required to flex the knee in the simulation were greater when differences between the flexion and extension gaps were addressed by joint line elevation alone. In mid-flexion, quadriceps forces were increased by 27% (as compared to the case in which no additional laxity was imposed) for the most extreme gap imbalance (Fig. 1). When a larger femoral component was used the corresponding increase in quadriceps force was 21%. In deep flexion, these differences were more striking; joint line elevation alone increased quadriceps forces by 16% for the worst gap imbalance, but introduction of a larger femoral component resulted in and increase of only 2%. This trend was also observed for simulations of lesser gap imbalances (Table 1).

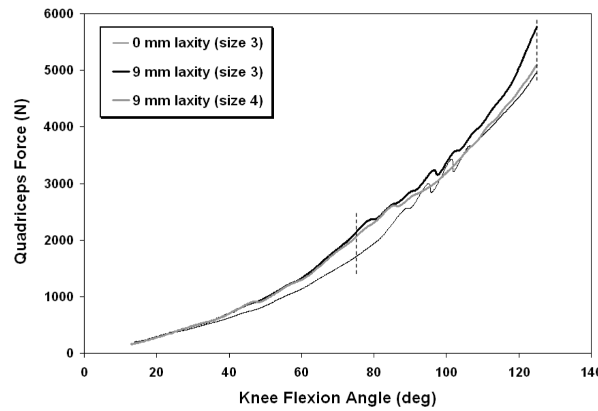

Figure 1. Simulated quadriceps forces required for controlled knee flexion when a 9.3 mm difference in the flexion and extension gaps was induced by increasing the slack lengths of the collateral ligaments by 9 mm. Both joint line elevation with a properly sized femoral component (*thick black line*) and upsizing the femoral component (*thick gray line*) increased demands on the quadriceps at 75° flexion, but upsizing produced demands closer to those for the default case at 125° flexion.

Collateral Slack Change	Gap Difference (Flex – Ext)	Quad Force @ 75°		Quad Force @ 125°	
		Size 3	Size 4	Size 3	Size 4
(mm)	(mm)	(N)	(N)	(N)	(N)
0	1.6	1706	n/a	4966	n/a
3	3.5	1774	1787	5021	4750
6	6.3	2014	1939	5319	4917
9	9.3	2172	2058	5776	5104

Table 1. Flexion-extension gap differences and required quadriceps forces for the default case (no additional collateral laxity and size 3 femoral component) and for simulations with additional collateral laxity and femoral component upsizing.

DISCUSSION

These simulation results suggest that the use of a larger femoral component when the flexion gap exceeds the extension gap better maintains quadriceps efficiency than does using a properly-sized component and raising the joint line. These results are consistent with previous findings that excessive joint line elevation is associated with poor outcome in revision TKA [4]. However, for the most extreme gap imbalance conditions, even the larger femoral component must be implanted with a raised joint line. Regardless of how gap inequality is addressed, the greatest increases in quadriceps demand were found to occur in mid flexion as opposed to deep flexion. In addition, soft tissue interference resulting from medial-lateral overhang accompanying component upsizing was not addressed in our simulations. This study suggests there may be opportunities to address the frequently observed gap balancing issue in revision TKA with improved implant design.

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