A Total Knee Arthroplasty Is Stiffer When the Intraoperative Tibial Force Is Greater than the Native Knee

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Abstract

We hypothesized that a total knee arthroplasty (TKA) with an intraoperative tibial force greater than the tibial force of the native knee has signs of stiffness as measured by loss of extension and flexion, and anterior translation of the tibia. Intraoperative forces in the medial and lateral tibial compartments were measured during passive motion in 71 patients treated with calipered kinematically aligned TKA. Maximum extension, flexion, and the anterior–posterior position of the tibia with respect to the distal femur at 90 degrees of flexion were measured. Measurements were repeated after exchanging to a 2 mm thicker insert. The sum of the average of the medial and lateral compartment forces at 0, 45, and 90 degrees of flexion represented the tibial force through a 90-degree motion arc. For the implanted insert, the tibial force averaged 28 ± 17 lb, which is comparable to the 20 ± 7 lb reported for the native knee. At 6 months, patients reported an average 40 point Oxford Knee and 15 point Western Ontario and McMaster Universities Osteoarthritis (WOMAC) score. For the 2 mm thicker insert, the tibial force averaged 50 ± 28 lb. A 30 lb tibial force greater than native generated a 3-degree loss of extension, a 3-degree loss of flexion, and 3-mm anterior translation of the tibia. Because a TKA with a tibial force greater than native has signs of stiffness, a strategy for lowering this risk is to match the tibial force of the native knee when balancing a TKA as this restored high function.

Keywords

- ► total knee arthroplasty
- ► kinematic alignment
- ► instrumented tibial insert
- ► tibial compartment force

Although total knee arthroplasty (TKA) is one of the most successful reconstructive procedures, approximately 20% of patients express some level of dissatisfaction.[1–3] Balancing the soft tissues increases patient-reported satisfaction and minimizes the risk of instability.[4,5] Methods for balancing include adjusting the level and angle of the femoral and tibial bone resections, releasing over-tight soft tissues, and changing the thickness of the insert.[6–8]

Loss of knee extension, loss of knee flexion, and anterior translation of the tibia with respect to the distal medial femoral condyle at 90 degrees of flexion are signs of stiffness that are clinically and mechanically undesirable (►**Figs. 1** and **2**). A TKA that does not fully extend may cause a limp, pain, stiffness, and an increase in energy expenditure.[9–12] A TKA that does not fully flex may lead to difficulties kneeling and may interfere with performing activities of daily living.[9,11] A TKA with an increase in anterior translation of the tibia at 90 degrees of flexion has a tight flexion gap that may cause a loss of flexion and increase the risk of polyethylene wear.[13–15]

Instrumented tibial inserts may be used intraoperatively to balance a TKA as they reliably measure compression forces in the medial and lateral tibial compartments during passive

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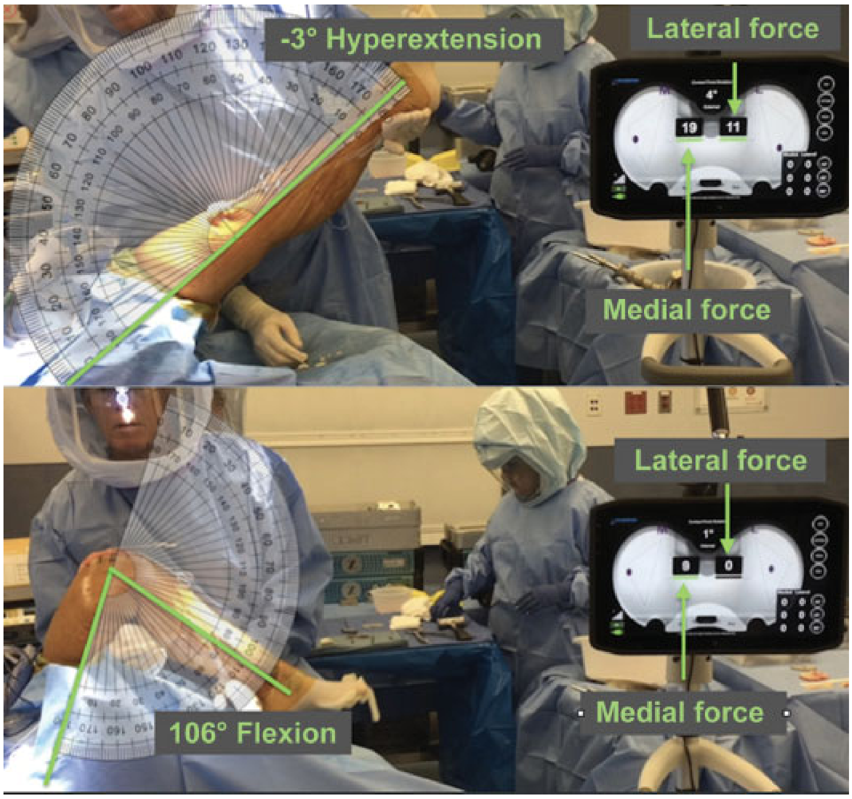

Fig. 1 A computer screen protractor superimposed on the limb is shown measuring the angle of maximum extension and flexion from video frames and the corresponding forces in the medial and lateral tibial compartments. Positioning of the hand on the posterior femur proximal to the popliteal fossa minimized the risk that positioning the limb limited maximum flexion.

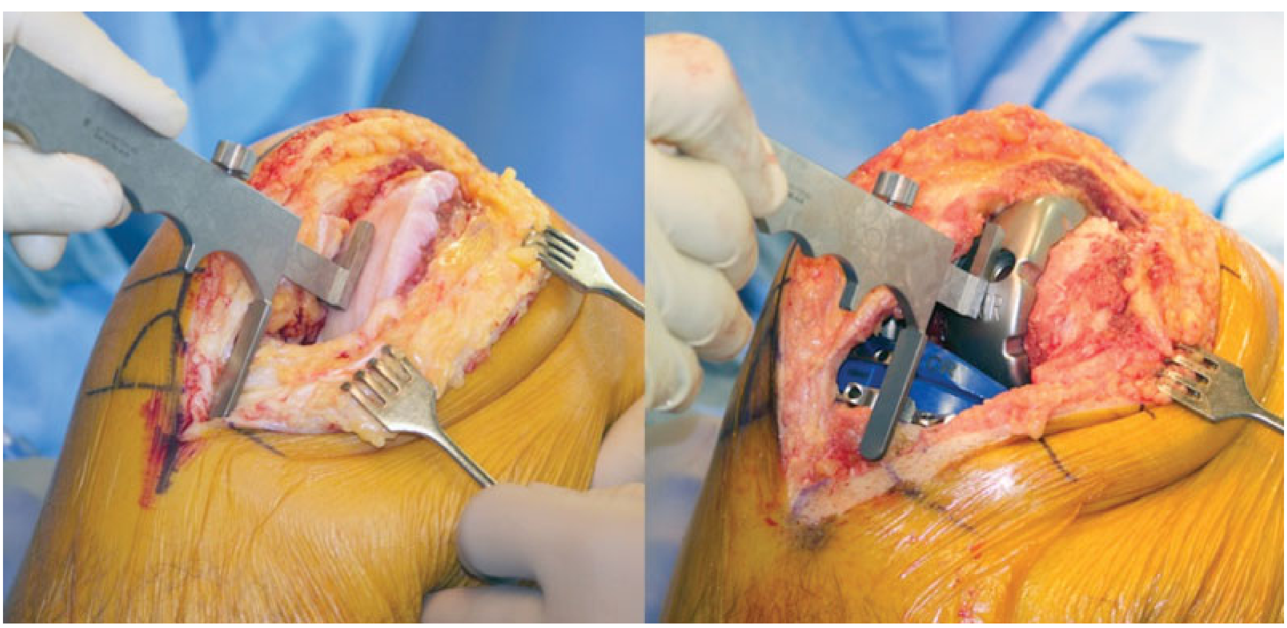

Fig. 2 Intraoperative photograph of a right knee in 90 degrees of flexion at the time of exposure (left) showing the caliper measurement of the anterior–posterior position of the tibia with respect to the worn distal medial femoral condyle (left). The flexion–extension angle of the tibial resection was adjusted until the caliper measurement of the anterior–posterior position of the tibia with respect to the distal medial condyle of the femoral component was 2 mm less than at the time of exposure (right). The measurement was 2 mm less to compensate for cartilage wear which averages 2 mm (right).[28]

flexion and extension.[16] A representative value for tibial force from 0 to 90 degrees of motion is the sum of the medial and lateral compartment forces averaged at 0, 45, and 90 degrees of flexion. In the native knee, the average tibial force is 20 ± 7 lb based on force transducer measurements provided by Verstraete et al in a personal communication.[17] A multicenter study reported that three fellowship trained orthopaedic surgeons judged a series of consecutive mechanically aligned TKAs as balanced after performing either measured resection or gap-balancing technique with navigation and ligament releases. When forces were measured after cementing the implant and choosing the insert thickness they reported an average tibial force of 112 ± 46 lb which is five times greater than those of the native knee.[18] A tibial compartment force that results in 13 lbs of tensile force in the ligamentous complex places the force-elongation curve in a region of high stiffness which indicates imbalance and over-tensioning of the knee.[19] Therefore, the intraoperative use of an instrumented tibial insert provides the surgeon with real-time feedback to lower compartment forces by fine-tuning implant positions and releasing ligaments which minimizes the risk of stiffness, tibial component overload, and insert wear.[16,20–24]

Because a 'balanced' TKA can have a tibial force five to six times greater than the native knee, and because a 13 lb tibial compartment force suggests over-tensioning of knee ligaments, the present study determined whether a TKA with an intraoperative tibial force greater than native has signs of stiffness as measured by a loss of extension, loss of flexion, and anterior translation of the tibia.

Materials and Methods

After institutional review board approval, a retrospective review was performed of patients who underwent primary kinematically aligned TKA with intraoperative measurements of the forces in the medial and lateral compartments. A total of 71 patients had primary kinematically aligned TKAs performed with intraoperative tibial compartment force measurements between July 2016 and November 2016 (►Table 1). A *post hoc* analysis compared patients in the present study with those in two representative studies of kinematically aligned TKAs and indicated no selection bias by showing no clinically significant differences in age, proportion of women, body mass index (BMI), preoperative extension, flexion, varus or valgus deformities, and the Oxford Knee Score.[25,26] The indications for TKA included disabling symptoms from the knee which had not resolved following conservative treatment, radiographic evidence of Kellgren–Lawrence Grade II to IV arthritic changes or osteonecrosis, any severity of varus or valgus deformity as measured when nonweight bearing with a goniometer and any severity of flexion contracture. Exclusion criteria included those undergoing a revision TKA and those with an inflammatory arthropathy.

All patients were treated with a posterior cruciate ligament (PCL) retaining (CR) primary TKA by a single surgeon using a midvastus approach (Vanguard CR, Zimmer Biomet, Warsaw, Indiana). Kinematic alignment was performed using a calipered technique with manual instruments without a soft-tissue release.[8,27–29] Five intraoperative quality assurance checks aligned the components to the restored joint line of the knee. The first minimized flexion of the femoral component by positioning the starting hole for the intramedullary positioning rod midway between the top of the intercondylar notch and aligning it parallel to the anterior femoral cortex.[30,31] The second set the femoral component relative to the native tibiofemoral articular surface using a caliper and adjusting the thickness of the distal and posterior femoral resections within ± 0.5 mm of the thickness of the condyles of the femoral component after compensating for cartilage wear and the bone cut.[8,27,28] The third set the rotation of the tibial compartment parallel to

Table 1 Comparisons of clinical characteristics and preoperative knee conditions and function for subjects in the present study and two representative studies of kinematically aligned tka with 3-year and 6-year follow-up[25,26]

Parameters	Present study ($n = 71$)	3-year study ($n = 215$)	6-year study ($n = 219$)	Significance (NS = nonsignificant)
Clinical characteristics				
Age (y)	70 ± 7[a]	69 ± 10[a]	74 ± 10[b]	$p < 0.0001$
Sex (male) *n* (%)	35 (49%)	87 (41%)	82 (39%)	NS ($p = 0.2575$)
Body mass index (kg/m^2)	29 ± 5	30 ± 5	31 ± 6	NS ($p = 0.0728$)
Preoperative knee conditions				
Knee extension (degree)	11 ± 7[a]	8 ± 8[b]	10 ± 8[a]	$p = 0.0031$
Knee flexion (degree)	111 ± 11	114 ± 13	113 ± 13	NS ($p = 0.2235$)
Valgus (−)/varus (+) deformity (degree)	2 ± 13[a]	−2 ± 8[b]	−1 ± 6[a, b]	$p = 0.0023$
Preoperative function				
Oxford Knee Score	23 ± 8[a]	20 ± 8[b]	18 ± 8[b]	$p < 0.0001$

Note: For each parameter, means annotated with a different letter ([a, b]) are significantly different at $p < 0.05$. Significance for continuous variables was determined with a single factor ANOVA (analysis of variance), means annotated with a different letter ([a, b]) are significantly different at $p < 0.05$ and differences determined with a post hoc Tukey's test. Significance for categorical variables was determined with a Fisher's exact test.

the anterior–posterior axis of the elliptically shaped lateral tibial plateau.[32] The fourth set, the tibial component relative to the varus–valgus angle of the native tibial joint line using a caliper to measure the thickness of the medial and lateral tibial condyles at the base of the tibial spines and adjusting the tibial resection until the varus–valgus laxity with trial components was negligible in full extension which replicates the laxity of the native knee in full extension.[27,33] Removal of posterior osteophytes without release of the posterior cruciate ligament allowed correction of a flexion contracture to full extension. Contractures of > 30 degrees occasionally required release of the posterior capsule from the femur but did not require additional resection of distal femoral bone. The final quality assurance check, performed with the knee in 90 degrees of flexion, adjusted the slope of the tibial component parallel to the native tibial joint line until: (1) the anterior position of the tibia with respect to the distal medial femoral condyle matched that of the knee at the time of exposure after compensating for cartilage wear and (2) the passive of internal-external rotation of the tibia approximated $\pm$ 14 degrees which replicates the laxity of the native knee (►**Fig. 2**).[8,27,33] Indicators of alignment, such as the femoral and tibial mechanical axes, the transepicondylar axis, and the border of the tibial tubercle are not used when performing kinematic alignment.[27] All components were cemented. The thickness of the tibial insert was selected and opened but not implanted at this stage.

An instrumented tibial insert that matched the thickness of the selected insert was placed in the cemented tibial baseplate (Verasense, Orthosensor Inc., www.orthosensor.com). The tablet screen that displayed the forces in the medial and lateral compartments in pounds was rotated away from the view of the surgeon. Towel clips were applied proximal and distal to the patella to close the extensor mechanism provisionally. One hand of the surgeon lifted the posterior thigh to flex the knee while the dorsum of the other hand supported the heel so as not to compress or rotate the limb. The knee was passively cycled from full extension to full flexion three times to precondition the knee. A video camera on a smartphone simultaneously recorded the forces on the tablet screen and the position of knee flexion during three cycles of passive movement.

For each cycle of passive motion with the implanted and 2 mm thicker insert, a computer screen protractor was superimposed on the limb and the video frames with the knee in 0, 45, and 90 degrees of flexion were selected (Protractor, 11.0, www.softlibs.com; ►**Fig. 1**). From each video frame, the forces in the medial and lateral tibial compartments were recorded. The sum of the average of the medial and lateral compartment forces at 0, 45, and 90 degrees of flexion represented the tibial force through a 90 degrees arc of motion.[24] The repeatability of force measurements is high as the intraclass correlation coefficient (ICC) ranged from 0.82 to 0.95 at full extension, 45, and 90 degrees of flexion for the medial and lateral compartments.[34] Patient-reported Oxford Knee Score and Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC) were obtained 6-month postoperatively.

Statistical Analysis

To quantify reproducibility, the intraclass correlation coefficient (ICC) was computed from measurements of the flexion angle of knee made on 10 randomly selected screenshots of the knee by three trained observers. A two-factor analysis of variance (ANOVA) with mixed effects computed the intraclass correlation coefficient. The first factor with three levels (observer 1, observer 2, and observer 3), was the fixed effect. The second factor with 10 levels (screenshots 1–10), was the random effect. An ICC value of 0.9 indicates excellent agreement and 0.75 to 0.90 indicates good agreement. The ICC was 0.0.9849

Continuous variables were reported as average $\pm$ standard deviation (SD), and categorical variables were reported as the number or percentage of patients. A Wilcoxon's rank-sum test determined whether the tibial force of the TKA with the implanted insert was different from those reported for the native knee.[17] A Wilcoxon's signed-rank test determined whether the tibial force, maximum extension, maximum flexion, and anterior–posterior position of the tibia of the TKA with the 2 mm thicker insert was different from the TKA with the implanted insert. Statistical software performed the computations (JMP Pro, 13.0, http://www.jmp.com). Significance was set at $p < 0.05$.

Results

Regarding the effect of insert thickness on tibial force, the tibial force for the implanted insert averaged 28 $\pm$ 17 lb (21 $\pm$ 17 lb in the medial compartment, 7 $\pm$ 8 lb in the lateral compartment) which was not different from the tibial force of 20 $\pm$ 7 lb (14 $\pm$ 7 lb in the medial compartment, 6 $\pm$ 3 lb in the lateral compartment) reported for those of the native knee ($p = 0.2387$).[17] For the 2 mm thicker insert, the tibial force averaged 50 $\pm$ 28 lb (39 $\pm$ 28 lb in the medial compartment, 11 $\pm$ 12 lb in the lateral compartment) which was 22 lb greater (18 lb in the medial compartment, 4 lb in the lateral compartment) than the TKA with the implanted insert ($p < 0.0001$).

Regarding the effect of tibial force on the signs of stiffness, a 30 lb increase in tibial force from those reported for the native knee caused a 3-degree loss in extension (from -2 ± 1 degrees of hyperextension to 1 $\pm$ 2 degrees of flexion contracture; $p < 0.0001$; ►**Fig. 3**), a 3-degree loss in flexion (from 113 $\pm$ 8 degrees to 110 $\pm$ 8 degrees; $p < 0.0001$; ►**Fig. 4**), and 3 mm of anterior translation of the tibia (from 14 $\pm$ 3 mm to 17 $\pm$ 3 mm; $p < 0.0001$; ►**Fig. 5**).

Regarding clinical outcome at 6-month post-operatively, the Oxford Knee Score averaged 40 $\pm$ 7 points (best 48, worst 0 points) and the WOMAC Index averaged 15 $\pm$ 15 points (best 0, worst 96 points).

Discussion

The goals of soft-tissue balancing a TKA are to lower the risks of stiffness and instability, restore extension and flexion of the native knee, and promote high knee function and patient satisfaction. The important findings of the present study

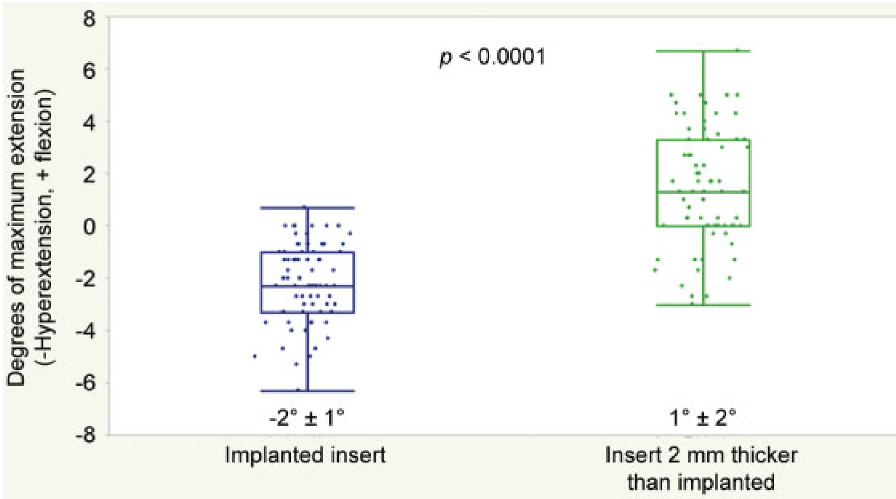

Fig. 3 Box and whisker plots show the distribution of maximum extension for each TKA with the implanted and 2 mm thicker insert. The 2 mm thicker insert increase the tibial force 30 lb greater than the native knee and caused a 3-degree loss in maximum extension, which is a sign the TKA is stiffer ($p < 0.0001$).

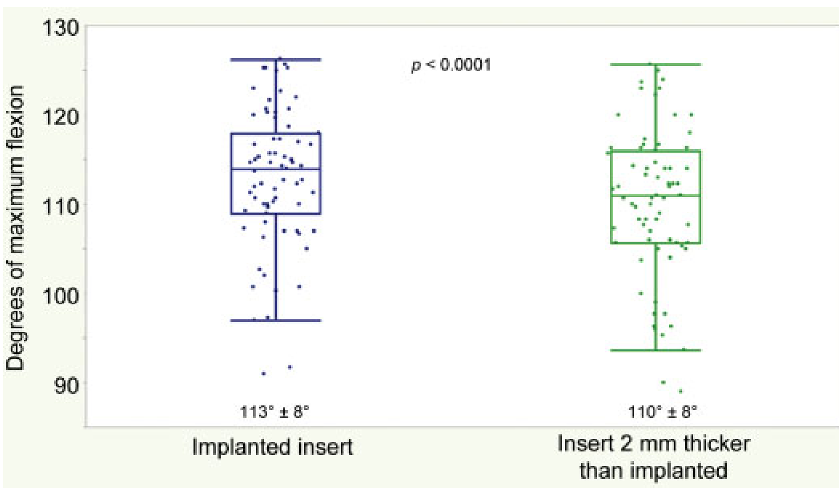

Fig. 4 Box and Whisker plots show the distribution of maximum flexion for each TKA with the implanted and 2 mm thicker insert. The 2 mm thicker insert increase the tibial force 30 lb greater than the native knee and caused a 3-degree loss in maximum flexion, which is a sign the TKA is stiffer ($p < 0.0001$).

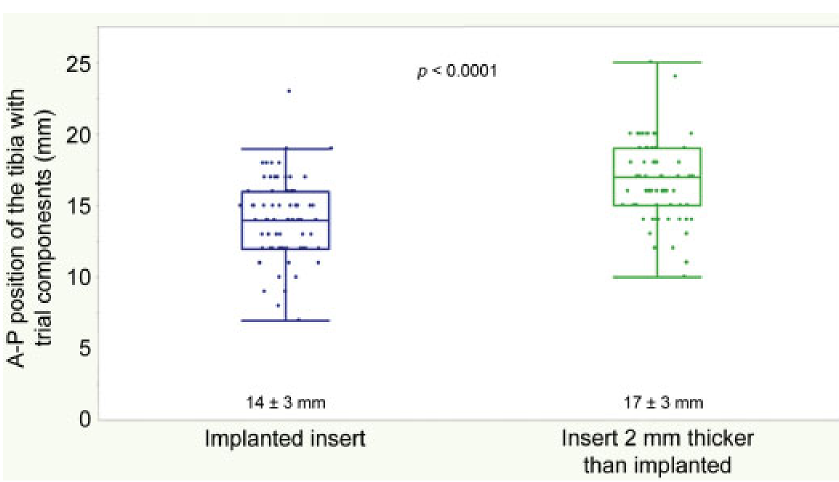

Fig. 5 Box and Whisker plots show the distribution of the anterior–posterior (A-P) position of the tibia with respect to the distal medial femoral condyle at 90 degrees of flexion with trial components for each TKA with the implanted and 2 mm thicker insert. The 2 mm thicker insert increased the tibial force 30 lb greater than the native knee and caused a 3 mm anterior translation of the tibia, which is a sign the TKA is stiffer ($p < 0.0001$).

were: (1) a kinematically aligned (KA) TKA with a tibial force 30 lb greater than those reported for the native knee had signs of stiffness as measured by a 3-degree loss of extension, a 3-degree loss of flexion, and a 3 mm anterior translation of the tibia at 90 degrees of flexion, and (2) a KA TKA with a tibial force comparable to the those of the native knee has physiological or native knee laxity.[35]

The native tibial force might be a good target for balancing a TKA.[17] In the present study, the surgeon was unaware of the intraoperative tibial compartment forces and yet inadvertently set the tibial force to match those of the native knee without a ligament release by adjusting the thickness of bone resections to restore native alignment using caliper measurements which are important quality assurance checks of the kinematic alignment technique. The calipered KA TKA is highly reproducible as the native left to right symmetry of the hip-knee-ankle angle, distal lateral femoral angle, and proximal medial tibial angle are restored in nearly all subjects with negligible risk of varus alignment of the tibial component with respect to the native tibial joint line.[36,37] With the tibial force in the TKA set to the native knee, patients reported high function as measured by the average 40 point Oxford Knee and 15 point WOMAC scores at 6 months.

A large increase in tibial force of 30 lb from native resulted from a small 2 mm distraction of the joint from use of an instrumented insert 2 mm thicker than implanted. The highly sensitive effect of joint distraction on tibial force can be understood by studying the interrelationship between the laxity of the native knee and the load–elongation curve of the ligamentous sleeve around the knee and the PCL. Distraction of ligaments generates a load–elongation curve comprised of two regions. The toe region is characterized by a nonlinear increase in stiffness that terminates when the tensile load removes the collagen crimp. The linear region is characterized by a linear increase in stiffness that terminates when the tensile load stretches the collagen fibers to the point of rupture. A tensile force increase of approximately 11 to13 lb transitions the curve from the toe to the linear region indicating over-tensioning.[19] Hence, balancing a TKA to the tibial force of the native knee reduces the risks of over-tensioning the ligamentous sleeve through a 90 degrees arc of motion and the undesirable effects of loss of extension, loss of flexion, and anterior translation of the tibia.

Two limitations should be discussed that might affect the generalization of the findings. First, the ease of setting the force target to that of the native knee was achieved with calipered kinematic alignment and PCL retaining implants and might not be generalizable to surgical instrumentation that does not use caliper measurements of resections (robotics, navigation, patient specific instrumentation), PCL substituting implant designs, and different alignment strategies (i.e., mechanical alignment with measured resection or gap-balancing). As one example, the tibia slope was fine-tuned using the caliper measurement of the anterior–posterior position of the tibia with respect to the distal medial femoral condyle with trial components until the position of the tibia matched that of the knee at the time of exposure after compensating for cartilage wear at 90 degrees of flexion (►Fig. 1).[28] This step restored the slope of the tibial component to those of the native tibia, thereby re-establishing the native trapezoidal gap, resting length, and tension in the ligamentous sleeve around the knee and the PCL at 90 degrees of flexion. Restoring the native slope lowers the risk of tibial component loosening minimizes posterior edge loading and wear of the tibial insert, and helps center the femoral component on the tibial insert.[8,13,14,27,38] Using these caliper measurements are unreliable in setting the tibial slope with PCL substituting implant designs because the cam-mechanism engagement of the post of the tibial insert in the femoral intercondylar box eliminates the interaction between the tibial slope and ligamentous sleeve around the knee and the PCL. Second, the use of instrumented tibial inserts that differed by 2 mm in thickness were used in the present study, and the use of inserts that differ by 1 mm in thickness might enable better refinement of the target for the tibial force when balancing a TKA.

In summary, the target for setting the tibial force when balancing a mechanically aligned TKA has been controversial.[4,5,19,24,34,39] In contrast, the target when performing calipered KA TKA is to adjust component positions without ligament release until the tibial force matches the native knee as a tibial force 30 lb greater than native knee causes a loss of extension, loss of flexion, and anterior translation of the tibia at 90 degrees of flexion.

Conflict of Interest
None.

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