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Posterior-stabilized versus mid-level constraint polyethylene components in total knee arthroplasty

A BIOMECHANICAL CADAVERIC ANALYSIS OF LAXITY AND COLLATERAL LIGAMENT FORCES

C. A. Kahlenberg,
E. E. Berube,
W. Xiang,
J. E. Manzi,
H. Jahandar,
B. P. Chalmers,
M. B. Cross,
D. J. Mayman,
T. M. Wright,
G. H. Westrich,
C. W. Imhauser,
P. K. Sculco

From Hospital for Special Surgery, New York, New York, USA

Aims

Mid-level constraint designs for total knee arthroplasty (TKA) are intended to reduce coronal plane laxity. Our aims were to compare kinematics and ligament forces of the Zimmer Biomet Persona posterior-stabilized (PS) and mid-level designs in the coronal, sagittal, and axial planes under loads simulating clinical exams of the knee in a cadaver model.

Methods

We performed TKA on eight cadaveric knees and loaded them using a robotic manipulator. We tested both PS and mid-level designs under loads simulating clinical exams via applied varus and valgus moments, internal-external (IE) rotation moments, and anteroposterior forces at 0°, 30°, and 90° of flexion. We measured the resulting tibiofemoral angulations and translations. We also quantified the forces carried by the medial and lateral collateral ligaments (MCL/LCL) via serial sectioning of these structures and use of the principle of superposition.

Results

Mid-level inserts reduced varus angulations compared to PS inserts by a median of 0.4°, 0.9°, and 1.5° at 0°, 30°, and 90° of flexion, respectively, and reduced valgus angulations by a median of 0.3°, 1.0°, and 1.2° ($p \leq 0.027$ for all comparisons). Mid-level inserts reduced net IE rotations by a median of 5.6°, 14.7°, and 17.5° at 0°, 30°, and 90°, respectively ($p = 0.012$). Mid-level inserts reduced anterior tibial translation only at 90° of flexion by a median of 3.0 millimetres ($p = 0.036$). With an applied varus moment, the mid-level insert decreased LCL force compared to the PS insert at all three flexion angles that were tested ($p \leq 0.036$). In contrast, with a valgus moment the mid-level insert did not reduce MCL force. With an applied internal rotation moment, the mid-level insert decreased LCL force at 30° and 90° by a median of 25.7 N and 31.7 N, respectively ($p = 0.017$ and $p = 0.012$). With an external rotation moment, the mid-level insert decreased MCL force at 30° and 90° by a median of 45.7 N and 20.0 N, respectively ($p \leq 0.017$ for all comparisons). With an applied anterior load, MCL and LCL forces showed no differences between the two inserts at 30° and 90° of flexion.

Conclusion

The mid-level insert used in this study decreased coronal and axial plane laxities compared to the PS insert, but its stabilizing benefit in the sagittal plane was limited. Both mid-level and PS inserts depended on the MCL to resist anterior loads during a simulated clinical exam of anterior laxity.

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Correspondence should be sent to Cynthia A Kahlenberg; email: KahlenbergC@HSS.EDU

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Introduction

Up to 20% of patients who undergo total knee arthroplasty (TKA) are dissatisfied with the outcome.[1,2] The feeling of knee instability is a common cause of patient dissatisfaction, which often leads to revision surgery.[3-6] Surgical factors including bone resection techniques, ligament balancing, and implant design all contribute to TKA stability and are active areas of research to improve outcomes.[6,7]

Regarding implant design, many TKA systems have introduced mid-level constraint tibial inserts to manage increased intraoperative coronal plane laxity that cannot be resolved using standard ligament balancing techniques and a posterior-stabilized (PS) insert.[8-10] Mid-level inserts are useful for patients with severe deformity and ligamentous laxity and have a low incidence of post-TKA instability or aseptic loosening at mid-t erm follow-up.[8] Mid-level constraint varies by manufacturer but it is typically defined as an insert that has a wider, taller post than a PS insert, articulates with a primary femoral component, and resists coronal plane moments via post contact with the femoral box.[8-11] Despite increased utilization of mid-level constraint, limited objective biomechanical data guiding rationale for their use are available.

While mid-level inserts provide constraint in the coronal plane,[8,9] achieving stability requires consideration of kinematics and ligament loading in multiple planes.[6,12,13] Unfortunately, the impact of PS and mid-level inserts on sagittal plane (anteroposterior; AP) laxity, axial plane (internal and external rotation; IE) laxity, and collateral ligament forces are not well understood. For example, excessive anterior tibial translation (ATT) of the tibia in midflexion may produce recurrent knee effusions, a sensation of 'giving way', difficulty with stair descent, and pain in the anterior periarticular soft-tissues.[14] Moreover, in PS TKA, loading of the collateral ligaments is not well understood despite their importance in maintaining knee stability in the absence of the resected cruciate ligaments.[15-20]

Our goal was to quantify the impact of a mid-level constraint tibial insert on coronal, sagittal, and axial plane laxities and collateral ligament loading compared to a PS insert design. We asked two questions: 1) Does laxity in the coronal, axial, and sagittal planes differ between a PS and mid-level insert with simulated clinical exams under minimal compressive load?; and 2) How much force is carried by the medial and lateral collateral ligaments (MCL and LCL) in these three planes with PS and mid-level tibial inserts?

Methods

Surgery. We performed TKAs on eight independent cadaveric legs (five male, three female; mean age 63 years (standard deviation (SD) 12; 47 to 79); all left). All cadavers were fresh frozen, stored at -20°C, and then thawed at room temperature for 24 hours prior to TKA installation. Axial CT scans were then performed with 0.625 mm slice thickness and 0.5 × 0.5 mm^2 in-plane resolution (Biograph mCT; Siemens, USA). The CT scans, together with medical history, physical examination, and direct inspection were used to ensure the absence of chondral, ligament, or meniscal injury, prior surgery, osteoarthritis, gross limb malalignment, and flexion contracture. One implant system (Persona; Zimmer Biomet, USA) was used. In this design, the mid-level insert has identical articular geometry as the PS insert but has a wider, taller post (Figure 1).

Subsequent TKA surgery utilized the measured resection technique targetting neutral mechanical alignment via manual instrumentation through a medial parapatellar approach. A typical dissection was performed with subperiosteal release of the deep MCL as is characteristic given the neutral limb alignment of our cohort.[21] After removal of the cruciate ligaments, a standard distal femoral resection (10 mm from the distal medial femoral condyle) was performed. A tibial cutting jig was placed between the middle and medial thirds of tibial tubercle, in line with the centre of the ankle joint, and with 3° of posterior slope. Nine millimetres of bone was measured from the lateral tibial plateau to set resection depth. Femoral sizing was conducted, and a 4-in-1 cutting jig was aligned with the transepicondylar and anteroposterior axes. Trialling was performed, and the PS insert size was chosen based on examination by a fellowship-trained arthroplasty surgeon as would be carried out in the operating room. A partial release of the posterior capsule was utilized to achieve full extension in two knees. No other releases were performed.

Robotic testing. After TKA installation, specimens were prepared for robotic testing (ZX165U; Kawasaki Robotics, USA). First, the femur and tibia were sectioned 15 cm proximal and distal to the joint line, respectively, and set in potting cement (Bondo; 3M, USA). Subsequently, the potted femur was rigidly fixed to the ground through a pedestal, and the tibia was fixed to the robotic manipulator at full extension (Figure 2).[22] The robot end effector was instrumented with a six-axis force/torque sensor (Theta; ATI Industrial Automation, USA). We performed repeated measures testing of the PS and mid-level inserts and alternated the order of insert testing from knee-to-knee to account for bias due to ligament stretching.

Next, the knee coordinate system was defined. Tibial rotations and translations relative to the femur were described using a coordinate system based on geometrical features of the tibial tray and femoral component (Supplementary Material, Knee Coordinate System Definition).[23] Specifically, the axis of internal-external (IE) rotation was oriented perpendicular to the tray, and the AP axis was aligned parallel to both the tibial tray and to the femoral box and centred within the tibial tray. Varus

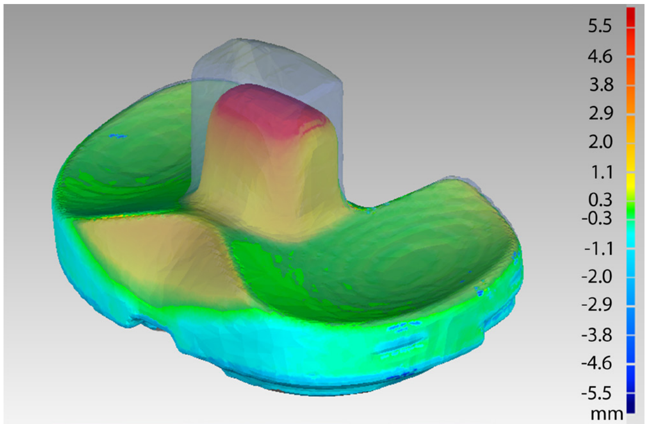

Fig. 1

Overlay of 3D scans of the posterior-stabilized insert (multicolored) and mid-level tibial insert (semitransparent) (Persona; Zimmer Biomet, USA). Inserts were imaged via CT (Biograph mCT; Siemens, Germany) and overlayed using 3D shape matching (Geomagic Wrap; 3D Systems, USA). The heat map indicates differences in insert geometries in millimetres. Hotter colors indicate distances and locations where the PS insert geometry is smaller than the mid-level insert geometry. The maximum difference at the articular surface was < 0.1 mm.

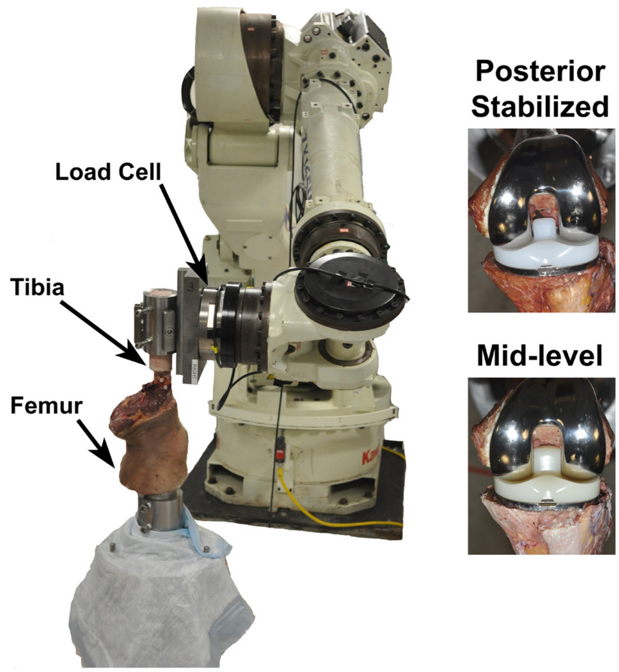

Fig. 2

Robotic manipulator with six-axis force/torque sensor (load cell) with cadaveric knee specimen mounted in place. Each specimen was tested with the posterior-stabilized and mid-level tibial inserts (Persona; Zimmer Biomet, USA) shown to the right.

and valgus (VV) and IE moments and AP forces were applied, and the resulting rotations and translations were measured about and along these axes.[22,24]

After defining the coordinate system, the knee was flexed from 0° to 90° in 1° increments under 10 N of compression with forces and moments in the remaining directions minimized. Convergence tolerances for the loading algorithms were resultant forces and moments within 5 N and 0.4 Newton-metres (Nm), respectively, of the target loads.[25]

Subsequently, the collateral and capsular tissues were preconditioned at full extension via five cycles each of varus and valgus loading to 6 Nm in each direction. After preconditioning, laxity assessments were conducted. All assessments were carried out under minimal compressive load (10 N) to emphasize the contribution of the collateral ligaments,[11] and since surgeons focus on insert selection and soft-tissue tensioning in the operative setting by examining the knee with minimal compressive loads. Coronal laxity was assessed by measuring varus and valgus angulations (in degrees) in response to varus and valgus moments of 6 Nm with the knee at 0° (full extension), 30° (midflexion), and 90° of flexion, as in previous work.[11] Anterior laxity was assessed by quantifying ATT relative to the fixed femur with 30 N anterior force applied at 0° and 30° of flexion and a 20 N anterior force applied at 90°. The 30 N anterior force was selected because it avoided tibial dislocation and excessive loading of the collateral ligaments. ATT was referenced to an applied posterior force of 20 N to ensure contact between the femoral cam and tibial post. IE laxity was assessed at the same three flexion angles by quantifying the net IE tibial rotation relative to the femur under applied moments of ± 5 Nm. Finally, coupled tibial axial rotation was defined as the net change in IE rotation with the applied anterior force.[16,26]

Finally, serial ligament sectioning and the principle of superposition were used to determine the resultant in situ MCL and LCL forces at the peak applied VV, anterior, and IE loads.[27] To calculate ligament force, the tibial insert was removed from the knee joint and then tibiofemoral kinematics corresponding to each knee condition were repeated immediately before and after sectioning each ligament. The collaterals were identified and sectioned at the joint line. Ligament force was then calculated as the resultant of the vector difference in force measured across the knee before and after sectioning each ligament. The order of sectioning and of replaying the kinematics was randomized. When replaying the kinematics, the velocity of the robot averaged 0.8 mm/second in the AP direction and 0.13°/second in the varus and valgus directions.

This study was approved by our organization's institutional review board.

Statistical analysis. We conducted a power analysis based on work by Luyckx et al,[28] who reported a mean of 7.5° (SD 1.9°) of coronal laxity at 90° of flexion. Using these data and defining a minimal clinically significant difference of 2.5° revealed that a sample size of seven knees would achieve 80% power to detect a difference between

Table I. Summary of kinematic outcome measurements for posterior-stabilized and mid-level tibial inserts.

			Median (IQR)		
Applied load	**Outcome measure**	**Flexion angle (°)**	**PS**	**Mid-level**	**p-value***
Varus 6 Nm	Varus angulation (°)	0	2.0 (1.2 to 2.7)	1.5 (0.7 to 2.1)	0.017
		30	4.2 (1.7 to 4.9)	1.9 (1.3 to 2.9)	0.018
		90	3.5 (3.1 to 6.8)	2.9 (2 to 4.4)	0.017
Valgus 6 Nm	Valgus angulation (°)	0	2.2 (1 to 3.2)	1.9 (0.8 to 2.8)	0.020
		30	3.2 (2.0 to 4.0)	2.3 (1.3 to 3.1)	0.027
		90	3.4 (2.7 to 4.2)	2.4 (1.8 to 2.8)	0.025
Anterior 30 N	Anterior translation (mm)	0	3.1 (2.3 to 3.4)	2.4 (1.8 to 3.4)	0.063
		30	9.7 (5.4 to 20)	7.0 (3.5 to 16.9)	0.050
Anterior 20 N		90	5.2 (4.6 to 5.9)	3.3 (0.9 to 5.2)	0.036
IE ± 5 Nm	Axial rotation (°)	0	19.3 (10.7 to 27.8)	13.1 (7.5 to 18.4)	0.012
		30	30.2 (22.1 to 47.3)	15.8 (12.1 to 22.9)	0.012
		90	34.5 (31.3 to 40.7)	18.7 (12.8 to 26.6)	0.012

*Wilcoxon signed-rank test.
IE, internal-external rotation; IQR, interquartile range; N, Newton; Nm, Newton-metres; PS, posterior-stabilized.

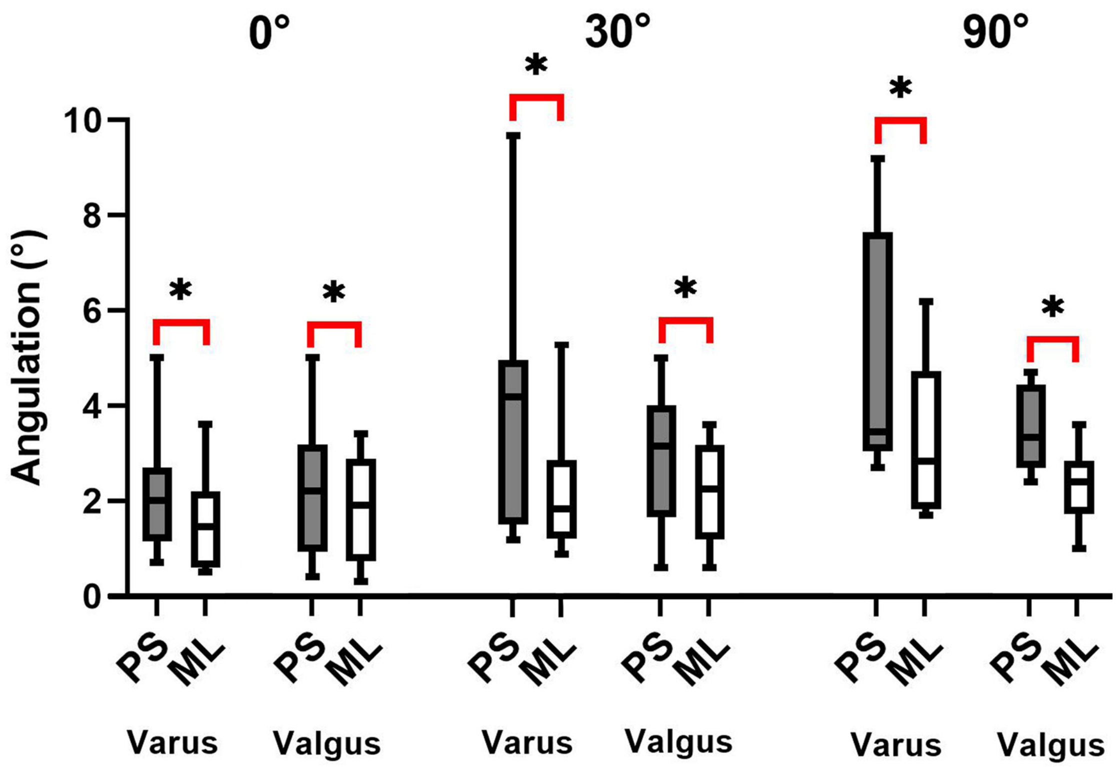

Fig. 3

Varus and valgus angulations in degrees in response to varus and valgus moments of 6 Nm at 0°, 30°, and 90° of flexion for posterior-stabilized (PS) and mid-level (ML) tibial inserts. Boxes and whiskers correspond to the quartiles and 5th and 95th percentiles, respectively. The horizontal black line within each box is the median. *$p < 0.05$.

groups with two-sided significance level (α) of 0.050 in a repeated measures study design.

Our data were not normally distributed as determined via Kolmogrov-Smirnov tests ($p < 0.05$). Therefore, all outcome measures were reported as medians and interquartile ranges (IQRs). Varus and valgus angulations, ATT, IE rotation, coupled axial rotation, and collateral ligament forces were compared across PS and mid-level inserts via individual Wilcoxon signed-rank tests. Signficance was set at $p < 0.05$.

Results

Regarding our first research question, the mid-level constraint insert reduced varus angulation by a median of 0.4° (IQR 0.1 to 0.8), 0.9° (IQR 0.4 to 2.0), and 1.5°

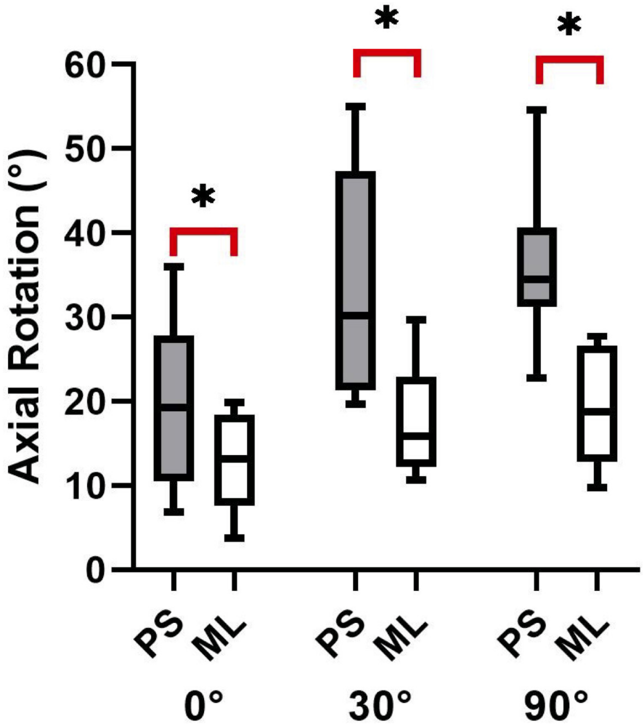

Fig. 4

Net internal-external (axial) rotation in degrees of the tibia in response to an applied moment of ± 5 Newton-metres at 0°, 30°, and 90° of flexion for posterior-stabilized (PS) and mid-level (ML) tibial inserts. Boxes and whiskers correspond to the quartiles and fifth and 95th percentiles, respectively. The horizontal black line within each box is the median. *p < 0.05.

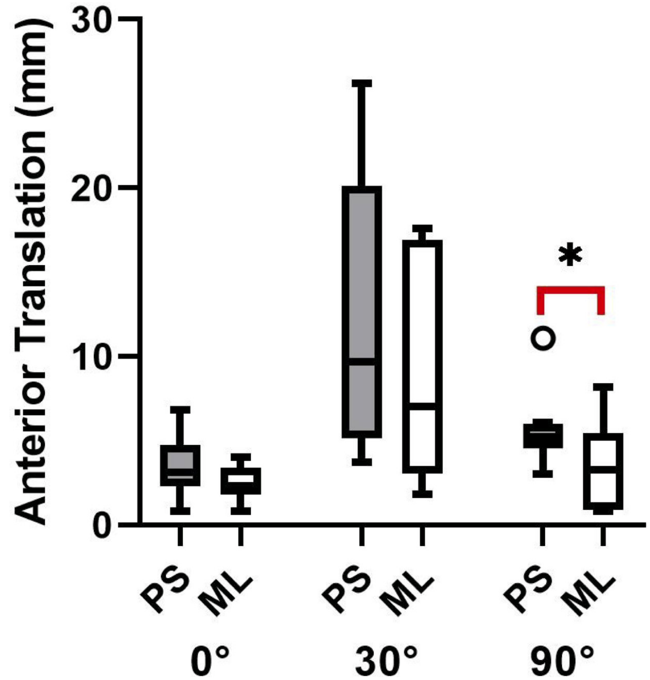

Fig. 5

Anterior tibial translation in miilimeters (mm) in response to a 30 N anterior force at 0° and 30° of flexion and a 20 N anterior force at 90° for posterior-stabilized (PS) and mid-level (ML) tibial inserts. Boxes and whiskers correspond to the quartiles and fifth and 95th percentiles, respectively. The horizontal black line within each box is the median. Circles indicate outliers. *p < 0.05.

(IQR 0.2 to 2.0) at 0°, 30°, and 90° of flexion, respectively ($p \leq 0.018$ for all comparisons; Table I; Figure 3). Similarly, the mid-level constraint reduced valgus angulation by a median of 0.3° (IQR 0.2 to 0.5), 1.0° (IQR 0.4 to 1.3) and 1.2° (IQR 0.4 to 1.8) at 0°, 30°, and 90°, respectively ($p \leq 0.027$ for all comparisons; Table I; Figure 3). In the axial plane, the mid-level inserts reduced net IE rotations by 5.6° (IQR 3.2 to 9.3), 14.7° (IQR 9.0 to 21.2), and 17.5° (IQR 13.0 to 19.7) at 0°, 30°, and 90°, respectively ($p = 0.012$ for all comparisons) (Table I, Figure 4). In the sagittal plane, knees with the mid-level insert showed less ATT than the PS insert; however, the decrease was only statistically significant at 90°of flexion, with a median reduction of 3.0 mm (IQR 0.9 to 3.7) ($p = 0.036$) (Figure 5). With the applied anterior tibial load, the mid-level insert decreased coupled axial rotation at 30° and 90° by a median of 2.2° (IQR 1.7 to 4.2) ($p = 0.012$) and 4.1° (IQR 3.0 to 6.5) ($p = 0.025$), respectively (Figure 6).

Regarding our second research question, under an applied varus moment the mid-level insert significantly decreased LCL force compared to the PS insert by a median of 4.4 N (IQR 1.8 to 8.6), 22.3 N (IQR 13.8 to 30.2), and 32.1 N (IQR 11.4 to 37.7) at 0°, 30°, and 90° of flexion, respectively ($p \leq 0.036$ for all comparisons). In contrast, the mid-level insert did not reduce MCL force with an applied valgus moment (Table II, Figure 7). With an applied internal rotation moment, the mid-level insert significantly decreased LCL force at 30° and 90° of flexion by a median of 25.7 N (IQR 15.1 to 40.0) and 31.7 N (IQR 8.8 to 48.7), respectively ($p \leq 0.017$ for all comparisons) (Table II). With an applied external rotation moment, the mid-level insert significantly decreased MCL force at 30° and 90° by a median of 45.7 N (IQR 26.4 to 82.4) and 20.0 N (IQR 6.7 to 50.0), respectively ($p \leq 0.017$ for all comparisons). With an applied anterior load, MCL and LCL forces showed no statistical differences between PS versus mid-level inserts at both 30° and 90° (Figure 8).

Discussion

Mid-level constraint inserts reduced varus, valgus, and IE rotational laxities compared to PS inserts with a smaller reduction in varus and valgus (median reductions ≤ 1.2° in valgus and ≤ 1.5° in varus) compared to axial rotation (median reductions ≤ 11.9°) (Table I). Mid-level inserts had minimal effect on AP laxity. The minor decreases in ATT are probably due to the observed reduction in coupled axial rotation. Mid-level inserts decreased LCL forces under a varus moment, but they did not reduce MCL forces under a valgus moment, likely because valgus angulations were

Table II. Summary of measured ligament forces for posterior-stabilized and mid-level tibial inserts.

			Median (IQR)		
Applied load	**Ligament force (N)**	**Flexion angle (°)**	**PS**	**Mid-level**	**p-value***
Varus 6 Nm	LCL	0	45 (22 to 81)	40 (18 to 61)	0.036
		30	63 (46 to 75)	40 (22 to 53)	0.017
		90	40 (36 to 54)	8 (3 to 17)	0.012
Valgus 6 Nm	MCL	0	69 (56 to 112)	49 (40 to 110)	0.327
		30	82 (69 to 115)	70 (46 to 105)	0.123
		90	55 (52 to 75)	50 (46 to 69)	0.161
Anterior 30 N	LCL	0	13 (3 to 30)	13 (2 to 26)	0.779
		30	9 (5 to 13)	6 (3 to 13)	0.263
Anterior 20 N		90	6 (2 to 6)	1 (0 to 2)	0.093
Anterior 30 N	MCL	0	19 (5 to 59)	26 (7 to 82)	0.017
		30	47 (30 to 72)	44 (29 to 73)	0.401
Anterior 20 N		90	10 (1 to 27)	12 (9 to 37)	0.050
Internal rotation 5 Nm	LCL	0	38 (8 to 50)	17 (6 to 27)	0.093
		30	37 (23 to 48)	2 (1 to 18)	0.017
		90	38 (13 to 56)	1 (1 to 7)	0.012
Internal rotation 5 Nm	MCL	0	57 (31 to 94)	35 (19 to 103)	0.484
		30	70 (37 to 113)	60 (34 to 89)	0.263
		90	39 (33 to 69)	19 (5 to 58)	0.017
External rotation 5 Nm	LCL	0	42 (17 to 78)	31 (12 to 47)	0.012
		30	28 (10 to 68)	20 (9 to 49)	0.093
		90	2 (1 to 4)	2 (1 to 3)	0.327
External rotation 5 Nm	MCL	0	45 (23 to 106)	31 (7 to 101)	0.208
		30	102 (88 to 123)	48 (3 to 84)	0.012
		90	67 (53 to 78)	41 (22 to 62)	0.017

*Wilcoxon signed-rank test.
IQR, interquartile range; LCL, lateral collateral ligament; MCL, medial collateral ligament; Nm, Newton-metres; PS, posterior-stabilized.

lower and therefore not as dependent on the tibial post (Figure 3). The mid-level insert also decreased collateral ligament loads with applied IE moments (Table II). Finally, the mid-level insert did not decrease the forces on the collateral ligaments with an anterior applied load (Figure 8). Importantly, the MCL was the primary ligamentous restraint to ATT in midflexion for both inserts (Table II). The key clinical message of this study is that since mid-level inserts are often selected intraoperatively in the setting of lax collateral ligaments for coronal stability, surgeons must be aware that mid-level inserts still depend on the MCL for anterior stability. Therefore, mid-level inserts would confer limited anterior restraint in the setting of MCL insufficiency, which, we speculate, may contribute to patient perceptions of knee instability.

Biomechanical data describing the impact of mid-level inserts on laxity and ligament loading are limited. In a robotic study of a constrained condylar knee (CCK) design, Wang et al[11] demonstrated varus angulations that increased from an average of 1.0° in extension to 1.5° at 90° of flexion and valgus angulation that increased slightly from 1.0° in extension to 1.7° in flexion. Our coronal plane testing of the mid-level insert also showed increasing VV angulations with increasing knee flexion and, as expected, showed greater varus and valgus laxity compared to the previously reported data for the CCK design (Table I). The net VV angulations of the mid-level inserts in our study were also larger than the manufacturer-reported 1.5°.[9] This discrepancy could be due to differences in testing conditions, which were not specified by the manufacturer; it highlights the importance of rigorously describing testing parameters such as the applied loads, coordinate system definitions, and allowable directions of tibiofemoral motion to enable comparison of implant behavior.

Mid-level inserts reduced IE laxity to a greater extent than VV laxity (Table I). We speculate that the increased axial constraint may have implications for aseptic loosening as the reduced motions could lead to increased loading at the fixation interface. Fortunately, this concern has not manifested in early clinical outcome studies of inserts with mid-level constraint.[8,10]

Our findings call into question the ability of mid-level inserts to address laxity in the sagittal plane. The mid-level insert used in this study, which has an identical articular surface profile as the PS insert (Figure 1), decreased ATT only at 90° of flexion by a median of 3 mm (Figure 5). Similar to a CCK insert,[11] this decrease in ATT is likely related to the reduced coupled axial rotation caused by increased conformity between the femoral box and the

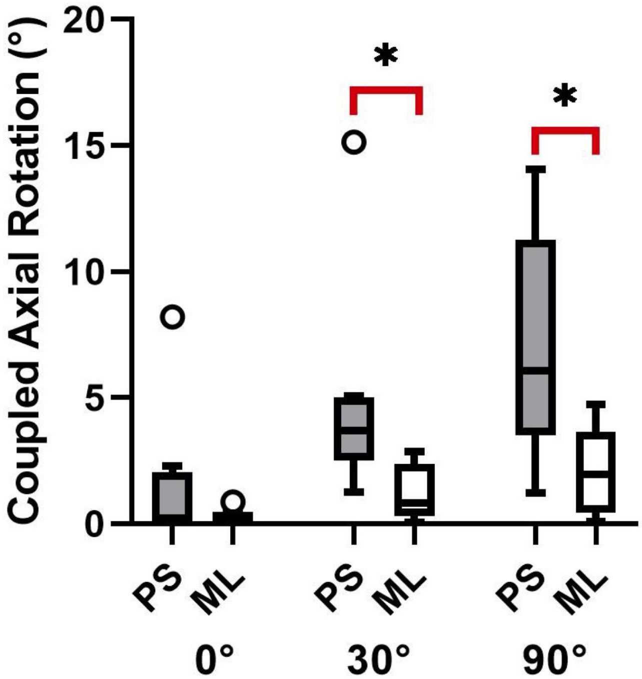

Fig. 6

Magnitude of coupled axial rotation in degrees during anteroposterior testing in response to a 30 N anterior force at 0° and 30° of flexion and a 20 N anterior force at 90° for posterior-stabilized (PS) and mid-level (ML) tibial inserts. Boxes and whiskers correspond to the quartiles and fifth and 95th percentiles, respectively. The horizontal black line within each box is the median. Circles indicate outliers. *$p < 0.05$.

wider, taller tibial post in the mid-level compared to the PS insert (Figure 6). However, we speculate that the additional anterior restraint afforded by the mid-level insert is likely inadequate to prevent instability. Clinically, in cases of MCL laxity, a surgeon choosing a mid-level insert should be aware that although the increased constraint could decrease laxity in the coronal and axial planes, the knee will still be left with increased ATT given the lax condition of the MCL. Given the dual role of the MCL in resisting coronal and sagittal loading in PS TKA, future investigation in mid-level polyethylene designs should also address AP laxity, particularly in midflexion.

Under applied VV moments, the mid-level insert offloaded the LCL with varus but not the MCL with valgus (Figure 7). This finding may be related to our coronal plane laxity data. Specifically, the maximum varus angulation for the PS insert was up to 94% greater than the maximum valgus angulation at 30° of flexion (9.7° varus vs 5.0° valgus) (Figure 3). Thus, the MCL likely engages (i.e. carries load) earlier with valgus loading than the LCL does with varus loading. This earlier engagement of the MCL likely causes it to carry load before the tibial post contacts the femoral box, thereby preventing the post from offloading the MCL. In contrast, the larger varus angulations enable the post and box to make contact and to share load with the LCL.

In the sagittal plane, the mid-level insert did not offload the collateral ligaments compared to the PS insert. The collateral ligaments, primarily the MCL, carried high forces at both 30° (midflexion) and 90° with both inserts (Table II). We speculate that this finding has important implications for using mid-level inserts for multiplanar ligamentous laxity, as this insert may not provide the desired sagittal plane constraint, potentially contributing to symptomatic flexion or mid-flexion instability and to postoperative discomfort around the MCL. The MCL of the replaced knee carries several times greater force than MCL in the native knee with an applied anterior load in midflexion.[29,30] We speculate that increased loading of the MCL following TKA could contribute to the commonly observed clinical scenario in which the MCL ‘stretches out’ over time, leading to a patient’s perception that the TKA does not feel ‘normal’, potentially contributing to patient dissatisfaction.

Regarding limitations, our study evaluated the PS and mid-level inserts of only one commercial implant system. Variations in PS and mid-level designs among manufacturers, including designs with taller posts and with single radius congruent designs, could limit the broader applicability of our results. Studies are needed to determine the extent to which our findings apply to other PS TKA designs. In addition, our study was performed in a cadaveric model without an extensor mechanism or hamstring forces. Thus, our study focused on the stabilizing role of the passive restraints (i.e. articular surfaces and ligaments). We also used minimal compressive load to simulate the intraoperative testing scenario, which maximizes the contribution of the soft-tissues to joint stability and minimizes the role of the bearing surfaces. Also, mechanical cutting jigs were used to implant the knee prosthesis with neither robotic assistance nor computer navigation, which reflects the most common clinical scenario. This approach likely increased variability in ligament balance among specimens. In addition, midflexion testing was limited to 30° of flexion to reduce the number of loading cycles and to mitigate soft-tissue stretching. We focused on this flexion angle because large increases in frontal plane laxity occur in early midflexion with PS TKA,[28,31] and our surgeon team prefers this angle of intraoperative assessment. Finally, testing was performed on knees with intact collateral ligaments, which differs from the clinical setting in which mid-level inserts are most used.

Mid-level inserts decreased coronal and axial laxities under loads simulating a clinical knee exam, but they were less effective in reducing sagittal plane laxity, particularly in midflexion. Thus, surgeons should be aware that mid-level inserts provide axial and coronal restraint with the potential to offload the collateral ligaments; however, they are not as effective in resisting anterior loads in the

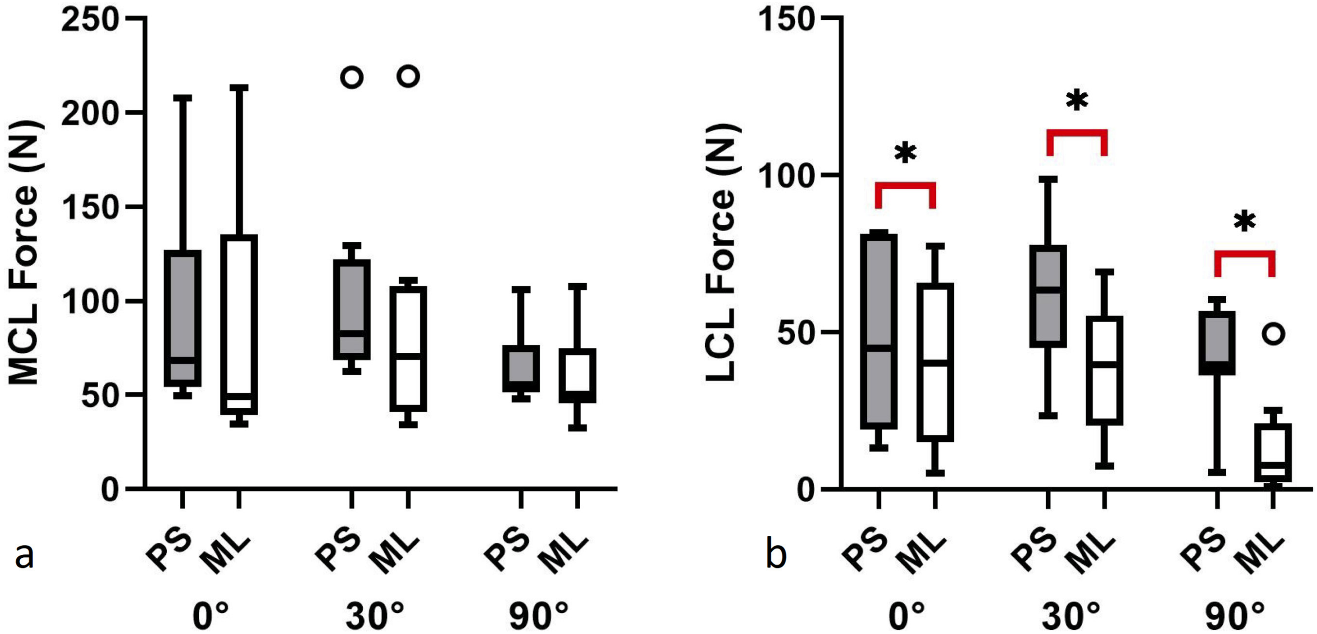

Fig. 7

a) Medial collateral ligament (MCL) force in Newtons (N) and b) lateral collateral ligament (LCL) force in response to applied moments of 6 Nm valgus and 6 Nm varus, respectively, at 0°, 30°, and 90° of flexion for posterior-stabilized (PS) and mid-level (ML) tibial inserts. Boxes and whiskers correspond to the quartiles and fifth and 95th percentiles, respectively. The horizontal black line within each box is the median. Circles indicate outliers. *p < 0.05.

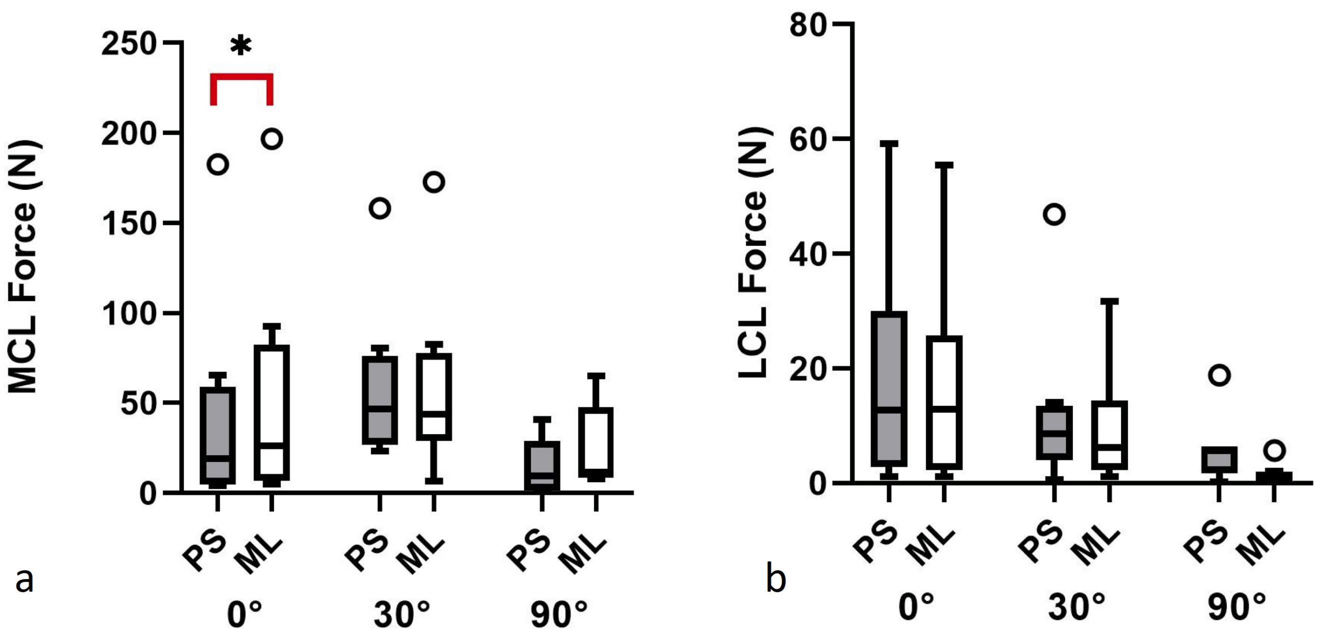

Fig. 8

a) Medial collateral ligament (MCL) force in Newtons (N) and b) lateral collateral ligament (LCL) force in response to a 30 N anterior force at 0° and 30° of flexion and a 20 N anterior force at 90° for posterior-stabilized (PS) and mid-level (ML) tibial inserts. Boxes and whiskers correspond to the quartiles and fifth and 95th percentiles, respectively. The horizontal black line within each box is the median. Circles indicate outliers. *p < 0.05.

sagittal plane. In the sagittal plane, ATT with the PS and mid-level insert designs used in this study is dependent on the MCL, which carries supraphysiological loads relative to the native knee.

Take home message

- The mid-level constraint insert used in this study decreased axial and coronal laxity compared to the posterior-stabilized insert; however, it did not decrease sagittal plane laxity.
- In the sagittal plane, anterior laxity following posterior-stabilized and

mid-level total knee arthroplasty is dependent on the medial collateral ligament, which carries supraphysiological loads compared to the native knee.

Supplementary material

Knee Coordinate System Definition.

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Author information:
- C. A. Kahlenberg, MD, MPH, Assistant Attending Orthopaedic Surgeon
- B. P. Chalmers, MD, Assistant Attending Orthopedic Surgeon
- M. B. Cross, MD, Assistant Attending Orthopaedic Surgeon
- D. J. Mayman, MD, Attending Orthopaedic Surgeon
- G. H. Westrich, MD, Attending Orthopaedic Surgeon
- P. K. Sculco, MD, Associate Attending Orthopaedic Surgeon
  Adult Reconstruction and Joint Replacement Service, Hospital for Special Surgery, New York, New York, USA.
- E. E. Berube, MS, Post-Bac Researcher
- W. Xiang, BA, Research Assistant
- J. E. Manzi, BA, Research Assistant
- H. Jahandar, MS, Research Engineer
- T. M. Wright, PhD, FM Kirby Chair of Orthopaedic Biomechanics
- C. W. Imhauser, PhD, Associate Scientist
  Department of Biomechanics, Hospital for Special Surgery, New York, New York, USA.

Author contributions:
- C. A. Kahlenberg: Conceptualization, Methodology, Project administration, Investigation, Data curation, Formal analysis, Writing – original draft, Writing – review & editing.
- E. E. Berube: Software, Investigation, Data curation, Formal analysis, Visualization, Writing – original draft, Writing – review & editing.
- W. Xiang: Methodology, Investigation, Data curation, Formal analysis.
- J. E. Manzi: Investigation, Data curation.
- H. Jahandar: Conceptualization, Methodology, Investigation, Data curation.
- B. P. Chalmers: Conceptualization, Formal analysis, Writing – review & editing.
- M. Cross: Conceptualization, Formal analysis, Writing – review & editing.
- D. J. Mayman: Conceptualization, Formal analysis, Writing – review & editing.
- T. M. Wright: Conceptualization, Formal analysis, Writing – review & editing.
- G. Westrich: Conceptualization, Formal analysis, Writing – review & editing.
- C. W. Imhauser: Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Writing – original draft, Writing – review & editing.
- P. K. Sculco: Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Writing – original draft, Writing – review & editing.

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