The Journal of Arthroplasty xxx (2017) 1–7

Contents lists available at ScienceDirect

The Journal of Arthroplasty

journal homepage: www.arthroplastyjournal.org

A Dual-Pivot Pattern Simulating Native Knee Kinematics Optimizes Functional Outcomes After Total Knee Arthroplasty

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ARTICLE INFO

Article history:
Received 7 February 2017
Received in revised form 20 April 2017
Accepted 24 April 2017
Available online xxx

Keywords:
total knee arthroplasty
kinematics
patient-reported outcomes
medial-pivot
lateral-pivot
sensors

ABSTRACT

Background: Few studies on kinematics correlate patterns to functional outcomes after total knee arthroplasty (TKA). The purpose of this study was to determine if lateral pivot motion in early flexion and medial pivot in high flexion, simulating native knee kinematics, produces superior clinical outcomes. A second objective was to determine if specific kinematic patterns produce superior outcomes.
Methods: One hundred twenty consecutive TKAs were performed using sensor trials to record intraoperative knee kinematics. Lateral and medial pivot pattern designations were based on the center of rotation within 3 flexion zones: 0°-45° (early), 45°-90°, and 90° to full flexion (late). Knee Society Scores, pain scores, and patient satisfaction were analyzed in relation to kinematic patterns.
Results: Knee Society function scores were higher in TKAs with early lateral pivot/late medial pivot intraoperative kinematics compared to all other kinematic patterns ($P = .018$), and there was a greater decrease in the proportion who reported that their knee never feels normal ($P = .011$). Early lateral/late medial pivot had greater function scores at 1-year ($P < .001$) and improvement from preoperative baseline ($P = .008$) compared to those with the least ideal pattern. All patients with the most ideal pattern compared to none of the least ideal pattern reported they were very satisfied ($P = .003$).
Conclusion: Patients with an intraoperative early lateral pivot pattern followed by medial pivot motion in later flexion, reported higher functional outcome scores along with higher overall patient satisfaction. Replicating the dual-pivot kinematic pattern observed in native knees may improve function and satisfaction after TKA.

Total knee arthroplasty (TKA) is exceptionally reliable in terms of implant longevity and survivorship; however, patient-reported outcomes after TKA reveal the disappointing fact that up to 20% patients are not satisfied [1], often with continued pain, stiffness, or an “unnatural” feel to the joint. Knee kinematics, which detail the tibiofemoral contact locations and movement patterns of the knee, have been studied for decades and are postulated to correlate with clinical outcomes after TKA. Furthermore, it has been hypothesized that knee arthroplasty systems that replicate kinematic patterns of the native knee with an intact anterior cruciate ligament (ACL), particularly unicompartmental and bicruciate-preserving knee arthroplasty, will reproduce normal knee motion and potentially optimize patient function, outcomes, and satisfaction after TKA. Although various implant designs and types have been studied with respect to kinematic patterns [2–14], the search continues for clinical evidence to support one kinematic pattern over another in producing superior patient outcomes.

Traditional understanding of native knee kinematics has supported a medial pivot kinematic pattern throughout the entire knee range of motion [15–18]. Since 2008, a more modern understanding of native knee kinematics has revealed a more complex kinematic pattern of differing pivot motions in the various flexion ranges within the full knee range of motion [19–23]. Although modern kinematics continue to support a medial pivot tibiofemoral contact pattern with deeper flexion activities in the native knee, it is now understood that native knee kinematics in earlier flexion angles occurring with activities like walking, running, or pivoting

One or more of the authors of this paper have disclosed potential or pertinent conflicts of interest, which may include receipt of payment, either direct or indirect, institutional support, or association with an entity in the biomedical field which may be perceived to have potential conflict of interest with this work. For full disclosure statements refer to http://dx.doi.org/10.1016/j.arth.2017.04.050.

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http://dx.doi.org/10.1016/j.arth.2017.04.050
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are characterized by a lateral pivot pattern [20–23]. Sensor-embedded tibial trials have been developed to provide real-time intraoperative tibiofemoral contact forces to objectively quantify soft-tissue balance during TKA procedures [24,25]. Sensor-embedded tibial inserts visually locate and characterize the kinematic femoral contact points on the tibia intraoperatively. The purpose of this study was to determine if an intraoperative pattern of lateral pivot motion in early flexion (0°-45°) and medial pivot motion in late flexion (90° to terminal flexion), simulating native knee kinematics, produces superior patient-reported outcomes compared with other kinematic patterns. A second objective of this study was to determine if a specific kinematic pattern, designated as medial or lateral pivot at the various flexion angle ranges of 0°-45°, 45°-90°, and 90° to terminal flexion, produces superior patient-reported outcomes after TKA.

Methods

With institutional review board approval, a retrospective review of a prospectively collected database of 120 consecutive primary TKAs was undertaken. Procedures were performed between April 2013 and April 2014 by 2 board-certified, high-volume arthroplasty surgeons at a single institution. All patients presenting for a primary TKA for a diagnosis of osteoarthritis or autoimmune-associated knee arthritis were included. In each case, sensor-embedded tibial trials (Verasense; OrthoSensor, Sunrise, FL) were used to track tibiofemoral contact points after TKA implantation using traditional balancing techniques based on manual and tactile surgeon judgment. The balancing technique used is a measured resection technique with diligent assessment of gap balance with spacer blocks or calibrated lamina spreaders and fine-tuning with soft-tissue balancing after bone resection cuts were made. Thirty-four TKAs were excluded to eliminate potential bias for the following reasons: unavailability of the required size of the Verasense device (n = 16), device malfunction (n = 5), atypical hardware creating additional soft-tissue trauma (n = 5), surgery performed at a nonstudy hospital without the availability of the Verasense insert trials (n = 4), unresurfaced patella (n = 1), early revision (n = 2; 1 for infection and 1 for tibial aseptic loosening), and death unrelated to the index TKA (n = 1). Of the remaining 86 TKAs, 7 (8.1%) were lost to minimum 1-year follow-up, resulting in a sample size of 79 TKAs.

A median parapatellar approach was used for all procedures. Standard coronal plane tibial and femoral bone cuts were made with computer-aided navigation (Navigation; Stryker, Kalamazoo, MI). One knee arthroplasty system (Triathlon; Stryker, Inc, Mahwah, NJ) was used in all patients. One surgeon routinely retained the posterior cruciate ligament and used a cruciate-retaining (CR) implant with a CR or a cruciate-stabilizing (CS) insert with an anterior lip. The other surgeon routinely sacrificed the posterior cruciate ligament and used a CS insert with an anterior lip. Posteriorly stabilized implants were not used in study TKAs.

Verasense data were acquired once the final implants were in place and the retinaculum was closed to most accurately measure intraoperative contact forces and kinematic patterns throughout the range of motion as has been described previously by numerous authors [26–29]. Tibiofemoral contact points were recorded for each patient at terminal extension (0°), at 45° and 90° of flexion, and at terminal flexion. Patient age, gender, body mass index, and surgeon were recorded.

Data Extraction

The Verasense device produces images of tibiofemoral contact locations within triangular areas representing the medial and lateral tibial plateau surfaces as the knee is moved through the range of motion intraoperatively (Fig. 1). Four static images per patient were cropped from the continuous Verasense video and graphic user interface feed, one each for the knee at 0°, 45°, 90°, and terminal flexion (Fig. 2). The cropped images were imported into MATLAB (MathWorks, Natick, MA) after alterations were conducted in Microsoft Paint (Microsoft, Redmond, WA) to determine the exact position of the contact points using a custom image–processing program. The custom image–processing program operated based on detecting color differences within the cropped images to isolate the colored dots associated with the medial and lateral tibiofemoral contact locations. Potential error in calculations by MATLAB was eliminated by "blacking out" all unnecessary colors from the image. The only remaining items from the original cropped image were the contact points and the universal origin explained below (Fig. 2).

Verasense device images uniformly had an "embossed" circle at the center of each tibial surface image produced in a standard and located in manufacturing. On each image, we placed a white dot in these circles to create a universal origin for all measurements (Fig. 2). This universal origin was determined based on the center of the tibial sensor trial and remained constant throughout data extraction for each patient and different implant sizes.

The centroid of each isolated tibiofemoral contact point was calculated with built-in MATLAB commands from the image-processing toolbox. Each image was appropriately scaled based on the screen resolution and screen size from which the image was cropped. The delta values between the contact points and the universal origin were then calculated and exported to an Excel (Microsoft Corporation, Redmond, WA) spreadsheet for further analyses via MATLAB. Medial and lateral tibiofemoral contact points at each range of motion were connected by lines (Fig. 3) to permit calculation of centers of rotation (CORs) as the intersection points of 2 lines at different ranges of motion (eg, the intersection of the line associated with medial-lateral contact points at 0° and the same line at 45°). CORs were calculated based on vectors for early flexion (0°-45°), midflexion (45°-90°), and late flexion (90° to terminal). COR values were then used to determine if the kinematic pattern between the 2 flexion angles was medial or lateral based on their location with reference to the medial and lateral compartments. If the COR was located in the medial compartment between 5 and 1000 mm, the kinematic pattern was determined to be a medial pivot knee between the 2 distinct flexion angles. If the COR was located in the lateral compartment between −5 and −1000 mm, the kinematic pattern was determined to be a lateral pivot knee between the 2 distinct flexion angles If the COR was <5 or >−5 mm, it was considered a central pivot. If the COR was >1000 mm or <−1000 mm, it was considered a translation of the implant owing to the COR value not allowing a detectable pivot pattern and therefore sliding instead of rotating.

Study Groups

To address the first study question (whether an intraoperative pattern of lateral pivot motion in early flexion and medial pivot motion in late flexion produces superior patient-reported outcomes), patients were placed into 2 distinct kinematic pattern groups. The first group ("early lateral/late medial pivot group") included those TKAs with a lateral pivot in early flexion (0°-45°) and a medial pivot in late flexion (90° to terminal flexion), simulating the kinematic pattern of the native ACL-intact knee. The second group ("other kinematic patterns group") included TKAs exhibiting all other patterns not included in the first group, which by definition included knees with any kinematic pivot (lateral or

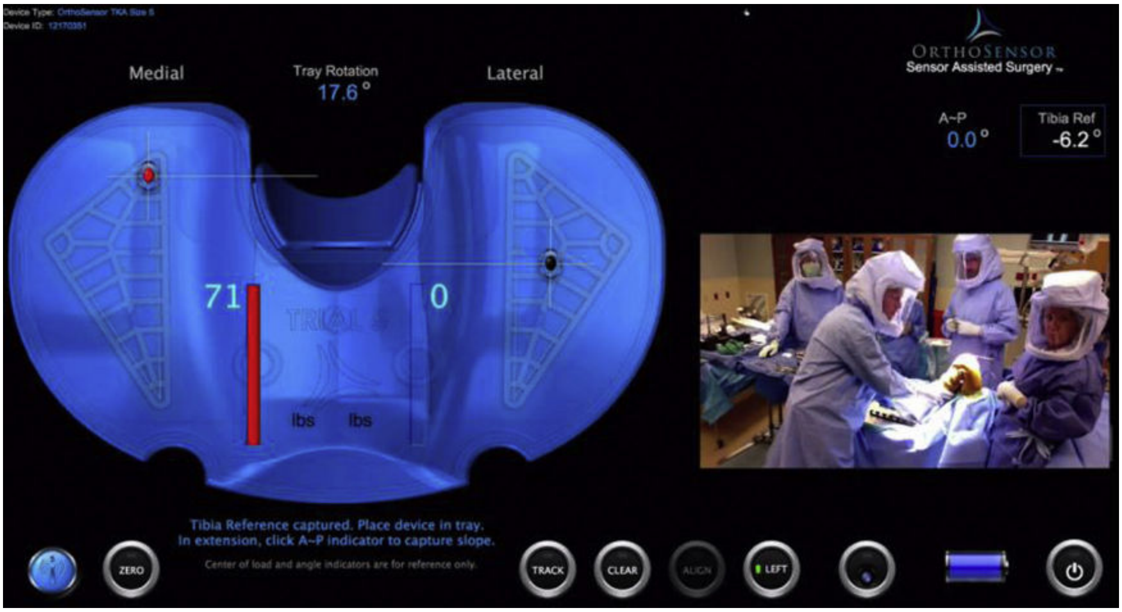

Fig. 1. Intraoperative measurements with embedded sensor tibial trial showing graphic user interface identifying loading contact points and peak loading forces (in lbs) in the medial (red dot) and lateral (dark green dot) compartments.

medial) other than lateral pivot from 0° to 45° and medial pivot from 90° to terminal flexion including lateral-lateral, medial-lateral, and medial-medial pivot patterns. Knees with central or translational pivot patterns in early or late flexion were excluded from statistical analyses resulting in samples of 16 early lateral/late medial pivot knees and 47 knees, which have been denoted as "other" kinematic patterns as described previously and represented graphically in Figures 4 and 5.

To address the second study question (whether a specific kinematic pattern produces superior patient-reported outcomes after TKA), the kinematic pattern in 3 distinct flexion zones—0°-45° (early flexion), 45°-90° (midflexion), and 90° to terminal flexion (late flexion)—was noted by a 3-letter designation according to the pattern within each flexion zone. For example, a designation of "lateral-lateral-medial (LLM)" was used to indicate that the TKA intraoperatively demonstrated lateral pivot motion in early flexion, lateral pivot motion in midflexion, and medial pivot motion in late flexion. Knees with central or translational pivot patterns in early, mid, or late flexion were excluded from statistical analyses. On review of Knee Society function Scores for all patterns, we proceeded with comparisons of the theoretically and statistically ideal (LLM; n = 8 knees) and least ideal (medial-lateral-lateral [MLL]; n = 6 knees) kinematic patterns.

Patient-Reported Outcomes

Patient-reported outcomes were evaluated preoperatively and at minimum 1-year postoperatively using the new Knee Society Scoring (KSS) system [30,31]. The new KSS system consists of validated objective and subjective scores. The Knee Society objective score, denoted "KSSO" in this article, evaluates knee pain (25 points), alignment (25 points), stability (25 points), and range of motion (25 points) for a total possible score of 100. Total possible points for the subjective satisfaction (denoted "KSSS" in this article) and functional (denoted "KSSF" in this article) components of the new KSS are 40 and 100 points, respectively. Individual items from

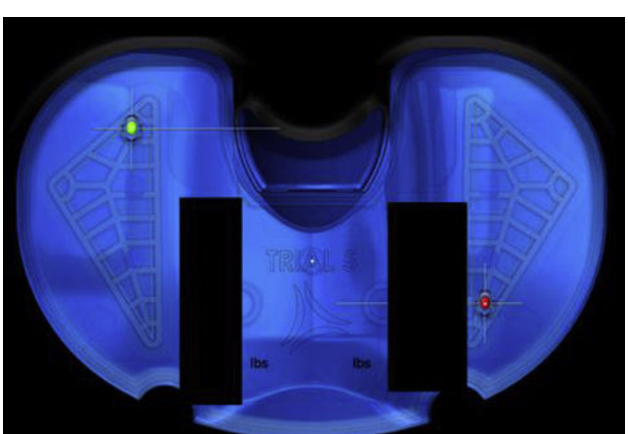

Fig. 2. Cropped images of embedded sensor tibial trial were imported into MATLAB to identify loading contact points (red and green dots) and calculate center of rotation values for pivot groupings.

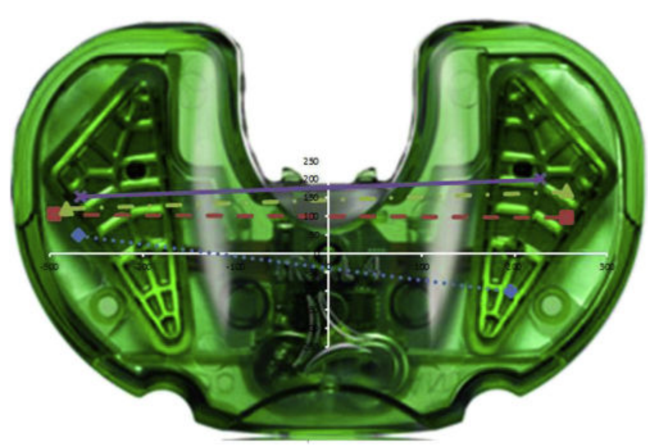

Fig. 3. Overlay of vector equations and trial tibial insert used to calculate center of rotation values to group patients into 1 of 8 kinematic pattern cohorts.

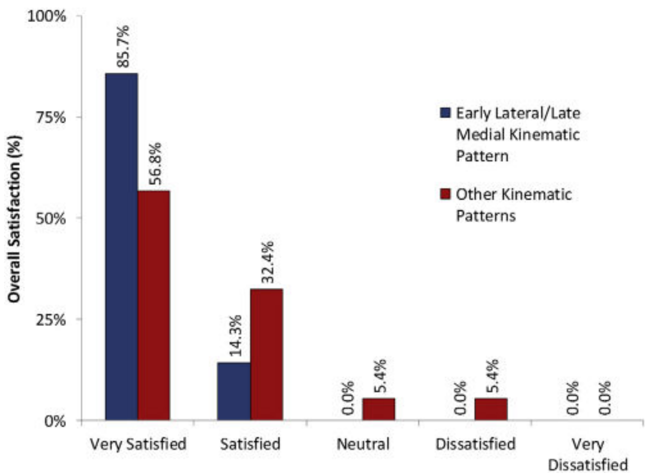

Fig. 4. Minimum 1-year overall satisfaction with total knee arthroplasty (TKA) in the early lateral pivot/late medial pivot kinematic pattern compared with all other groups.

the Knee Society questionnaire, including pain with level walking and pain with stairs or inclines (both scored 0 = none to 10 = severe), are also reported. In addition, responses to a global question "What is your current level of satisfaction with your knee replacement surgery?" (very satisfied, satisfied, neutral, dissatisfied, very dissatisfied) were analyzed. The University of California, Los Angeles (UCLA), activity level score [32] asks patients to choose their highest level of current activity, ranging from 0 (wholly inactive: dependent on others, cannot leave residence) to 10 (regularly participate in impact sports such as jogging, tennis, skiing, acrobatics, ballet, heavy labor, or backpacking).

Statistical Analysis

Patient-reported outcome scores were analyzed in relation to kinematic patterns. Minitab 17 (State College, PA) was used for statistical analysis. Data were evaluated for normality using Anderson-Darling tests. Normally distributed continuous variables were analyzed with the Student 2-sample t test (t) and the analysis of variance (F) while non-normally distributed continuous variables were compared with the Mann-Whitney test (W) or the Kruskal-Wallis test (H) adjusted for ties. The Pearson chi-square (χ^2) test was used to test independence among categorical variables, with the Fisher exact test P values reported for 2 × 2 contingency tables. A significance level of .05 was used for all statistical analyses.

Table 1
Demographics in Early Lateral/Late Medial Pivot Kinematic Pattern Knees Compared With Knees With All Other Kinematic Patterns.

Demographics	Kinematic Pattern		Statistic	P Value
	Early Lateral/Late Medial Pivot Kinematic Pattern	All Other Kinematic Patterns		
N	16	47		
Mean age (y)	66.8	66.4	$t = -0.16$	.878
Female, %	68.8	78.7	$\chi^2 = 0.419$	.501
Mean BMI (kg/m^2)	32.0	33.6	$t = 0.84$	.406
Median follow-up (mo)	19.2	25.4	$W = 1642.0$	.030

BMI, body mass index.

Results

Early Lateral Pivot/Late Medial Pivot Group Compared With All Other Kinematic Patterns

Age, gender, and body mass index did not differ between the early lateral pivot/late medial pivot group and the other kinematic patterns group (Table 1). Median follow-up in the former group was shorter by 6.2 months ($P = .030$; Table 1). There were no differences in preoperative outcome scores between the 2 groups (Table 2).

There were 11 CR with CR insert knees, 34 CR with CS insert knees, and 18 cruciate-sacrificing with CS insert knees. With one exception, outcomes did not vary by implant type ($P \geq .163$). Median UCLA activity level score was 6 in CR/CR knees, 5 in CR/CS knees, and 4 in cruciate-sacrificing/CS knees ($H = 6.63$; $P = .036$), reflecting a difference in regular participation in moderate activities such as swimming and unlimited housework or shopping; sometimes participating in these moderate activities; and regular participation in mild activities such as walking, limited housework, or limited shopping, respectively.

At minimum 1-year follow-up, mean KSSF were significantly higher in TKAs with early lateral/late medial pivot intraoperative kinematics compared with all other kinematic patterns (80 vs 69; $t = -2.51$; $P = .018$; Table 2). All other clinical outcome scores at minimum 1-year follow-up did not differ between the 2 kinematic pattern groups (Table 2).

Improvement from preoperative baseline to minimum 1-year outcome scores showed statistical trends for greater improvement in mean KSSF (41.1 vs 32.2 points; $t = -1.67$; $P = .108$) and median KSSS (26 vs 20 points; $W = 1401.5$; $P = .107$) in the early lateral/late medial pivot kinematic pattern group compared with other kinematic pattern groups (Table 2).

Overall satisfaction with TKA is shown graphically in Figure 4 separately for the early lateral/late medial pivot kinematic pattern group and the other kinematic patterns group. Eighty-six percent of the former group compared with that of only 57% of the latter group reported that they were very satisfied with their TKA ($\chi^2 = 3.729$; $P = .099$). Figure 5 shows the percent change from preoperative baseline in the proportion of patients in each group who reported that their knee always, sometimes, or never feels normal. Although percent change in the proportions of the early lateral/late medial pivot kinematic pattern group and the other kinematic patterns group reporting that their knee always feels normal was not statistically different (a 56.3% increase vs a 47.6% increase; $t = 1.081$; $P = .284$); there was a significantly greater decrease in the proportion of patients in the former group compared with the

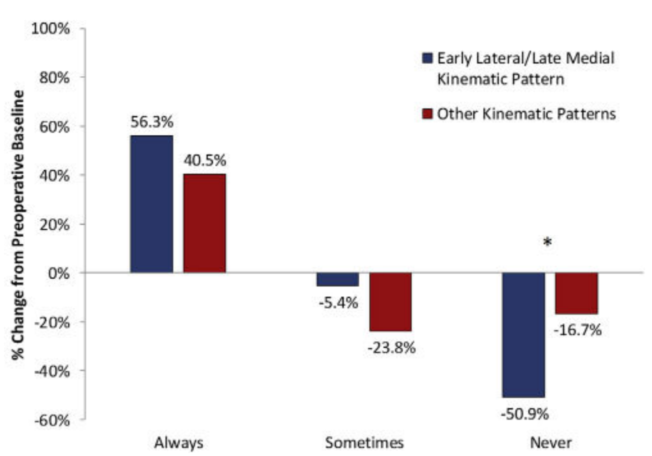

Fig. 5. Percent change from preoperative baseline in the proportion of patients in the early lateral pivot/late medial pivot kinematic pattern groups and all other kinematic patterns groups who reported that their knee always, sometimes, or never feels normal. *Statistically significant difference.

Table 2
Preoperative, Minimum 1-y, and Delta Outcome Scores in Early Lateral/Late Medial Pivot Kinematic Pattern Knees Compared With Knees With All Other Kinematic Patterns.

Outcome Score	Preoperative Outcomes			Minimum 1-y Outcomes			Preoperative to Postoperative Improvement in Outcomes		
	Early Lateral/Late Medial Pivot Kinematic Pattern	Other Kinematic Patterns	*P* Value	Early Lateral/Late Medial Pivot Kinematic Pattern	Other Kinematic Patterns	*P* Value	Early Lateral/Late Medial Pivot Kinematic Pattern	Other Kinematic Patterns	*P* Value
KSSO	60.5	48.0	.794	98.0	95.0	.920	43.0	40.0	.413
KSSF	38.9[a]	38.1[a]	.849	80.0[a]	69.3[a]	**.018**	41.1[a]	32.2[a]	*.108*
KSSS	11.5[a]	13.2[a]	.420	38.0	36.0	.541	26.0	20.0	*.107*
Walking pain	5.5	5.0	.439	0.0	0.0	.135	−5.0	−5.0	.267
Stair pain	8.0	8.0	.809	1.0	1.0	.889	−6.5	−6.0	.597
UCLA activity level	5.0	4.0	.730	4.0	5.0	.437	0.0	1.0	.254

Bold *P* value indicate a statistically significant difference was detected. Italicized *P* values indicate a trend was detected.
KSSF, Knee Society Function Score; KSSO, Knee Society Objective Score; KSSS, Knee Society Satisfaction Score; UCLA, University of California, Los Angeles.
[a] Outcome Scores reflect means while all other measures reflect medians based on the normality of the outcome being evaluated.

latter group who reported that their knee never feels normal (a 50.9% decrease vs a 16.7% decrease; $t = 2.650$; $P = .011$).

LLM and MLL Kinematic Patterns

In this analysis, there were 2 CR with CR inserts knees, 9 CR with CS insert knees, and 3 cruciate-sacrificing with CS insert knees. Outcomes did not vary by implant type ($P \geq .291$). Analysis of minimum 1-year KSSF ($F = 3.80$; $P = .004$) and the amount of improvement in KSSF from preoperative baseline ($F = 1.21$; $P = .321$) suggested a clear distinction in mean functional outcome scores among all available kinematic patterns based on early, mid, and late flexion (Fig. 6). In particular, as shown in Table 3, patients with the most ideal LLM kinematic pattern had significantly higher mean function scores at minimum 1-year follow-up (87.5 vs 51.2 points; $t = 6.89$; $P < .001$) and improvement from preoperative baseline (48.3 vs 25.7 points; $t = 3.26$; $P = .008$) than patients with the least ideal MLL kinematic pattern. Table 3 also shows that patients with an LLM kinematic pattern compared with those with the MLL pattern were significantly more satisfied with their TKA as measured by KSSS at minimum 1-year follow-up (medians of 40 vs 33 points; $W = 75.5$; $P = .043$) and improvement in KSSS from baseline (mean improvements of 27.5 and 18 points; $t = 2.68$; $P = .022$).

As shown in Figure 7, all patients with an intraoperative LLM kinematic pattern in early, mid, and late flexion (n = 8 knees) compared with none of the patients with the MLL kinematic pattern (n = 6 knees) reported that they were very satisfied with their TKA at minimum 1-year follow-up ($\chi^2 = 11.0$; $P = .003$).

Discussion

Kinematic patterns in TKA have been extensively studied to date [2–14,33]; however, the search continues for clinical evidence to support one kinematic pattern over another in producing superior patient outcomes. Dennis et al [33] published a comprehensive kinematic analysis of 811 TKAs of numerous designs, from multiple institutions and surgeons, and reported that substantial variability occurred in all designs and groupings with respect to kinematic patterns. Furthermore, the authors reported that a desirable medial pivot pattern in flexion was present in only 55% of TKAs in the analysis, suggesting that as surgeons we have little ability to reliably induce a particular kinematic pivot pattern in TKA. This

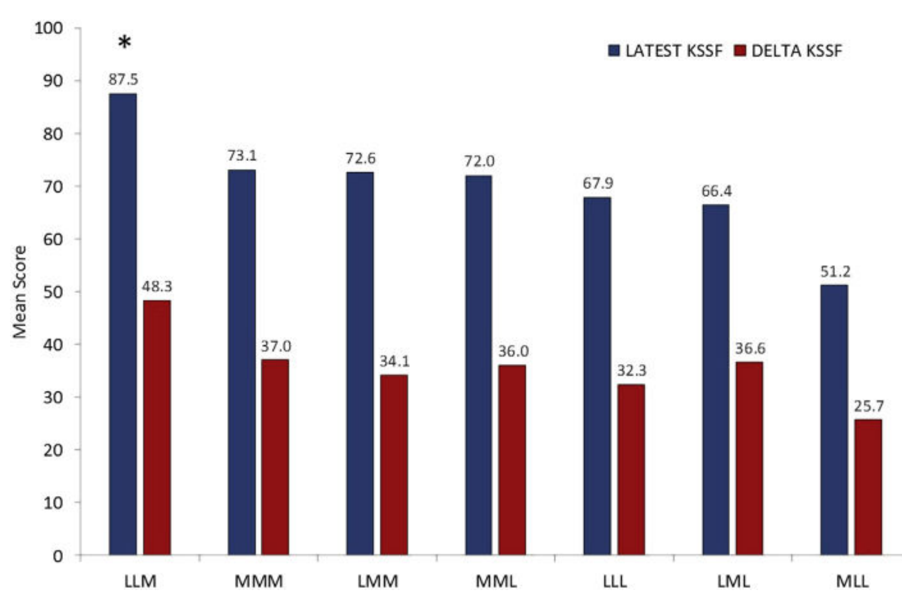

Fig. 6. Minimum 1-year and preoperative to postoperative improvement in Knee Society Function Score (KSSF) across all kinematic patterns. LLM, lateral-lateral-medial; MMM, medial-medial-medial; LMM, lateral-medial-medial; MML, medial-medial-lateral; LLL, lateral-lateral-lateral; LML, lateral-medial-lateral; MLL, medial-lateral-lateral pivot in early, mid, and late flexion. *Statistically significant difference.

Table 3
Preoperative, Minimum 1-y, and Delta Outcome Scores in LLM and MLL Kinematic Pattern Groups.

Outcome Score	Preoperative Outcomes			Minimum 1-y Outcomes			Preoperative to Postoperative Improvement in Outcomes		
	LLM	MLL	*P* Value	LLM	MLL	*P* Value	LLM	MLL	*P* Value
KSSO	68.0	43.5	*.061*	98	95	.640	31.6[a]	47.7[a]	*.077*
KSSF	39.3[a]	25.5[a]	*.086*	87.5[a]	51.2[a]	**<.001**	48.3[a]	25.7[a]	**.008**
KSSS	8	10	.844	40	33	**.043**	27.5[a]	18.0[a]	**.022**
Walking pain	4.5	5.5	.793	0	1.5	[b]	−5.4[a]	−3.7[a]	.323
Stair pain	7.1[a]	7.7[a]	.665	0.5	2.5	.220	−6.5[a]	−4.7[a]	.207
UCLA activity level	4.5	3.5	.156	4.9[a]	3.7[a]	.181	0	0	.886

Bold *P* values indicate a statistically significant difference was detected. Italicized *P* values indicate a trend was detected.
KSSF, Knee Society Function Score; KSSO, Knee Society Objective Score; KSSS, Knee Society Satisfaction Score; LLM, lateral-lateral-medial; MLL, medial-lateral-lateral; UCLA, University of California, Los Angeles.
[a] Outcome scores reflect means while all other measures reflect medians based on the normality of the outcome being evaluated.
[b] Group medians could not be tested because all values for in the LLM group were 0.

variability in kinematic patterns observed in modern TKA and the inability to reproduce an ideal target kinematic pattern may contribute to the reported 15%-20% of TKA patients who are not satisfied with their TKA [1].

Traditionally, understanding of native knee kinematics has supported a medial pivot kinematic pattern throughout the entire range of knee flexion [15–18]. In 2003, Komistek et al [17] published an elegant fluoroscopic study on 5 native knees and reported predominantly medial pivot kinematic patterns throughout flexion on average in the 5 subjects. However, the authors also observed that substantially less tibial rotation occurred in gait (<5 degrees) when compared with greater flexion activities such as a deep knee bend (<13 degrees), and one of the knees demonstrated a lateral pivot motion in gait and deeper flexion. Since 2008, a more modern understanding of native knee kinematics has revealed a more complex kinematic pattern of differing pivot motions in the various knee flexion ranges [20–23]. Although modern kinematics continue to support a medial pivot pattern with deeper flexion activities, it is now understood that native knee motion in earlier flexion angles, occurring with activities like walking, running, or pivoting, are characterized by a lateral pivot pattern [19–23]. Koo and Andriacchi [21] first reported the kinematic patterns of the native knee in 46 patients specifically with regard to walking. Using a point-cluster gait analysis technique, it was demonstrated that the COR during the stance phase of walking was in the lateral compartment for all 46 knees. In addition, the instantaneous COR occurred on the medial side on average <25% of the time during the stance phase. Further supporting this notion, Hoshino and Tashman [19] reported the kinematic tibiofemoral contact patterns of 29 native knees during downhill running. The authors used 3-dimensional computed tomography scans and dynamic biplanar fluoroscopy and discovered that the sliding contact path of the femur on the tibia was significantly greater on the medial side compared with the lateral side, suggesting that lateral pivot kinematic pattern is present during running. These studies support the evolution of knee kinematics in the ACL-intact native knee to an understanding that in early flexion activities, such as walking and running, the dominant pattern is lateral pivot motion, while the traditional medial pivot pattern continues to predominate in deeper flexion activities.

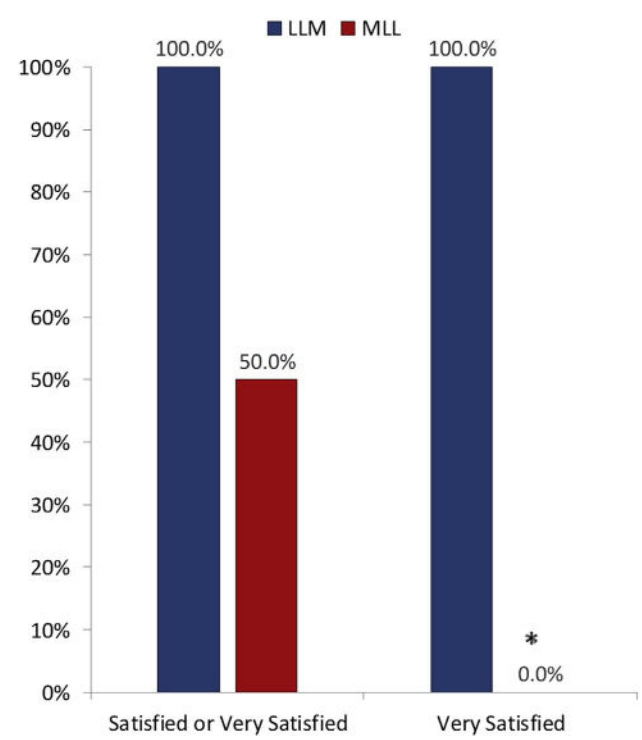

Fig. 7. Minimum 1-year overall satisfaction with TKA for patients with the ideal lateral-lateral-medial (LLM) and least ideal medial-lateral-lateral (MLL) kinematic patterns. *Statistically significant difference.

Sensor-embedded tibial trials have been developed to provide real-time intraoperative contact forces to objectively quantify soft-tissue balance during a TKA procedure [24,25]. The sensor-embedded tibial inserts also visually locate and characterize the kinematic femoral contact points on the tibia, which can provide intraoperative kinematic pattern data acquisition in real-time. Our findings suggest that patients who intraoperatively exhibit the early flexion lateral pivot pattern and late flexion medial pivot kinematic pattern possess higher overall satisfaction with their knee arthroplasty surgery as well as an improvement with the function of their knee as measured by modern KSSF. When defining the kinematic pattern in a more complex manner using the patterns in all 3 flexion ranges, patient-reported outcome scores of the “LLM” kinematic pattern (lateral pivot pattern in 0°-45° and 45°-90° degree ranges and medial pivot in the high flexion range beyond 90°) suggest this pattern to be the best overall in terms of satisfaction and function. Conversely, the kinematic pattern identified as the worst kinematic pattern to experience was the exact opposite pattern “MLL,” further supporting the optimal outcomes are potentially more likely if kinematic patterns exist in TKAs that replicate the native knee kinematics with an intact ACL. Although “LLM” was the optimal pattern observed in this data analysis, the midflexion zone of 45°-90° flexion remains to be further studied, as the ACL-intact native knee studies referenced previously are nonspecific and variable with respect to the exact flexion point where the pattern switches from lateral pivot in early flexion to medial pivot in greater flexion and likely varies among individual patients.

This study has limitations. First, the kinematic patterns observed were obtained intraoperatively during non–weight-bearing conditions with a patient anesthetized and may not represent the actual kinematic patterns observed in vivo during weight bearing through the range of flexion described. However, there is some support that intraoperative measurements of force and balance obtained with intraoperative sensors, can predict in vivo kinematic patterns [34]. This is certainly an area of further study to determine if a correlation exists between kinematic patterns obtained during surgery and those exhibited in vivo during weight-bearing functional activities. Second, sensor-embedded tibial trial inserts have not been validated as measurements of tibiofemoral contact patterns, and thus, this study represents the first to utilize this technology for kinematic motion intraoperatively. Finally, owing to the relatively small numbers of patients in kinematic pattern groups based on all 3 flexion ranges, nonsignificant study results may be attributable to insufficient statistical power. Power for nonsignificant findings ranged from <10%-90.6%. Further confounding this issue is the inclusion of both cruciate-substituting and cruciate-sacrificing TKA designs of both varus and valgus alignments, which ultimately could affect kinematic patterns in vivo. However, based on previous kinematic studies which traditionally have relatively small numbers, the authors believe this work provides valuable information for consideration in future research on knee kinematics after TKA. Furthermore, our analysis used the modern KSS, which has been validated to more aptly discern a patient's ability to perform various functional activities compared with previous generations of less-robust outcome measures. The authors are unaware of any published study that correlates kinematic data and modern KSS outcome in patients undergoing primary TKA.

Based on modern understanding of the dual-pivot kinematic pattern observed in the native ACL-intact knee, more appropriate analysis can be performed regarding TKA kinematics and their correlation with clinical outcomes. It appears that patients who exhibit an early flexion lateral pivot kinematic pattern accompanied by medial pivot motion in late flexion, as measured intraoperatively, may have higher functional outcome scores along with higher overall patient satisfaction. Therefore, replicating the dual-pivot kinematic pattern observed in native knees may improve function and satisfaction after TKA. Further work to identify the extent to which intraoperative kinematic patterns are correlated with in vivo weight-bearing kinematic patterns is necessary. In addition, investigation into the various characteristics of patient anatomy, implant alignment and design, ligament balance, and surgical technique that might facilitate a kinematic pattern more closely approximating the native knee is warranted.

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