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Differential Effect of Total Knee Arthroplasty on Valgus and Varus Knee Biomechanics During Gait

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ABSTRACT

Background: Total knee arthroplasty and its relation to gait abduction or adduction moment has not been fully described.
Methods: Gait analysis was performed on 25 patients (27 knees) preoperatively, 6 months and 1 year after total knee arthroplasty. Reflective markers were placed on the lower extremity, and motion data were collected at 60 Hz using 6 infrared cameras. Ground reaction forces were recorded at 960 Hz with a force plate. Stance phase was divided into braking and propulsive phases. Coronal knee angles and moments were calculated. Repeated-measures analysis of variance was used to compare frontal plane knee impulse over time and between the braking and propulsive phases of stance.
Results: In varus knees, static alignment was corrected from 2.2° varus to 3.3° valgus and in valgus knees from 15.2° valgus to 2.7° valgus ($P < .010$). Braking phase adduction impulse decreased from 0.145 to 0.111 at 6 months but increased to 0.126 Nm/kg s ($P > .05$) at 1 year. Propulsive phase impulse changed from 0.129 to 0.085 and persisted at 1 year. Impulse changed from 0.01 (abduction) to 0.11 Nm/kg s (adduction) at 6 months and persisted ($P = .01$).
Conclusion: Restoration of anatomic alignment and soft tissue balancing changes the lateral loading conditions of valgus knees. Both cases, between 6 months and 1 year, increased peak moment.

Knee biomechanics have been well studied and documented [1-17]. Ground reaction forces (GRFs) work by exerting force from the ground onto the body in contact with it. This force acts on the normally aligned knee by passing medially from the foot toward the body's center of mass; as such, a characteristic adduction moment, typical of human gait, occurs.

Patients with knee osteoarthritis (OA) and medial compartment narrowing walk with a higher knee adduction moment were compared to control subjects [5]. For every 1% increase in knee moment above baseline, the risk of OA progression increases 6.5 times [11]. Consequently, many interventions for knee OA center on the reduction of this knee moment [10,12,18-20]. Although less prevalent, as many as 9%-17% of patients with valgus type deformity end up requiring total knee arthroplasty (TKA) [21].

Gait analysis studies have been performed to examine the dynamic loading patterns in postoperative TKA patients, with the purpose of comparing different implant designs [17,20]. However, an inherent lack of literature comparing valgus and varus knee patient performance pre- and post-TKA prompts for more studies allowing us to determine the effectiveness of the arthroplasty in restoring normal knee loading patterns, and it may also provide important information regarding potential wear-related complications.

By 6 months, it has been proposed that the correction of knee deformity and reaction forces accomplished by TKA can be equated to that of healthy subjects [22]. Yet, even though this suggests improved mechanics, retrieval studies of tibial inserts have shown a predominance of medial compartment wear after TKA. These results imply that the preoperative loading conditions (ie, high peak knee moment) might have returned [23-25].

Investigation performed at Lenox Hill Hospital, New York, NY.

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Basic definitions used in this analysis include moment, defined as the angular or rotational effect of a force about the joint. In this specific case, we are examining the adduction moment about the knee. This means, how much moment the GRF exerts on the knee to rotate it into varus. An abduction moment would be the same idea, except it would rotate the knee into valgus. Impulse, or more specifically, rotational impulse, is the area under the moment-time curve. It represents the moment multiplied by the amount of time it is applied to the joint. The dynamic knee angle represents the position of the knee (in the frontal plane) as it progresses from heel strike to toe off. This data point is measured during movement (ie, walking), and it is not just a static measurement of alignment such as a full-length X-ray.

The purpose of this study was 3-fold. First, to determine whether the changes in dynamic knee gait angle and frontal knee moment remained at long-term follow-up (6 months and 1 year) post TKA. Second, to assess whether the changes in frontal knee moment are in fact related to the static and dynamic knee angular correction at the 6-month and 1-year post-TKA follow-up. Third, determine if these biomechanical changes are related to changes in the Knee Society (KS) scores.

Our primary hypothesis was that the observed preoperative moment would be reduced after TKA. The secondary hypothesis was that the magnitude of reduction in observed moment would be proportionate to the tibiofemoral correction.

Methods

In a 2-year period, 25 patients (27 knees) were recruited from the practice of 2 fellowship-trained orthopedic surgeons (J.A.R. and S.J.N.). All patients were subjected to a standardized gait analysis protocol performed preoperatively, 6 months and 1 year after TKA. There were 9 men and 16 women; of those, 15 patients had varus type deformity and 10 patients had valgus type deformity. The valgus deformity group had a mean height of 168 cm (range, 152-180 cm) and mean weight of 75 kg (59-117 kg) with a mean age of 63.7 years (56-72 years). The varus deformity group had a mean height of 171 cm (range, 151-185 cm) and mean weight of 84 kg (range, 62-91 kg), with a mean age of 65 years (range, 56-70 years).

In order to be included in the study, patients were required to have a (1) diagnosis of primary (medial or lateral) compartment OA and voluntary consent for TKA, (2) no previous arthroplasty surgery (hip or knee) or history of high tibial osteotomy in the affected lower extremity, and (3) the ability to walk without an assistive device. Varus knees were enrolled first, and on completion, valgus knees were enrolled. During each recruitment period, all patients meeting the previously mentioned criteria were offered the opportunity to participate in the study. Before participation, subjects provided informed consent in accordance with the institutional review board.

A previously published technique of alignment and soft tissue release was utilized for varus knees [21] and valgus knees, respectively [26]. All varus knees received a posterior-stabilized knee implant (Depuy Sigma PFC, Warsaw, IN or Biomet Vanguard, Warsaw, IN). Valgus knees (Depuy Sigma PFC or Smith Nephew Legion, Memphis, TM) received a posterior-stabilized implant in 7 cases. A mid-level constrained insert was used in 2 knees based on mild lateral condylar liftoff after lateral soft tissue release and a cruciate-retaining implant by patient request in 1.

Preliminary power analysis from previous analyses on gait data from our laboratory [12] determined that in order to detect a change of 5° in peak knee angle and 15% knee moment, 12 patients were needed ($P = .05$, 80% power).

Radiographic follow-up was performed by using preoperative and postoperative (6-month and 1-year follow-up) standing anteroposterior (AP) radiographs. Clinical function surveys (KS and Function Scores) were completed at each laboratory visit (preoperative, 6 months, and 1 year).

For both groups, kinematic and GRF data were recorded as subjects walked initially at a self-selected pace across a 6-m walkway. Reflective markers were placed over the calcaneus, first and fifth metatarsals, medial and lateral malleoli, anterior shank, medial and lateral femoral condyles, anterior thigh, greater trochanter, sacrum and anterior superior iliac spine of the involved leg, and the greater trochanter and anterior superior iliac spine of the contralateral leg. Marker positions were collected at 60 Hz using 6 infrared cameras (Qtrac, Qualisys, Gothenburg, Sweden). The motion data were then filtered with a fourth-order Butterworth low-pass filter with a cutoff frequency of 10 Hz in order to eliminate any high frequency noise. GRFs were recorded at 960 Hz with a multicomponent force plate (Kistler Instrument Corp., Amherst, NY) incorporated into the walkway. Subjects performed 5 gait trials and were instructed to walk as naturally as possible and contacting the force plate with only the involved limb. Trials in which the foot did not land completely on the force plate or the subject altered his or her gait pattern to target the force plate were discarded, and the trial was repeated. Previous reliability analysis for gait data from our laboratory [27] has shown, with 12 subjects, we could detect changes of 55 has shown, with 12 subjects, we could detect changes of The motion data were then.

Sagittal (flexion/extension) and frontal plane (abduction/adduction) knee angles and moments were calculated using specialized computer software (Visual 3D; C-Motion, Inc, Rockville, MD). Based on the anterior/posterior GRF, the stance phase of each trial was divided into a braking phase and a propulsive phase. The area under the knee abduction and/or adduction moment curve (knee moment impulse) was calculated for each phase.

Statistical analyses consisted of separate, single-factor (time) repeated-measures analysis of variance to compare static AP alignment, KS and Functional Scores, gait velocity, and range of motion (ROM) and dynamic knee angle during gait over time. Repeated-measures (time × phase) analysis of variance was also used to compare changes in knee moment and impulse for the braking and propulsive phases, from preoperatively to postoperatively (6 months and 1 year). Dynamic knee angle and peak moment were defined as the maximum valgus/varus angle or moment observed at a given period. Bonferroni corrections were applied for post hoc comparisons where applicable. Finally, Pearson correlations were done to investigate the association between knee moment and impulse and gait velocity, static alignment, and dynamic gait angle. Additional Pearson correlations were done to investigate the association between the change in knee moment and impulse and the change in either static alignment or change in peak angle during gait. P values less than or equal to .05 were considered significant.

Results

KS and Function scores significantly improved in both groups ($P < .001$ and $P < .001$, respectively) (Table 1). In the valgus group, measured static knee alignment changed from 15.2 degrees valgus (standard deviation: 5.6) to 2 degrees valgus (1.2) ($P < .001$) at 6 months, with nonsignificant change to 2.7 (2.1) degrees valgus at final follow-up. For the varus group, preoperative static knee alignment was 2.2 degrees varus (2.5) and was corrected to 3.5 degrees valgus (2.7), as measured at both 6 months and 1 year ($P < .001$).

In both groups, gait velocity progressively increased following TKA (main effect of time, valgus: $P = .069$; varus: $P = .010$). The valgus group showed an increase of 3% in velocity at 6 months

Table 1
Valgus vs Varus: Gait Kinematics and Knee Scores at Preoperative, 6-Month, and 1-Year Evaluations (N = 27).

Parameter	Valgus	Varus	Valgus	Varus	Valgus	Varus	Valgus	Varus
	Preoperative		6-mo Follow-Up		1-y Follow-Up		*P* Values	
Static knee alignment[a]	−15.2 (5.6)	2.2 (2.5)	−2.0[a] (1.2)	−3.5[a] (2.7)	−2.7[a] (2.1)	−3.5[a] (2.7)	<.001	<.001
Gait velocity (m/s)	1.02 (0.19)	0.93 (0.24)	1.05 (0.16)	0.99 (0.26)	1.11 (0.14)	1.03[a] (0.21)	.069	.034
Knee flexion ROM[a]	38.5 (13.8)	41.7 (9.7)	39.1 (4.8)	43.2 (6.4)	37.9 (4.0)	45.5 (6.4)	.647	.094
KS scores	44.3 (12.8)	51.7 (14.2)	67.9 (15)	83.5 (13.3)	88.3 (18.3)	90.0 (9.7)	<.001	<.001
KF scores	48.1 (13.9)	59.4 (11.8)	67.5 (24.2)	81.8 (11.3)	85.0 (7.3)	86.5 (10.0)	<.001	<.001

Values are expressed as mean and (SD).
[−] Valgus angulation.
ROM, range of motion; KS, Knee Society; SD, standard deviation.
[a] Significant difference from preoperative evaluation.

(*P* = 1.000) and 8% increase at 1 year (*P* = .115 vs preoperatively). For the varus knee group, gait velocity increased 6.5% by 6 months (*P* = .157) and 11% by 1-year follow-up (*P* = .034 vs preoperatively) (Table 1).

No correlation was found between gait velocity and peak knee moment in either group at the braking or propulsive phases of gait. Additionally, there was no association between gait velocity and knee impulse (area under the moment curve) in the braking or propulsive phases of gait.

Knee flexion/extension ROM and knee extension moment during gait did not change in any follow-up time for either group (Table 1). Collective averages of peak dynamic angle for the preoperative, 6-month and 1-year evaluations are shown in Figure 1. In the valgus group, the dynamic knee angle was reduced to 45% at 6 months (*P* = .020) and continued to decrease to 41% by 1 year (*P* = .015 vs preoperatively). For the varus group, the dynamic knee angle was initially reduced to 37% of preoperatively at 6 months (*P* = .001) but increased to 53% of the preoperative levels at 1-year (*P* = .128 vs preoperatively) (Table 1).

Collective averages of the measured knee moments are shown in Figure 2. In both valgus and varus groups, a significant time interaction was found for both knee moment and impulse. The valgus group moment and impulse (braking phase) increased by 2.3 and 12.2 times, respectively (from abduction to adduction) at 6 months (*P* < .001 and *P* = .017, respectively) and continued increasing to 2.8 and 14.6 times at 1 year (*P* = .174 and *P* = .002, respectively) (Fig. 3). In the propulsive phase, knee moment and impulse were significantly increased to 2.4 and 6.3 times (from abduction to adduction) at 6 months (*P* = .008 and *P* < .001, respectively) remained significantly increased at 1 year (7.1 times, *P* = .003 and 2.7 times, *P* < .001, respectively). Of note, the preoperative peak moment (abduction) occurred in the propulsive stage of gait, whereas at both follow-up times, the peak moment (adduction) was in the braking phase. Peak impulse values are shown in Figure 3.

In the braking phase for the varus group, knee moment was significantly reduced to 85% of preoperative levels at 6 months (*P* = .037) but subsequently increased to 94% of preoperative levels at 1 year (*P* = .539 vs preoperatively). In propulsive phase, knee impulse and moment were significantly reduced to 65% and 74% of preoperative levels, respectively, at 6 months (*P* = .006 and *P* = .004, respectively). At 1-year follow-up, propulsive impulse and moment remained significantly reduced (64%, *P* = .033 and 78%, *P* = .034, respectively).

In the valgus group, preoperative static alignment did not correlate with any knee moment or impulse. Conversely, preoperative static alignment for the varus group correlated with preoperative knee moment (r = 0.508, *P* = .037) in the braking phase and both the preoperative knee moment (r = 0.524, *P* = .031) and knee impulse (r = 0.527, *P* = .030) in the propulsive phase.

Preoperative dynamic knee angle was significantly correlated to preoperative knee moment and knee impulse in the braking (r = −0.793, *P* = .006; r = −0.853, *P* = .002, respectively) and propulsive (r = −0.873, *P* = .001; r = −0.963, *P* < .001, respectively) phases of the valgus group. Dynamic knee angle was not correlated to peak knee moment or knee impulse in the braking or propulsive phases in the varus group.

At 6 months, the valgus group demonstrated no correlation between static knee alignment and knee moment and impulse for braking and propulsive phases, but significant correlation between the dynamic knee angle and knee moment for the propulsive phase was found (r = −0.739 and *P* = .015, respectively)—with no significance with the braking knee moment. Significant correlation between the dynamic knee angle and knee impulse was seen for the propulsive phase (r = −0.794 and *P* = .006, respectively)—with no significance with the braking knee impulse.

At 6 months postoperatively, varus group data showed that neither the static knee alignment nor the dynamic knee angle during gait were correlated with knee moment or knee impulse in the braking or propulsive phases.

At 1-year follow-up, the valgus group continued to have no correlation with static knee alignment and any knee moment or knee impulse for both the braking and propulsive phases. Correlation found was between the dynamic knee angle and the knee moment and impulse of the braking phase (r = −0.676 and *P* = .032; r = −0.765 and *P* = .010). Dynamic knee angle during gait also correlated with the propulsive impulse phase (r = −0.683 and *P* = .030) at 1 year but not the propulsive moment. For the varus knee group, the 1-year postoperative follow-up only showed correlation between the dynamic knee angle and the knee moment in the braking phase (r = 0.536, *P* = .026).

In the valgus group, the change in static knee alignment from preoperative to 6 months or 1 year did not correlate with the change in knee moment or knee impulse phase of gait. Conversely, the decrease in dynamic knee angle from preoperative to 6 months did correlate with the change in dynamic knee moment (braking: r = −0.643, *P* = .045; propulsive: r = −0.785, *P* = .007) and knee impulse (braking: r = −0.774, *P* = .009; propulsive: r = −0.875, *P* = .001). The change in peak knee angle from 6 months to 1 year did correlate with the change in peak knee moment (braking: r = −0.821, *P* = .004; propulsive: r = −0.759, *P* = .011) and knee impulse (braking: r = −0.851, *P* = .002; propulsive: r = −0.882, *P* = .001).

In the varus group, the change in static knee alignment and dynamic angle from preoperative to 6 months did not correlate with the change in knee moment or knee impulse, but significant correlation was found between the change in dynamic knee angle during gait and the change in peak knee moment (braking: r = 0.620, *P* = .008; propulsive: r = 0.665, *P* = .004) and knee impulse (braking: r = 0.507, *P* = .038; propulsive: r = 0.638, *P* = .006) from 6 months to 1 year.

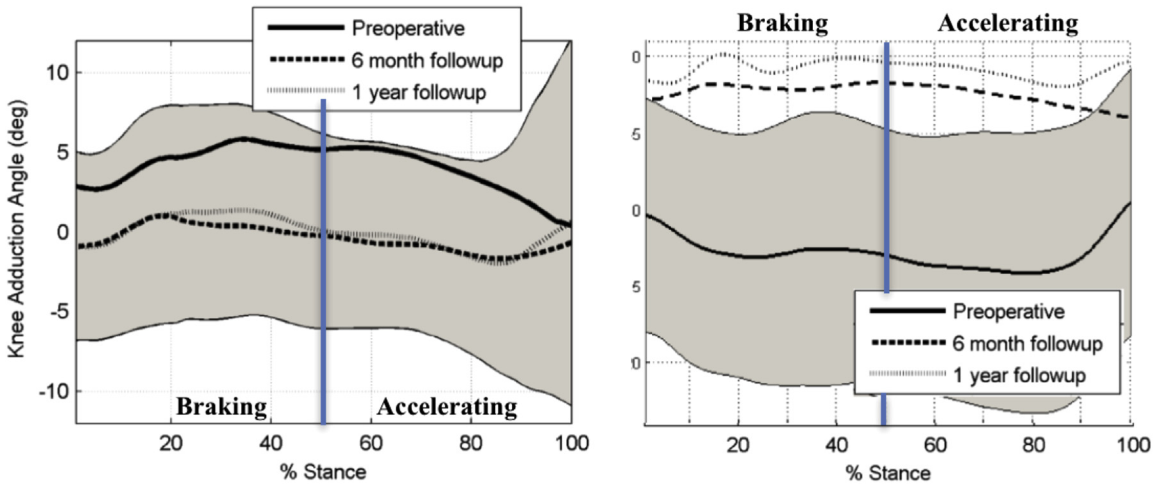

Fig. 1. Collective averages of peak dynamic angles: varus (right) vs valgus (left). The figure shows the standing phase (dynamic angle) for both varus and valgus knees, respectively. First half (~0%-50%) represents the braking phase—second half represents the propulsive phase (~50%-100%). Preoperative values show a decrease in angle for both stance phases. Both groups tended toward minimal angulation at the 1-year mark.

Discussion

Our hypothesis of a reduction in the observed moment was proven for both groups at the 6-month follow-up. The valgus group showed a decrease in the abduction moment, and conversion to an adduction moment, and the varus group showed a decrease in the adduction moment. At 1-year follow-up, the valgus group continued to acquire more adduction moment, and in the varus group, they also increased in the adduction moment tending to revert back to the presurgical levels. The differences in how both types of knees react post TKA have not been previously reported. From these results it can be concluded that both knees will end up having similar behavioral characteristics and that an adduction moment will eventually prevail for both knees. In both the valgus and varus group, the adduction moment increased slightly between 6 months and 1 year, revealing similar behavior.

Additionally, this study could not demonstrate any correlation between the static knee alignment correction and changes in moment post-TKA. This may indicate that static alignment alone does not determine the dynamic loading patterns of the knee. As supported by a previous study [28], the observed postoperative moment may be a better predictor of progression of OA than the static alignment.

While there was no correlation in the varus group between the change in dynamic knee angle and the change in knee moment or knee impulse from preoperative to the 6-month follow-up, the subsequent change observed from the 6-month to the 1-year follow-up did indeed correlate with the change in dynamic knee angle. Interestingly, the valgus group did show an initial correlation in the pre- to 6-month follow-up change observed in for the knee moment and dynamic knee angle and continued to show correlation with an increase in adduction for both the dynamic knee angle and the knee moment. This difference may be due to the greater degree of correction achieved in the valgus group compared to the varus group. At the 1-year mark, both groups were behaving similarly and demonstrated an alike correlation between the change in dynamic knee angle and moment. Thus, the dynamic knee angle may ultimately be the factor that tells how knee moment in the post-arthroplasty setting will behave and how component wear may occur.

Therefore, despite both the valgus and varus group undergoing a different correction in static alignment and soft tissue balancing,

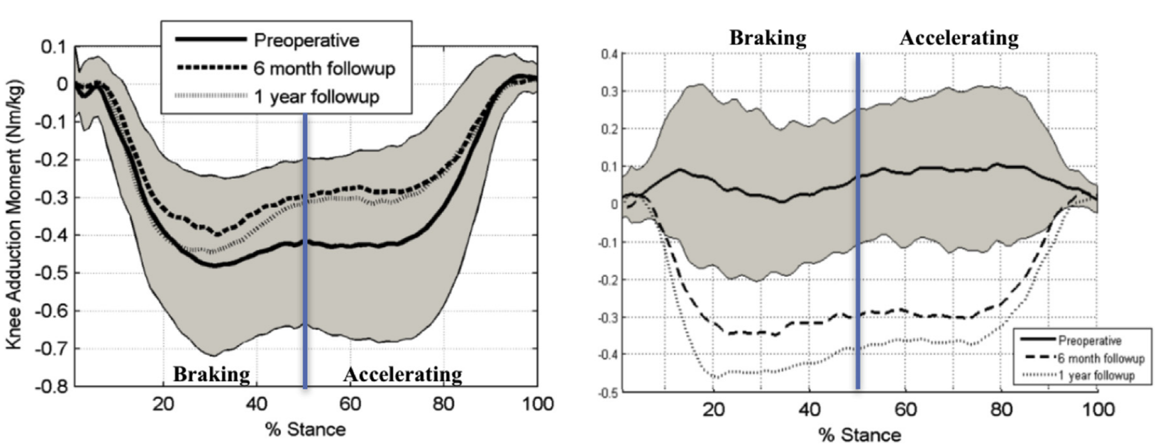

Fig. 2. Collective averages of measured knee moments: varus vs valgus. The figure shows the measured knee moments for both varus and valgus knees, respectively. First half (~0%-50%) represents the braking phase—second half represents the propulsive phase (~50%-100%). After TKA, the varus group shows decreased peak adduction knee moment for both phases. The valgus group shows a change from preoperative abduction moment into peak adduction values for both braking and standing phases. Upon comparison, both groups show similar behavior at the 1-year mark.

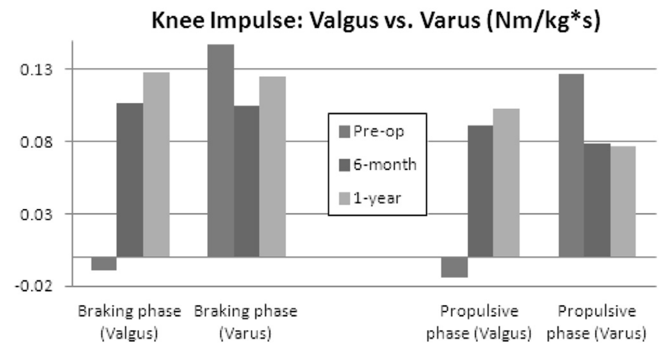

Fig. 3. Knee impulses are compared between both groups at the preoperative, 6-month, and 1-year evaluations. Valgus group shows an initial valgus impulse that progresses to a varus impulse at the 6-month mark that continues to progress.

the observed dynamic knee adduction angle and the relative medial compartment loading still occurred. Furthermore, markedly improved Knee Society Score and Knee Function Score values post TKA at 6 months and 1 year may also suggest that clinically improved response does not correlate to knee moment or dynamic knee angle during gait.

The relationship between knee alignment, peak knee moment, and progression of compartmental OA has been well documented [11,15,29]. A higher knee moment creates a higher compressive load on the compartment. A previous study [26] showed approximately 30% reduction in the observed peak knee moment (adduction) in 21 patients with varus OA 1 year after high tibial osteotomy. It was concluded that at long-term follow-up, the preoperative static knee alignment did not influence measured preoperative knee moment, and thus, a high preoperative adduction moment was associated with a poorer outcome and that the recurrence of static knee deformity is more likely with high preoperative moment.

In this study, the gait velocity increased for both groups throughout the different follow-up times, but no correlation was seen with any other study variable. A study looking at gait velocity found that the knee moment increased about 7% with a 15% increase in gait velocity [12]. Other studies [30] have identified that a decrease in velocity may be one possible compensatory mechanism used by knee OA patients in order to reduce knee moment. From this perspective, the improvement in KS and KF scores could explain the observed increase in velocity.

One study limitation is that both groups have 2 different types of implants. The varus group had 2 different posterior-stabilized (PS) knees, while the valgus group had mostly PS knees, with 1 cruciate retaining and 2 mid-level constrained polyethylene inserts. Numerous studies have sought to compare kinematic patterns and gait following knee arthroplasty using different knee designs [15,31-33]. Most gait studies demonstrate substantial variability among patients but no detectable differences between PS and cruciate-retaining implants [15,32]. Image-guided kinematic studies [31] have shown notable differences in anteroposterior movements and axial rotation expectedly influenced by the posterior cruciate ligament function or substitution but no measured adduction or abduction moments. The authors are aware of no publications documenting differences in the coronal plane movements attributed to implant designs. Moreover, recent data [31] suggest no differences in ROM or function with increasing post constraint in PS knee arthroplasty. Finally, the patterns of movement evident in our measurements were similar among the 3 implant designs used in both cohorts, corroborating the inclusion of the different knee designs in the analysis. The different surgical techniques and the difference in the group sizes are additional variables. Moreover, our use of short AP films of the knee rather than long-leg films from the hip to the ankle may lead to a less reliable depiction of the tibiofemoral angle.

Even though our study did not show any significant correlation with the achieved post-TKA static knee alignment, the arthroplasty consisting of correction of bony alignment and soft tissue balance, achieved a correction in postoperative dynamic knee alignment, which did correlate with knee moment postoperatively. This correlation seen with the dynamic knee angle and knee moment may direct future aims in TKA.

In summary, knee arthroplasty can alter the dynamic alignment of the knee and affect loading patterns. In varus knees, the adduction moment in the braking phase of gait is initially diminished at 6 months, with partial reversion to further adduction moment near the preoperative level at 1 year, whereas the adduction moment in the propulsive phase remains improved. In valgus knees, the preoperative abduction moment is greatest in the propulsive phase of gait. At 6 months postoperatively, the moment is converted to adduction with the peak moment in the braking phase, and at 1 year, additional adduction moment is achieved. As such, the loading patterns in the valgus knee are more meaningfully altered by total knee arthroplasty than varus knees. In both cases, peak moments increase between 6 months and 1 year.

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