Publisher's version: Hatfield, Gillian L., et al. "The effect of total knee arthroplasty on knee joint kinematics and kinetics during gait." The Journal of arthroplasty 26.2 (2011): 309-318. doi:10.1016/j.arth.2010.03.021. Epub 2010 May 31

THE EFFECT OF TOTAL KNEE ARTHROPLASTY ON KNEE JOINT KINEMATICS AND KINETICS DURING GAIT

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Abstract

This study determined how Total Knee Arthroplasty (TKA) altered knee motion and loading during gait. Three-dimensional kinematic and kinetic gait patterns of 42 patients with severe knee osteoarthritis were collected one-week prior and one-year post-TKA. Principal component analysis extracted major patterns of variability in the gait waveforms. Overall and mid-stance knee adduction moment magnitude decreased. Overall knee flexion angle magnitude increased due to an increase during swing. Increases in the early stance knee flexion moment and late stance knee extension moment were found, indicating improved impact attenuation and function. A decrease in the early stance knee external rotation moment indicated alteration in the typical rotation mechanism. Most changes moved toward an asymptomatic pattern and would be considered improvements in motion, function and loading.

Introduction

Total knee arthroplasty (TKA) is the most common treatment for end-stage knee osteoarthritis (OA). Based on self-reported measures of pain and function, such as WOMAC and SF-36, TKA is considered a huge success (1-5) with patient satisfaction extremely high (1, 6, 7). TKA surgeries have had a dramatic increase over the past decade (8, 9) and projected increases will result in a huge burden on the health care system (10). The increase in the number of younger recipients of TKA (11) supports the need for more objective measures to assess longevity and functionality of the numerous implant designs. Subjective outcome measures have limited sensitivity and unrealistic effect sizes because they primarily reflect the reduction in pain with surgery and are of limited value when determining the long-term effectiveness of treatment. Post-TKA improvements in more objective outcome measures, such as walking velocity (5, 12), knee range of motion (1, 4, 5), and functional tests including the timed-up-and-go, stair climbing and six-minute-walk tests (4) have been reported. While these tests may be more sensitive to change, they do not give insight into the actual effect of the implant on the mechanical environment of the knee joint.

Three-dimensional gait analysis provides comprehensive joint kinematic and kinetic changes during walking that enhance our understanding of altered joint function and loading with pathology and treatment options such as TKA. The net resultant knee adduction moment during gait is a key variable in understanding the mechanical loading environment of those with medial compartment knee OA. Altered magnitude (13-18) and waveform shape (18, 19) characteristics have been reported and associated with medial compartment loading and knee OA progression (13, 20) as well as to evaluate changes effects of treatments (i.e. high tibial osteotomies) on medial joint loading (3, 21). Other gait changes at the knee joint associated with knee OA include a decreased flexion angle and flexion moment during early stance, decreased knee extension moment at toe-off, and decreased external rotation moment in the early stance (15, 17, 18). These changes alter knee joint loading and contribute to a negative mechanical environment that can have a deleterious effect on the progressive nature of the disease and potentially a deleterious effect on the mechanical environment of a knee prosthesis following TKA.

Only a few studies have examined changes in the knee adduction moment after TKA and these studies had limitations including small sample sizes or heterogeneity in sample. Benedetti et al. (2003) found decreases in the two characteristic peaks of the knee adduction moment profile during the stance phase of the gait cycle at six, 12 and 24 months post-TKA (22) compared to an asymptomatic control group, however the effect of TKA could not be evaluated because pre-operative values were not presented. Decreases in knee adduction moments have been found post-TKA compared to pre-TKA measures, but these decreases were not statistically significant (5, 23). Both varus and valgus knee joint alignments were included, in these studies explaining the lack of significant differences. More work has focused on pre and post TKA sagittal plane kinematics and kinetics as increased knee flexion angles and moments during initial stance have been related to both implant failure (23, 24) and anterior knee pain (5, 25). In contrast, decreased knee flexion after heel strike has been proposed to impair shock absorption of impact loading by the quadriceps muscles (26). Inconsistent changes have been reported for discrete measures from flexion angle and moment curves for post-TKA waveforms (5, 12, 22, 23, 25, 27, 28). Few details were provided on the patient groups, in particular which compartment was most affected, and apparent discrepancies may be attributed to differences in patient groups, implant types or in the analysis techniques employed. No studies have looked at changes in the knee rotation moment post-TKA; however, Simon et al (1983) reported no difference in knee rotation angles between asymptomatic age-matched controls and post-TKA patients (28). Rotational alterations may be important to prosthesis loading as changes in knee rotation patterns during gait have been proposed to shift the dynamic loads to unconditioned areas of cartilage, accelerating degradation (29).

The above studies on post TKA kinematics and kinetics report discrete values (i.e. peak values at predetermined points) from the waveforms during the gait cycle. Unfortunately these measures do not capture the dynamic nature of walking related to the different phases of gait that can be gained by analyzing patterns over the gait cycle. Principal component analysis (PCA) is a multivariate statistical technique that extracts important features from the time varying gait waveforms, while maintaining and exploiting both the amplitude and temporal information over the gait cycle (17, 18). This approach provides stability in interpreting joint loading differences among OA patient groups whereas peak values of the knee adduction moment were affected by walking velocity (18), and by the model used in inverse dynamic calculations (16). One study used PCA to examine differences in post-TKA results and a feature from the PCA that captured the relative amplitude of the peak flexion moment during early to mid stance was the best predictor of post surgical anterior knee pain (25). PCA provides a comprehensive picture of the kinematic and kinetic changes throughout the entire gait cycle thus better represents the dynamic loading and motion of the knee joint.

The primary purpose of this study was to determine if TKA surgery changed the dynamic loading environment and knee motion of those with medial joint OA involvement during gait at one-year post-surgery. We hypothesized that following TKA surgery there would be i) decreased loading on the medial compartment of the joint, ii) increased knee flexion motion, iii) improved knee flexion moment and extension moment in early and late stance respectively indicative of improved knee function and iv) a decrease in the external rotation moment indicative of a reduction in the normal screw home mechanism during self selected walking. PCA was used to examine the dynamic characteristics of the three dimensional knee moments and knee flexion angle. Understanding how these key variables change provides important information on how TKA alters the mechanical environment of the knee joint postoperatively. Objective data on function and joint loading are necessary to evaluate effectiveness of TKA surgery and provides a foundation for evidence based pre and post-TKA management.

Materials and Methods

Sixty patients with severe knee OA visited the Dynamics of Human Motion laboratory for gait testing approximately one week before TKA surgery (mean of 6.1 ± 9.6 days prior). Patients were included in the study if they were able to walk along a six meter walkway without a gait aid, and were excluded if they had any neuromuscular disease, cardiovascular disorders or lower limb surgeries (at least one year prior to entry into the study) that would affect their gait or put them at risk while participating. All subjects were informed of the experimental risks and signed a written consent form in accordance with the Capital Health Research Ethics Board.

Patients visited the laboratory for gait testing a second time approximately one year (mean of 355.4 ± 62.4 days) following TKA surgery. Thirteen patients did not return for follow-up, three had incomplete gait data, one deceased, and one patient could not participate in the follow-up exam within an appropriate time period (<18 months). This left 42 patients to complete the second gait assessment (70% follow-up). Only data from patients who had completed pre-TKA and post-TKA gait testing were included in the analysis. All patients had standard anterior-posterior radiographs taken within 12 months prior to their initial visit to the gait lab. These radiographs were graded for OA severity by one orthopaedic surgeon (MJD) using the Kellgren Lawrence (KL) global rating (30). All patients had KL scores of three or four, indicative of severe osteoarthritic joint changes. All had medial compartment involvement with thirty-three predominantly medial compartment knee OA and nine equally affected in both medial and lateral compartments based on Scotts rating (31). Prior to each gait testing session, subjects filled out a WOMAC OA-specific questionnaire (32). One experienced high volume arthroplasty fellowship trained surgeon (MJD) performed all knee replacements. Two different knee systems were used: the NexGen Posterior Stabilized Complete Knee System (Zimmer, Warsaw, Indiana) and the Medial Pivot Knee System (Wright Medical International, Memphis, Tennessee) (N=9). Two subsets of NexGen knees were used. One subset included the traditional cemented titanium baseplate (N=20) and the other the uncemented Trabecular Metal tibial base plate (N=13). The polyethylene articulation and femur were the same in both subsets. All knee arthroplasties in this study were performed with intramedullary alignment with a five degree valgus distal femoral cut and a neutral (0 degree) tibial cut. The anterior and posterior cruciate ligaments were resected in all cases and all patellae were resurfaced using an inset patellar button. The measured resection technique was used in all cases in order to obtain a balanced flexion and extension gap. All knees were considered balanced at the end of the case with full extension and a minimum of 110 degrees flexion. The patellar tracking was balanced in all cases and no lateral retinacular releases were required. All patients were immobilized for the first post-operative day and then started on a standardized physiotherapy regime including immediate and full weight bearing, continuous passive motion machine application on a daily basis and routine quadriceps strengthening. All patients were placed on Warfarin post-operatively while in hospital for deep vein thrombosis prophylaxis. The average length of hospital stay was five days.

Gait Analysis

Electromyography, motion and ground reaction force data were collected. However, since the focus of the present study was to examine kinetic and kinematic changes post-TKA, only the motion and force methodology is described. Three-dimensional motion data of the lower limb and external ground reaction forces were recorded with a synchronized Optotrak^{TM} 3020 motion capture system (Northern Digital, Inc., Waterloo, ON) and a force platform (AMTI^{TM}, Watertown, MA) as the patients walked at their self-selected walking velocity along a six meter walkway. Walking speed was monitored using infrared timing gaits controlled by Labview software (National Instruments Corporation, Austin TX), and patients were required to complete five trials within 5% of their self-selected velocity.

Three-marker triads of infrared light emitting diodes were placed on the pelvis, thigh, shank, and foot segments. Individual markers were placed on the shoulder, greater trochanter, lateral epicondyle and lateral malleolus. Eight virtual markers (right and left anterior superior iliac spines, medial epicondyle, tibial tuberosity, fibular head, medial malleolus, second metatarsal, and heel) were identified during quiet standing. All markers were used to define anatomical coordinate systems in the four segments (18), and their kinematics were computed for one complete gait cycle using a least squares optimization method (33). Motion and force data were used to define heel contact and toe off for stride and step identification, and this information identified one gait cycle (heel contact to heel contact). Hip-Knee-Ankle (HKA) angles in three planes were calculated from the motion data during a standing calibration to provide a measure of static knee varus alignment (34, 35). Three-dimensional net external joint moments were calculated using an inverse dynamics approach (36-38) and represented in the joint coordinate system (39). Moments were normalized to body mass (5, 17-19), and all gait measures were time-normalized to 101 data points.

Principal Component Analysis

Five walking trials were averaged to create an ensemble average profile for each subject (40) for the knee flexion joint angle and the three dimensions of net external knee joint moment waveforms (four waveforms total). PCA is based on orthogonal expansion theory that aids in the reduction and interpretation of gait waveform data (17). Detailed description of PCA applied to gait waveform data is outlined elsewhere (17). Briefly the time and amplitude normalized gait waveforms for the 42 patients pre and post-TKA form a matrix ($X=101x84$) for each angle or moment variable separately. The pattern recognition procedure was applied and the eigenvectors of the covariance matrix of $\mathbf{X}$ were extracted and called principal components (PCs). The PCs capture the major amplitude and shape characteristics of the original waveform data (contained in $\mathbf{X}$). *PC Scores* for each principal component for each gait variable were calculated and these *scores* indicate how much a principal component contributed to each original measured waveform. The number of principal components (k) included in the analysis was based on two standard criteria: i) a percent trace greater than 90% for the k principal patterns to capture the salient features of the waveforms, and ii) principal patterns that explained less than 1% of the variance were excluded (41, 42). Retained *PC scores* were used in the statistical hypothesis testing of the differences in amplitude and shape of the waveforms between pre and post TKA. *Scores* for each PC were standardized by dividing by the standard deviation for that PC.

Statistical Analysis

Means and standard deviations were calculated for all demographic characteristics and for the *PC scores* for *k* principal patterns for the knee flexion angle, flexion moment, adduction moment, and rotation moment. Regression analysis determined the proportion of the postoperative knee adduction moment variance explained by the static hip-knee-ankle angle. Minitab (version 15) statistical software (Minitab Inc, State College, Pa) was used for all statistical analyses.

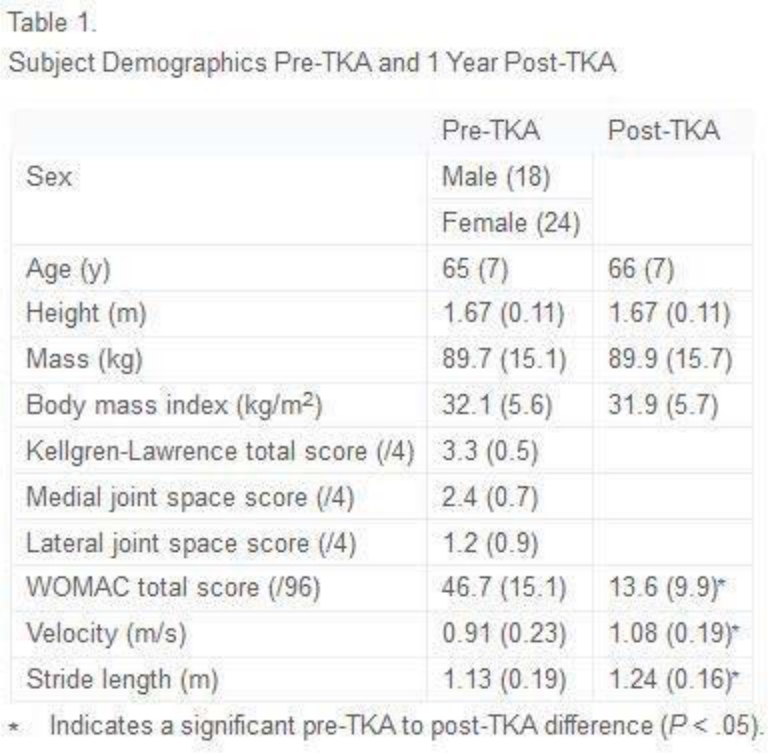

Table 1.
Subject Demographics Pre-TKA and 1 Year Post-TKA

	Pre-TKA	Post-TKA
Sex	Male (18)	
	Female (24)	
Age (y)	65 (7)	66 (7)
Height (m)	1.67 (0.11)	1.67 (0.11)
Mass (kg)	89.7 (15.1)	89.9 (15.7)
Body mass index (kg/m^2)	32.1 (5.6)	31.9 (5.7)
Kellgren-Lawrence total score (/4)	3.3 (0.5)	
Medial joint space score (/4)	2.4 (0.7)	
Lateral joint space score (/4)	1.2 (0.9)	
WOMAC total score (/96)	46.7 (15.1)	13.6 (9.9)*
Velocity (m/s)	0.91 (0.23)	1.08 (0.19)*
Stride length (m)	1.13 (0.19)	1.24 (0.16)*

* Indicates a significant pre-TKA to post-TKA difference ($P < .05$).

Results

Patient demographics are in Table 1. There were no significant differences in body mass, or BMI between the pre-operative and post-operative gait testing sessions. WOMAC scores, walking speed and stride length significantly improved post-operatively ($p<0.05$).

Pre and post-TKA ensemble average knee moment and flexion angle waveforms are shown in Figure 1. As a visual reference for typical patterns, bands of one standard deviation of a healthy asymptomatic adult group of 68 participants from previous studies from our laboratory are included in the figures (18, 19). The first three principal components of the knee flexion angle, knee flexion moment, and knee adduction moment were retained for further analysis, explaining 92.9%, 91.8% and 92.2% of the variation in the original waveforms respectively. The first two principal components of the knee rotation moment were retained, explaining a total of 90.7% of the variability. Significant differences ($p<0.05$) between pre-operative and post-operative states were found in the knee adduction moment PC1, PC2 and PC3, the knee flexion moment PC2, the knee rotation moment PC2 and the knee flexion angle PC1 as illustrated in Table 2.

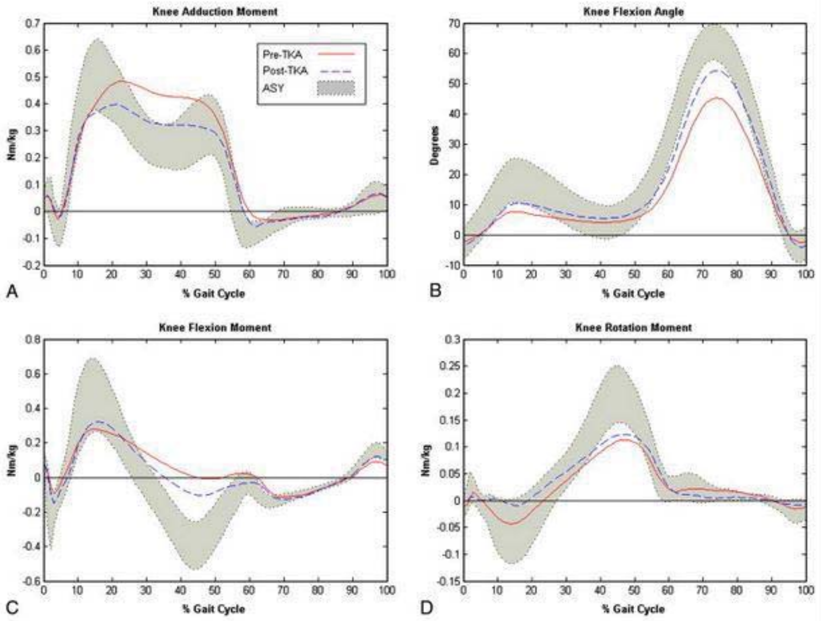

Fig. 1.

Sample ensemble average waveforms. The mean waveforms (n = 42) of the pre-TKA (solid) and post-TKA (dash) states are shown for the knee adduction moment (A), the knee flexion angle (B), the knee flexion moment (C), and the knee rotation moment (D). The shaded regions represent one SD around the mean waveforms for a group of 68 asymptomatic individuals from a previous study 17 and 18.

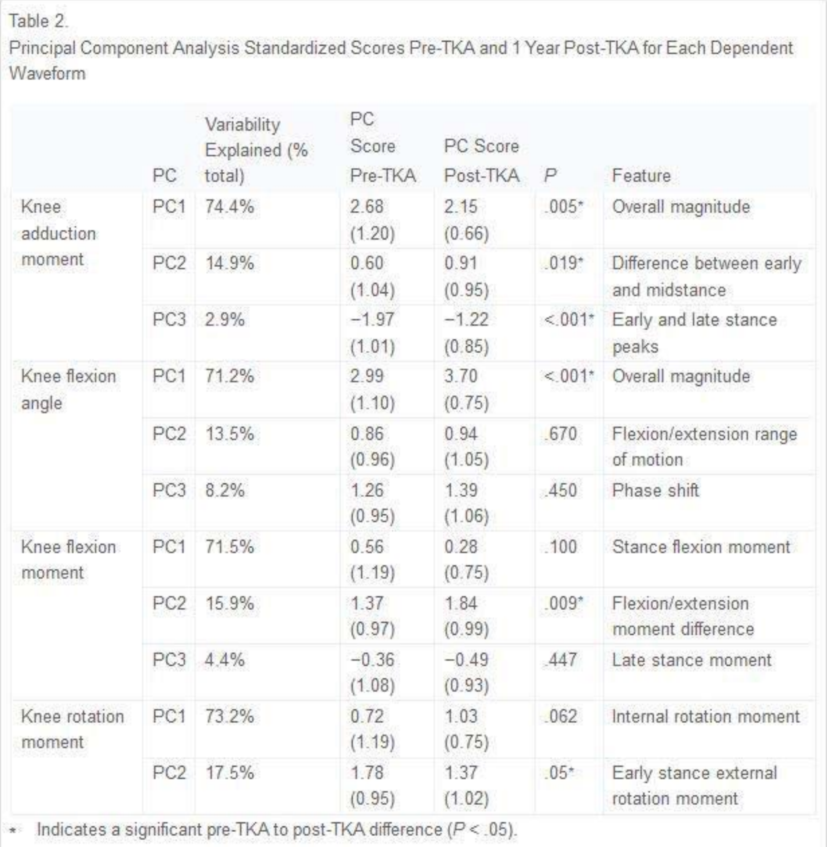

Table 2.

Principal Component Analysis Standardized Scores Pre-TKA and 1 Year Post-TKA for Each Dependent Waveform

	PC	Variability Explained (% total)	PC Score Pre-TKA	PC Score Post-TKA	*P*	Feature
Knee adduction moment	PC1	74.4%	2.68 (1.20)	2.15 (0.66)	.005*	Overall magnitude
	PC2	14.9%	0.60 (1.04)	0.91 (0.95)	.019*	Difference between early and midstance
	PC3	2.9%	−1.97 (1.01)	−1.22 (0.85)	<.001*	Early and late stance peaks
Knee flexion angle	PC1	71.2%	2.99 (1.10)	3.70 (0.75)	<.001*	Overall magnitude
	PC2	13.5%	0.86 (0.96)	0.94 (1.05)	.670	Flexion/extension range of motion
	PC3	8.2%	1.26 (0.95)	1.39 (1.06)	.450	Phase shift
Knee flexion moment	PC1	71.5%	0.56 (1.19)	0.28 (0.75)	.100	Stance flexion moment
	PC2	15.9%	1.37 (0.97)	1.84 (0.99)	.009*	Flexion/extension moment difference
	PC3	4.4%	−0.36 (1.08)	−0.49 (0.93)	.447	Late stance moment
Knee rotation moment	PC1	73.2%	0.72 (1.19)	1.03 (0.75)	.062	Internal rotation moment
	PC2	17.5%	1.78 (0.95)	1.37 (1.02)	.05*	Early stance external rotation moment

* Indicates a significant pre-TKA to post-TKA difference (*P* < .05).

Knee adduction moment PC1 represented the overall magnitude of the moment during stance phase of the gait cycle (Figure 2a). A high *score* indicates higher overall magnitude as illustrated in Figure 2b. Post-operatively, patients had significantly lower *PC1 scores*, and so had significantly lower knee adduction moments during the majority of stance phase. Knee adduction moment PC2 represented the relative difference between the magnitude of the knee adduction moment in early stance and mid-stance (Figure 2c). Higher *PC2 scores* therefore represented the pattern of a greater difference between the first peak of the knee adduction moment in early stance and the value of the moment at midstance (see Figure 2d), or more unloading of the medial compartment during midstance relative to early stance. Post-operatively, patients had significantly higher *PC2 scores* ($p<0.05$), and so had a greater difference between the first peak and midstance knee adduction moment than they did pre-operatively. PC3 for the knee adduction moment captured the early and late stance peaks in the waveform (Figure 2e). A high *score* indicated a waveform with clear peaks in early and late stance (Figure 2f). Post-operatively, patients had significantly higher *PC3 scores* ($p<0.05$).

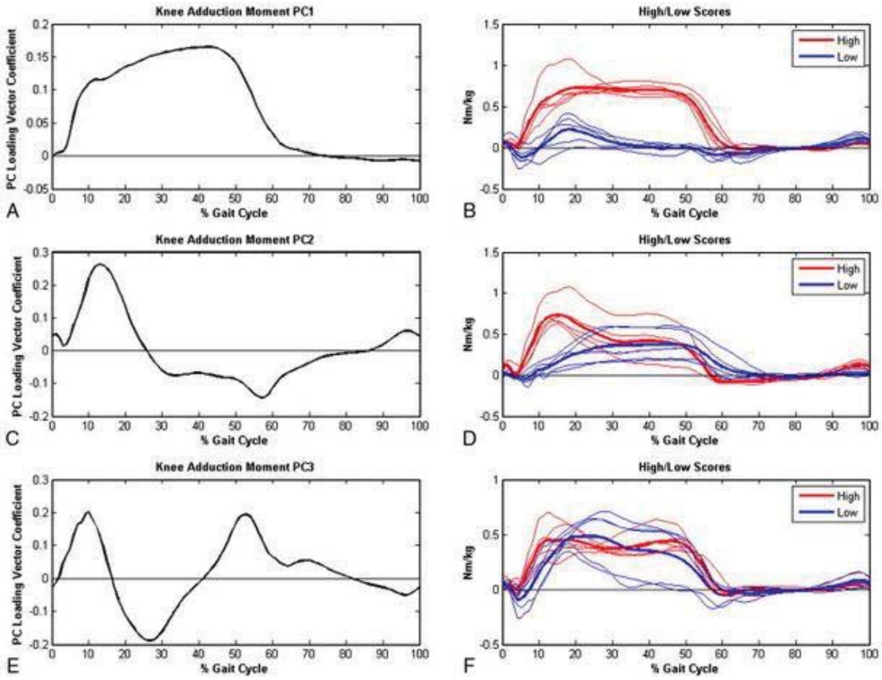

Fig. 2.

Knee adduction moment PCs. The pattern of the first (A), second (C), and third (E) PCs of the knee adduction moments are shown. A subset of waveforms with high (90th percentile) and low (10th percentile) PC1 scores indicated that PC1 captured the overall magnitude of the knee adduction moment during the stance phase of the gait cycle (B). Lower PC1 scores, and therefore lower adduction moment magnitudes, were associated with the post-TKA state. A subset of high and low PC2 scores indicated that PC2 captured a difference between the early stance peak of the knee adduction moment and the midstance magnitude of the moment (D). Post-TKA PC2 scores were higher than the pre-TKA scores, indicating a lower midstance knee adduction moment relative to early stance. A subset of high and low PC3 scores indicated that PC3 captured the early and late stance peaks in the knee adduction moment (F). Post-TKA PC3 scores were higher than the pre-TKA scores.

Although the change in hip-knee-ankle angle moved toward a less varus value postoperatively by 1.6° (±6.4°), this difference was not significant ($P > .05$). Regression analysis showed that this change explained 30% of the variance ($P < .05$) in the change in knee adduction moment PC1 scores pre-TKA to post-TKA but only explained 0.3% ($P = .719$) and 0.1% ($P = .851$) of the variance in PC2 and PC3 scores.

Knee flexion angle PC1 represented the overall magnitude of the angle over the gait cycle (Figure 3a). Post-operatively, patients had higher *PC1 scores* and so had higher overall magnitudes of knee flexion throughout the gait cycle. The effect of a higher *score* is depicted in

Figure 3b. However, PC2, which represented the overall range of motion of knee flexion throughout the gait cycle showed no difference post-operatively.

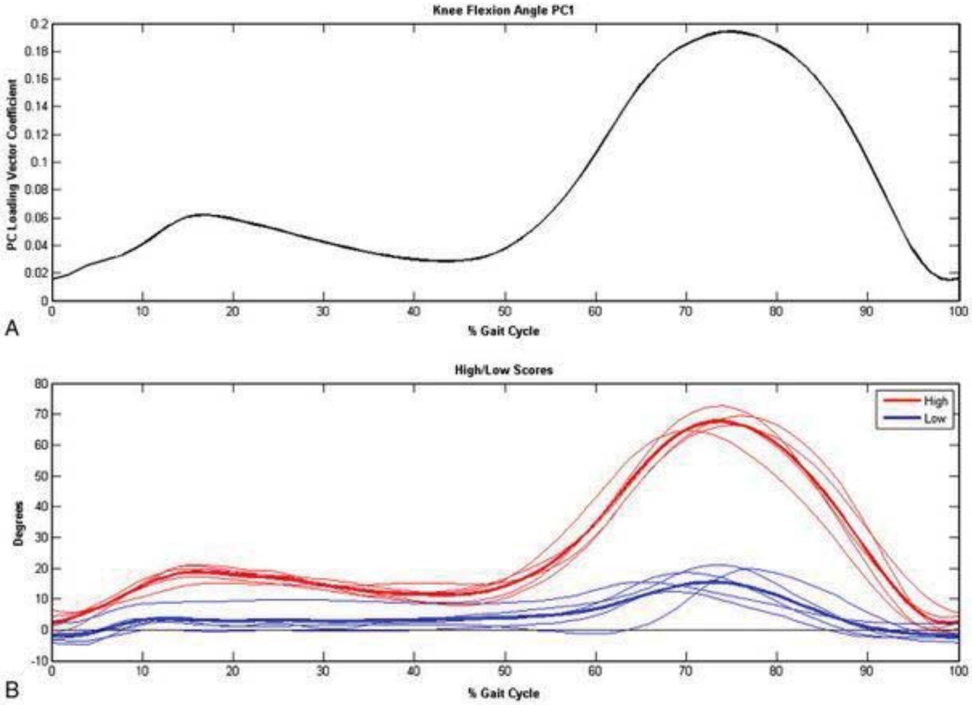

Fig. 3.
Knee flexion angle PC. (A) The pattern of the first PC of the knee flexion angle is shown. (B) A subset of waveforms with high (90th percentile) and low (10th percentile) knee flexion angle PC1 scores indicated that PC1 captured the overall magnitude of the angle throughout the entire gait cycle. Post-TKA scores were higher than pre-TKA scores, indicating a greater overall magnitude of knee flexion during gait post-TKA.

PC2 of the knee flexion moment represented the relative difference between the early stance knee flexion moment and late stance knee extension moment (Figure 4a). Higher *scores* represented a more bi-modal pattern of the waveform, with higher early stance knee flexion moment peaks and higher late stance knee extension moment peaks as illustrated in Figure 4b. Post-operatively, subjects had higher *PC2 scores* and therefore had knee flexion moment patterns that followed a more typical bi-modal pattern during stance.

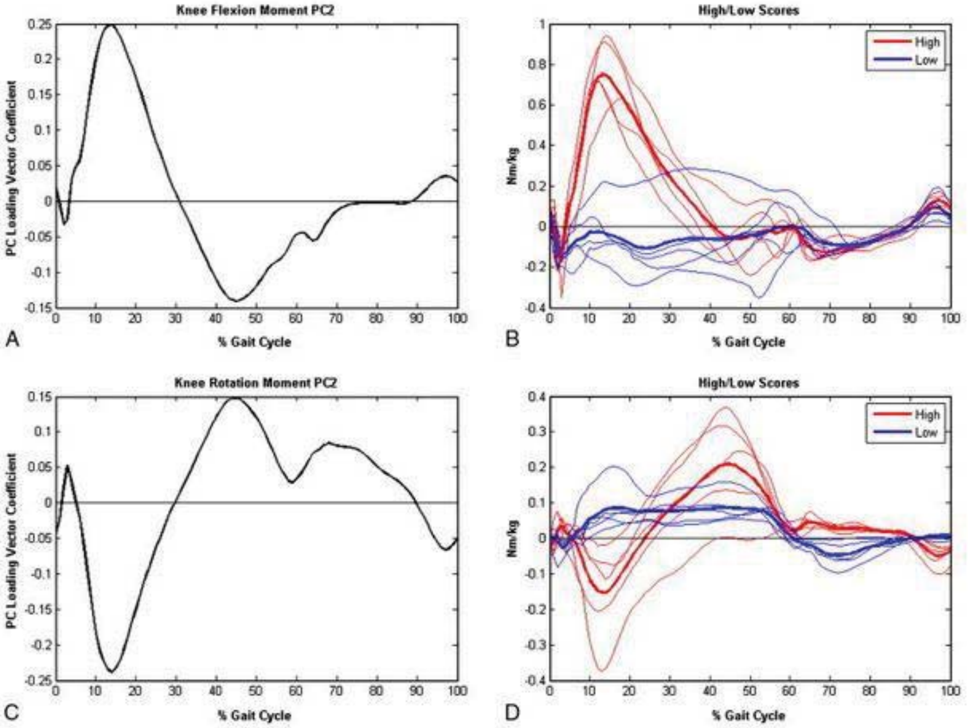

Fig. 4.

Knee flexion and rotation moment PCs. The pattern of the second PC of the knee flexion moment (A) and the knee rotation moment (C) are shown. A subset of waveforms with high (90th percentile) and low (10th percentile) knee flexion moment PC2 scores indicated that PC2 captured the magnitude of the stance knee flexion and extension moment difference (B). Higher post-TKA scores, and therefore greater knee extension moments in late stance, were associated with the post-TKA state. A subset of high and low knee rotation moment PC2 scores indicated that PC2 captured the early stance magnitude of the rotation moment (D). Post-TKA PC2 scores were lower than the pre-TKA scores, indicating a more internal rotation moment in early stance than the pre-TKA state.

PC2 of knee rotation moment represented the magnitude of the moment in early stance phase (Figure 4c). Higher *scores* were associated with a greater resultant external rotation moment of the knee in early stance as shown in Figure 4d. Patients had lower *PC2 scores* post-operatively and therefore had less of an early stance external rotation moment pattern than they did pre-operatively.

In summary, significant changes in the knee flexion angle pattern and the patterns of all three knee joint moment patterns were found post-operatively and all but the external rotation change moved toward the typical patterns previously reported for healthy individuals.

Discussion

Outcome measures such as WOMAC scores and walking velocity improved post-TKA similar to reports from previous studies (5, 12). Important to the present study was that TKA surgery changed the dynamic loading environment during gait, as illustrated by the significant changes in knee joint motion and three dimensional moments of force acting about the knee joint during the entire gait cycle. Previous studies examined discrete values from waveform (5, 22, 23), whereas the present study examined the entire waveform to better understand dynamic loading during the different phases of gait as PCA allows the examination of the entire waveform, yet discriminates between the different phases.

Our findings illustrate that TKA changes specific features of the dynamic loading environment and knee motion during gait at one-year post-surgery. They support an improvement in most variables with the exception of the change in the external rotation moment indicates a decrease in the normal rotational moment and is the only post-TKA variable to move away from the asymptomatic curves. This change may be related to the implant designs tested since less than 25% of the implants were a medial pivot.

First, the reduction in the overall knee adduction moment and a decrease in mid stance values supported our hypotheses of improved loading on the medial compartment of the joint. PC1 for the knee adduction moment waveforms is similar to what has been reported in previous studies by our group for those with moderate and severe knee OA, as it captures the overall magnitude of the knee adduction moment and general shape (17, 18). The decrease in *PC1 Scores* at one-year post-TKA implies an overall decrease in medial compartment loading during gait (Figure 1a, 2a). This is an interesting finding since walking velocity increased post-TKA and the magnitude of the peak knee adduction moment during early stance has been shown to increase with walking velocity (18, 43). The second phase is mid stance, where there is typically a decrease in the knee adduction moment in asymptomatic individuals as shown in Figure 1 (17, 19), implying an unloading of the medial compartment during single-leg stance. PC2 of the adduction moment (Figure 2c) was similar to a previously reported pattern associated with moderate OA that captured the difference between the early and midstance knee adduction moment (18). The significant increase in *PC2* and *PC3 scores* implies that there was more unloading of the medial compartment during mid-stance post-TKA compared to the initial peak in early stance and the second peak in late stance. Therefore the shape, not just the magnitude of the waveform, was altered. The knee adduction moment has been found to be lower during mid stance compared to the initial peak with faster walking speeds for asymptomatic controls and those with moderate OA (18). The increase in walking speed found post-operatively may partially explain our findings as the pattern was moving toward a more typical asymptomatic curve (Figure 1A). Our results generally support previous findings for discrete measures post-TKA (5, 22, 23), but they also show that the changes occurred at different phases of gait. This is important as cumulative loading, not just peak loading is considered a factor in the progression of knee OA changes (44), and implies a better mechanical loading environment for the prosthesis. In contrast to previous studies, our differences were statistically significant which can be explained by our homogeneous sample with respect to medial compartment pathology, which was not the case in previous studies (5, 23). The change in Hip-Knee-Ankle angle explained 30% of the variance in the change in overall magnitude of the knee adduction moment (PC1), but did not explain changes in the other two PC features for the knee adduction moment.

This finding is consistent with previous work (45), indicating that alignment changes explain only some of the variability in frontal plane dynamic loading.

Knee flexion angle was not increased post-TKA during early stance nor was the range of motion increased during stance; however the overall flexion was increased which was primarily associated with swing phase. PC1 of the knee flexion angle captured overall magnitude of the angle during gait, and this pattern has been reported in the literature for those with mild to moderate and severe knee OA (17, 18). *PC Scores* for this pattern increased post-TKA, indicating an overall increase in knee flexion during gait and a reversal in the typical decreased knee flexion angle pattern observed in those with knee OA relative to asymptomatic individuals (13, 15). However, there was no difference in the knee flexion angle PC2, which captured the overall dynamic range of flexion/extension throughout the gait cycle. This latter result may have important implications for dysfunction and would not be reflected in a peak value of the waveform. Figure 1b shows a small difference in early stance, minimal difference in late stance and the greatest difference during swing, in which there is no joint loading.

Improved impact attenuation during early stance was seen, as evidenced by the increase in the flexion moment during early stance, and improved function was indicated by the increase in extension moment during late stance. Our results showed that patients had more bimodal flexion moment waveforms (Figure 1c, PC2), with a combination of greater knee flexion moments in early stance and greater knee extension moments prior to toe-off in the post-operative test, consistent with the results of Smith et al (2006) (5). This increase in the extension moment supports an improvement in push off and thus improved knee function post-TKA.

PC1 of the knee rotation moment captured the internal rotation moment prior to push-off, and was not affected by TKA. PC2 of the rotation moment was similar to the first PC reported by

Landry et al (2007) for rotation moments, and captured the external rotation moment in early stance (18). This pattern was reduced (less external rotation moment early stance) in those with moderate knee OA compared to asymptomatic individuals (18), and interestingly this moment was also reduced following TKA compared to pre-TKA surgery. This was the only change post-TKA that moved away from the asymptomatic pattern (Figure 1d). As mentioned the changes in the post-TKA external rotation moment may be due to the type of implant the patients received. Only nine patients received the medial pivot implants, which are designed to mimic the natural knee extension coupled with external rotation, and would therefore likely influence the net rotational moments at the knee. Other implants allow minimal rotational motion, thus a larger sample sizes of different implant designs in future work will be required to determine kinematic and kinetic pattern changes with specific implant design.

These results support some of the findings from previous studies on post-TKA kinematics and kinetics changes, but the temporal patterns measured over the gait cycle provided unique insight into the dynamic loading and functional changes post-operatively. Important questions that arise in the investigation of post-TKA mechanics are: i) what are the desired outcomes of the intervention in terms of function, and ii) how can we accurately measure and represent these outcomes? The former question is difficult because the desired outcome will likely depend on characteristics specific to the individual such as their state of health, age, physical abilities, and other medical indications and joint involvements. Further research on larger subject groups is required to determine how different patient characteristics relate to functional and clinical outcome and longevity of implant survival. In terms of the latter question, *if* the functional goal of an intervention such as TKA was to move toward the asymptomatic state, then it is important that we appropriately characterize the asymptomatic and post-treatment dynamic states. The results of this study suggest that important post-TKA changes are reflected in the *pattern* of the variables over the gait cycle that may not be evident from subjective selection of discrete values from gait waveforms. While the decrease in adduction moment parameters may be considered positive with respect to the knee joint loading environment, the sagittal plane kinetics raise some questions regarding whether the change is positive with respect to both prosthesis survival and anterior knee pain based on previous studies (5, 23-25).

Characterizing the complete set of dynamic joint changes from the pre to post-operative state provides objective information on implant function for the purpose of rehabilitation and long term prognosis. Future study should therefore aim to characterize changes associated with different implant designs and examine the associations between implant function, physical activity, long-term survivorship and mobility of the knee and the other joints of the lower extremity.

The results of the present study need to be interpreted within the limitations of the study design. A number of factors can change between the pre-TKA and post-TKA periods including pain, stiffness, joint alignment, soft tissue balancing, and others, and we cannot attribute the change in dynamic loading to any individual factor. However, all of these factors are related to the treatment, TKA surgery, which was what we attempted to examine in this study. To differentiate exactly which features are responsible for which changes will require larger sample sizes and multivariate statistical analyses methods. Not associated with the TKA treatment are any additional therapeutic interventions. Although we monitored therapy within the first 5 weeks postoperatively, we did not monitor therapy and activity throughout the entire year. This may be considered a limitation; however, the changes in dynamic loading characteristics were clear between the pre-TKA and post-TKA tests, and given the progressive nature of these variables in knee OA 15 and 19, one would not expect significant improvements in joint loading and motion to spontaneously occur in those with severe knee OA. So the generally positive findings are most likely related to the TKA treatment; however, this does not mean that the effectiveness could not be enhanced by adjunct therapies such as gait retraining or other physiotherapeutic interventions. In fact, none of the post-TKA waveforms were within the typical waveforms for the entire gait cycle (Fig. 1) suggesting the potential for further improvement. A final limitation is that we do not have total leg x-rays as a measure of alignment; however, we did have a measure that has been shown to be highly correlated with radiographic measures [35]. This represents the most comprehensive study to date on pre-TKA and post-TKA gait biomechanics providing a foundation for future work. These results are relevant to current practice and have potential implications for influencing how we evaluate implant design, for patient triage and for pre-TKA and post-TKA management.

In conclusion, changes in knee joint motion and joint loading were found for the dynamic characteristics measured during walking following TKA surgery. Most changes moved toward a more typical asymptomatic pattern and in general would be considered an improvement in motion, function and the joint loading environment. The external rotation moment did not and this change was considered a function of the prosthesis type. These findings provide an improved understanding of how these key variables are altered post-TKA surgery.

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