

The effect of total knee replacement on the knee varus angle and moment during walking and stair ascent

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Abstract

Background. This study examined the effect of total knee replacement surgery on the frontal plane knee varus angle and moment. Secondly, the relationships between knee varus angle and moment to a clinical outcome measure were assessed.

Methods. Twenty-one patients with total knee replacement and 21 controls performed level walking and stair ascent at two testing periods, pre- and 6-months post-surgery. The dependent variables included frontal plane knee angle and moment, and Western Ontario and McMaster Universities Osteoarthritis Index scores.

Findings. During level walking the mean knee varus moment of the patient group was significantly greater than controls at pre-surgery but was restored to control level post-operatively. During stair ascent the patient group produced a significantly smaller knee varus moment post-surgically. The mean frontal knee valgus angle of total knee replacement patients increased significantly from pre- to post-surgery during level walking. The Western Ontario and McMaster Universities Osteoarthritis Index score was not significantly correlated to the knee variables. However, the knee angle and moment were significantly correlated during level walking pre- and post-operatively and stair ascent post-operatively.

Interpretation. The decreased frontal plane knee moment in total knee replacement patients during level walking appeared to be affected by surgical realignment of the tibio-femoral joint, as the frontal knee angle and varus moment were strongly correlated. The subjective Western Ontario and McMaster Universities Osteoarthritis Index and the objective gait measures appeared to capture different dimensions of knee osteoarthritis.

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1. Introduction

A relationship between knee varus alignment, knee varus moment and knee osteoarthritis (OA) disease progression has been established (Sharma et al., 2001; Miyazaki et al., 2002; Wada et al., 2001). The frontal plane knee moment is believed to characterize the load distribution of knee OA patients such that high varus moments

equate to higher compressive load concentrations in the medial joint compartment (Andriacchi et al., 2004). A varus alignment of the tibia relative to the femur involves adduction of the distal tibia that compresses the medial femoral condyle and the medial tibial plateau. The result of medial compartment compressive load concentration has been thought to be decreased medial femoral condyle cartilage thickness and concomitant bony hypertrophy (Andriacchi et al., 2004). Increased medial compartment loading was believed to drive the progression of knee OA and thus is likely related to the symptomology of the disease.

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Consequently, primary goals of total knee replacement (TKR) are to correct frontal plane bony deformity, alleviate pain and restore function (Andriacchi, 1990). The procedure typically corrects deformity via tibio-femoral realignment and ameliorates pain via joint resurfacing. Although static measures of knee varus moment and angle are thought to be important indicators of knee OA progression and TKR outcome (Wada et al., 2001; Hurwitz et al., 2002; Hilding et al., 1995), few studies report the effect of TKR on these variables during ambulation. Because knee osteoarthritic subjects have demonstrated the ability to alter knee loading by adapting their gait (Andrews et al., 1996; Prodromos et al., 1985), a need exists to examine how TKR affects the knee varus angle and moment under conditions of dynamic loading. Level walking and stair ascent are ambulatory tasks, important to quality of life, which present significant demands to the knee (Mandeville et al., 2007). Stair climbing, in particular, can be a robust indicator of OA progression and TKR outcome as the increased loads placed on the knee, compared to level walking, may help to separate patients from controls (Saari et al., 2004; Kaufman et al., 2001; Andriacchi et al., 1982).

Therefore, the aims of this study were to determine the effect of TKR on knee varus angle and moment during level walking and stair ascent compared to controls, and to assess the relationship of the knee varus angle and moment to the clinical outcome as measured by the Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC/VAS). It was hypothesized that pre-surgical TKR subjects would have greater knee varus angle and moment than controls for both level walking and stair ascent, but these values would normalize as a result of surgery. Patients with high varus moments were expected to have greater self-reported pain and disability than those with low varus moments.

2. Methods

Two experimental groups, those scheduled for total knee replacement surgery (TKR; $n = 21$, age = 62.80 ± 1.65 yr, BMI = 32.90 ± 1.12) and healthy age-matched controls (CON; $n = 21$, age = 62.85 ± 0.90 , BMI = 26.60 ± 0.73). A power calculation based on previously reported knee varus moment effect size data with a sample size of 20 yielded a statistical power value of 0.89. All subjects performed level walking (10 m walkway) and stair ascent using gait analysis protocol previously described (Mandeville et al., 2007), and were tested initially (P1) and again 6 months later (P2). For TKRs, P1 occurred within 2 weeks of surgery, while P2 occurred 6 months post-surgery. Standard posterior stabilized total knee replacement procedures were performed by three experienced surgeons affiliated with a common orthopedic practice. The experimental protocol was approved by the Institutional Review Board and written consent was obtained from all subjects.

For level walking and stair ascent trials, ground reaction force data were sampled (960 Hz) via three force plates

(Advanced Mechanical Technologies, Inc., Newton, MA, USA), two of which were positioned adjacent to each other in the runway and the third comprising the first step of the stair assembly. An array of 33 reflective markers (diameter = 13 mm) was applied to define a 13-segment model of each subject (Hahn and Chou, 2004) and three-dimensional (3-D) marker trajectory data were collected (60 Hz) and low-pass filtered using a recursive Butterworth filter (cutoff frequency = 8 Hz). OrthoTrak software (Motion Analysis Corp., Santa Rosa, CA, USA) was used to estimate the frontal knee angle and net moment. Knee joint angles were estimated using the floating axis model proposed by Grood and Suntay (1983). Internal knee joint moments were calculated using inverse dynamics and were decomposed into three axes of the thigh anatomical coordinate system. Their magnitudes at the first peak vertical ground reaction force (F_z), which corresponds to single-limb body support (Anderson and Pandy, 2003), were obtained for data analysis (Figs. 1 and 2).

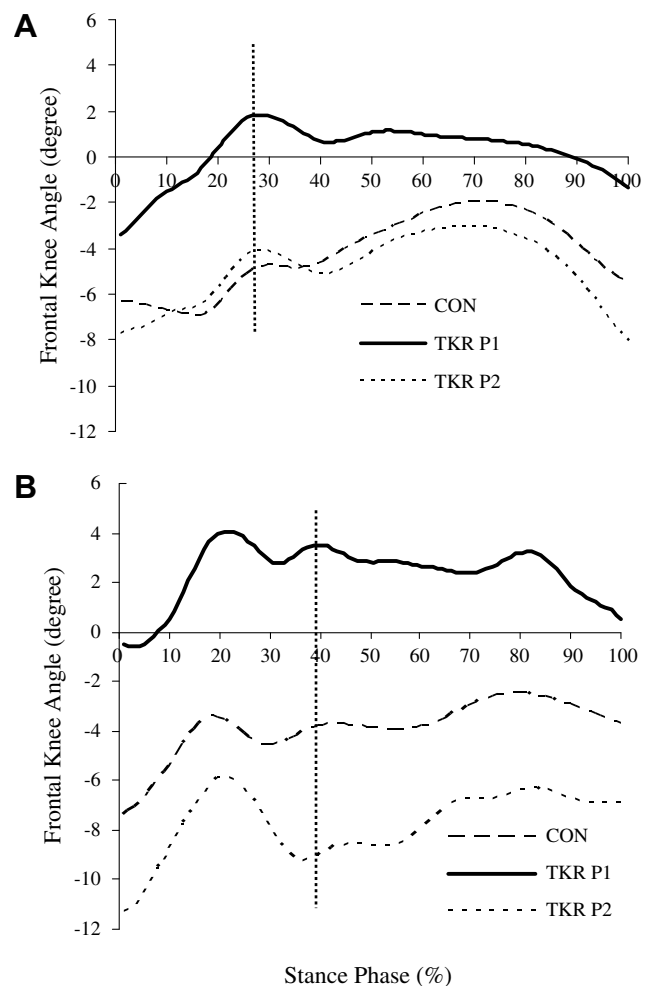


Fig. 1. Frontal knee angle ensemble curves for patients at pre-surgery (TKR P1), 6-months post-surgery (TKR P2), and controls (CON) during (A) level walking and (B) stair ascent. Positive angle values indicate varus; negative values are valgus. The dashed vertical line represents the average 1st peak F_z for the groups.

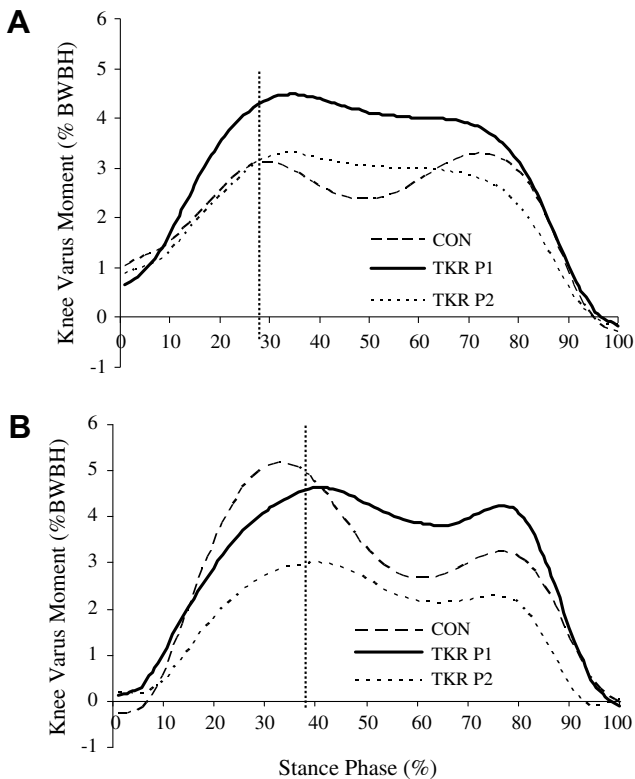


Fig. 2. Frontal knee moment ensemble curves for patients at pre-surgery (TKR P1), 6-months post-surgery (TKR P2), and controls (CON) during (A) level walking and (B) stair ascent. Dashed vertical line represents the average 1st peak F_z for the groups.

Clinical outcome was measured with the WOMAC/VAS questionnaire, which was administered to the TKR and controls groups at the two time periods. The WOMAC/VAS has been shown to be a reliable and valid multidimensional health status instrument (Bellamy et al., 1988). The total WOMAC/VAS score was determined by summing the normalized pain, stiffness, and functional disability subscales to a percent score so that higher scores equate to greater pain and disability.

The effect of TKR on the following dependent variables was measured: frontal plane knee angle (FKA) and moment (FKM), and total WOMAC/VAS score. Additionally, the relationship between the knee variables and the clinical outcome score was assessed. Two-way mixed analyses of co-variance (ANCOVAs) with factors of period

and group, and repeated measures for period and trials were used to analyze between and within-group effects across time for each variable (SAS 9.1, Cary NC, USA). Walking velocity was used as a covariate to control for its effect on the kinematic and kinetic measures. Four simple effects were explored for each condition: within-group differences for CON and TKR at P1 and P2, and between-group differences at P1 and P2. A Bonferroni correction was used to adjust the alpha level to 0.0125. Pearson correlation coefficients were used to assess the relationship between FKA and FKM and total WOMAC/VAS score of TKR patients at P1 and P2 for both level walking and stair ascent ($\alpha = 0.01$).

3. Results

No between-group differences were seen at P1 for level walking FKA (Fig. 1A; Table 1). However, post-operatively, the TKR frontal knee angle became significantly less varus from P1 to P2 ($P = 0.0122$).

Prior to surgery, FKM magnitudes of the TKR group during level walking were significantly greater than CON at P1 ($P = 0.009$, Fig. 2A; Table 1). The FKM significantly decreased from P1 to P2 such that the P2 values for both groups were similar (Table 1). No significant frontal knee angle or moment differences between periods were observed for the controls during level walking.

For stair ascent, no significant within or between-group differences were found for FKA at P1 and P2 (Fig. 1B; Table 1). However, the P2 TKR frontal plane moment was significantly less than CON post-surgically ($P = 0.0046$, Fig. 2B; Table 1).

The total WOMAC/VAS score for TKR was significantly greater than CON at P1 ($P < 0.001$, Fig. 3), decreased significantly across testing periods ($P < 0.001$), but remained significantly greater than CON at P2 ($P = 0.0004$).

For level walking, the frontal knee angle was significantly related to the frontal knee moment at P1 and P2 ($P < 0.001$; Table 2, Fig. 4). However, no significant correlations were found between the FKA or FKM and the total WOMAC score. When the difference scores for level walking were correlated, the FKA and FKM showed a significant relationship ($r = 0.56$, $P < 0.05$, Table 2). No significant difference score correlations were found for stair climbing.

Table 1

Adjusted mean frontal plane knee angle and knee moment^a at 1st peak F_z during level walking and stair ascent for TKR and CON across testing period (standard error)

Condition period	TKR level		CON level		TKR ascent		CON ascent	
	P1	P2	P1	P2	P1	P2	P1	P2
Knee angle (degrees)	-1.87 (1.38)	-5.81* (0.89)	-4.18 (1.31)	-5.46 (0.89)	3.90 (5.70)	-5.42 (4.59)	0.17 (4.71)	-1.14 (3.72)
Knee moment (%BW*BH)	4.07 [#] (0.38)	3.01* (0.30)	2.70 (0.35)	3.07 (0.30)	3.70 (0.58)	3.13 [#] (0.38)	4.07 (0.52)	4.69 (0.37)

^a Varus angles and moments are positive, valgus angles are negative.

* Indicates significant within-group difference ($P < .0125$).

[#] Indicates significant between-group difference ($P < .0125$).

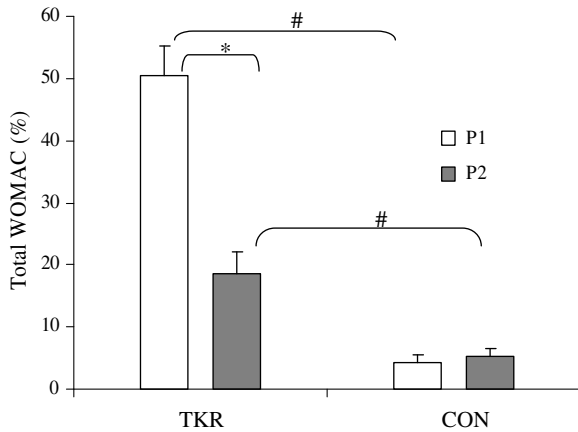


Fig. 3. Mean total WOMAC/VAS score for TKR and CON across testing periods (standard error). The * indicates significant within-group difference ($P < 0.0125$); the # indicates significant between-group difference ($P < 0.0125$).

Table 2

Pearson product-moment correlation coefficients for relationships between frontal knee angle (FKA), frontal knee moment (FKM) and total WOMAC/VAS score during level walking, stair ascent and the between condition difference for TKR subjects

Comparison	Level walking		Stair ascent	
	P1	P2	P1	P2
FKA with FKM	0.92*	0.73*	0.14	0.45
FKA with WOMAC/VAS	-0.01	0.10	-0.28	0.07
FKM with WOMAC/VAS	0.04	-0.03	0.23	0.08
Difference scores FKA with FKM	0.56#		-0.10	
Difference scores FKA with WOMAC/VAS	-0.23		0.16	
Difference scores FKM with WOMAC/VAS	-0.09		-0.09	

* Significant correlation ($P < 0.01$).

Significant correlation ($P < 0.05$).

4. Discussion

The aims of this study were to determine the effect of TKR on knee varus angle and moment during level walking and stair ascent compared to controls, and to assess the relationship of the knee varus angle and moment to the clinical outcome as measured by the WOMAC/VAS. The hypotheses that pre-surgical TKR subjects would have greater knee varus angle and moment than controls for both level walking and stair ascent, but that these values would normalize as a result of surgery were confirmed in the study. However, the hypothesis that patients with high varus moments would have greater self-reported pain and disability than those with low varus moments was not supported.

In this study, knee varus deformity was quantified for TKRs at P1 by assessing the FKA at the 1st peak F_z , coincident with single-limb support of the body (Fig. 1). A dynamic determination of the FKA was used to quantify the tibio/femoral orientation under loading conditions

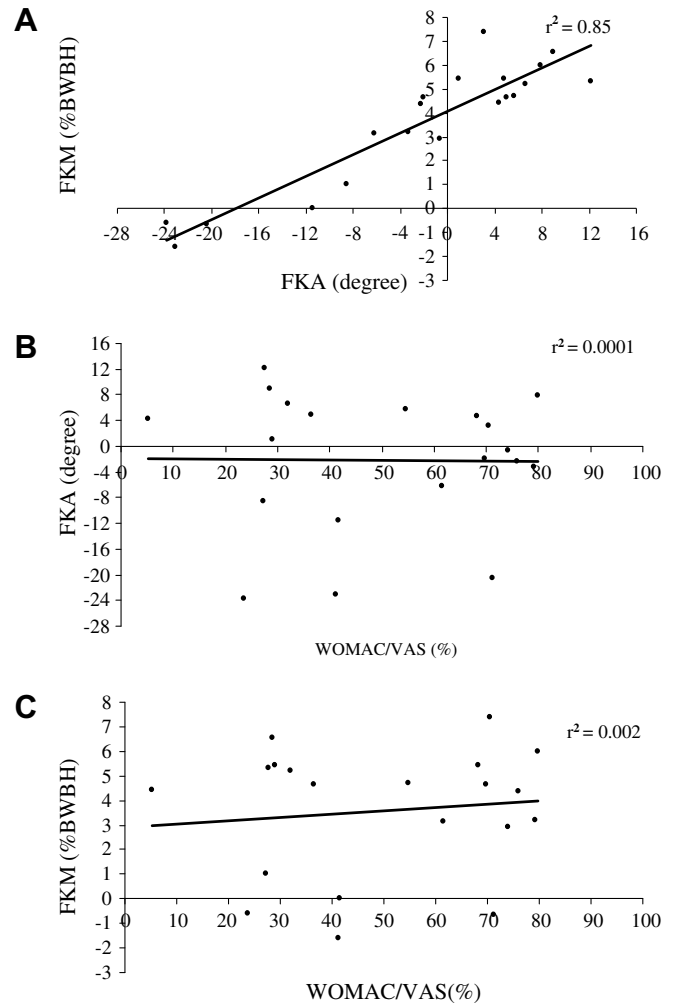


Fig. 4. Scatter plots showing the TKR level walking relationships between (A) the frontal knee angle (FKA) and the frontal knee moment (FKM), (B) the FKA and the total WOMAC/VAS score, and (C) the FKM and the total WOMAC/VAS score.

which knee OA progression occurs. This dynamic FKA value served to differentiate end-staged knee OA subjects from post-TKR subjects. However, the interpretation of this value requires a consideration of its mid-stance context. The FKA values for healthy subjects were approximately 4° of valgus. This valgus orientation is consistent with the mid-stance valgus thrust, described by Perry (1974), which is incurred at the knee as the body weight is supported by the single limb. However, the FKM at this time is varus. Interestingly, the controls showed a mean varus FKM (2.7% BWBH) that was close to twice as large as the knee extension moment (1.52% BWBH) previously reported (Mandeville et al., 2007). Thus, despite the valgus knee inclination as the proximal femur abducts under the body weight, considerable joint loading is passed through the medial compartment of the knee during level walking. These findings are consistent with those of Schipplein and Andriacchi (1991) who showed that the medial compartment bears a majority of the knee load for normal subjects.

The relationship between statically determined knee deformity and the FKM for knee OA subjects has been reported previously (Sharma et al., 1998), which showed a significant negative relation between medial knee joint space width and peak FKM. In the present study, the mean valgus knee angle under dynamic conditions was less than half of the controls during the support phase of P1 (Fig. 1), allowing for a significantly greater varus moment (44%) and a potentially greater load applied to the medial compartment. Both the TKR and CON group frontal plane knee moment values were consistent with those previously reported (Hurwitz et al., 2002; Sharma et al., 1998; Prodromos et al., 1985).

As a result of the total knee replacement surgery, the mean patient frontal knee angle and moment were significantly altered to approach control values. Hilding et al. (1995) reported a realignment effect for total knee replacement surgery as a 9° shift into decreased varus for subjects measured statically. A similar resolution of FKM values to control levels as a result of surgery has been reported for HTO patients (Prodromos et al., 1985) and for TKR patients (Hilding et al., 1995).

The critical effect of knee alignment on the FKM for knee OA/TKR subjects is seen in the strong positive relationship for walking at P1 ($r = 0.92$) and P2 ($r = 0.73$) such that 53–85% of the variation in the FKM was explained by the FKA. These results are consistent with the strong positive relationship reported by Hurwitz et al. (2002) between static FKA and the 1st peak FKM ($r^2 = 0.53$). However, the dynamic FKA, assessed in the present study, resulted in a stronger positive relationship with FKM, suggesting that dynamically assessed tibio/femoral orientation may more accurately predict knee loading for end-stage knee pre- and post-surgical OA patients. Although substantive TKR stair ascent FKA change occurred as a result of surgery, significant findings may have been masked by higher variability of the stair ascent FKA values for both groups when compared to level walking. This variability may have arisen from differences in the use of a forefoot base of support and the flexed knee position (35–50°) during stair climbing which allows for greater frontal plane knee motion compared to a flat foot base of support and a more closed-packed, extended knee position (10–16°) in level walking. While stair ascent has been shown to elicit greater demands on the knee extension moment compared to level walking for these TKR subjects (Mandeville et al., 2007), the FKM values for stair ascent were similar to their level walking values. However, the significant reduction in varus FKM from pre- to post-surgery suggests that the subjects accommodate to the demands of stair ascent as well as they do to level walking by reducing knee medial compartment loading. Kaufman et al. (2001) reported knee varus moments for knee OA subjects during stair ambulation, which were noticeably less than those presently reported, despite the use of similar step heights and joint models. These differences may have been due to the limited joint deformity of their early stage knee OA subjects who

showed full range of knee motion during stair ascent, compared to the end-stage subjects of the present study who exhibited limited flexion.

The dynamic FKA and the FKM were not significantly correlated to the clinical outcome measured by the total WOMAC/VAS score. This result was unexpected as pain has been thought to be a stimulus for knee unloading gait adaptations (Schnitzer et al., 1993). Hurwitz et al. (2002) reported a significant negative relationship between FKM and total WOMAC/VAS score ($r = -0.330$), such that knee OA subjects with greater symptoms walked with less FKM. However, when fitted into a regression equation predicting the first peak FKM, the total WOMAC score contributed an increase of only 2% to the prediction accuracy. Thus, the clinical outcome measure may be of little utility when predicting dynamic knee loading for knee OA subjects. The present results suggest an uncoupling between patients' perception of pain and dysfunction and their objective knee function.

The difference in Body Mass Index (BMI) between TKR and control subjects is a limitation of this study. However, DeVita and Hortobagyi (2003) reported that healthy obese and lean adults (mean BMI = 42.3 kg/m² vs. 22.7 kg/m²) had identical knee torques and powers when walking at the same speed. In the current study, the difference in BMI between the TKR and control groups is consistent with BMIs found in TKR patients and the otherwise healthy age-matched population. The mean pre- and post-surgery TKR BMI of ~32.65 kg/m² reflects typical values for patients undergoing this procedure (Namba et al., 2005) while the mean control BMI of ~26.73 kg/m² approximates the norm for individuals 60–74 yr of age (Ogden et al., 2004). Hence, the values in this study are representative of typical BMI characteristics of the two populations under investigation (Mandeville et al., 2008).

The findings of this study were also limited by the variability seen for the frontal plane knee angle and moment values. While these measures are inherently characterized by large variability, as seen in the CON values (Table 1), an effort was made to minimize this variability by statistically controlling for the effect of gait velocity on frontal plane knee measures (Mundermann et al., 2004). However, an additional source of variability was a degree of heterogeneity of our TKR sample, which contained subjects with both varus and valgus deformities. While this variability could have been minimized by including only patients with knee varus deformity, the present results apply more generally to the end-staged knee OA population for which ~13% show valgus static FKA (Ritter et al., 1994).

An additional source of error is the floating axis about which the frontal plane knee angle was estimated, which is based on the assumption that the medial/lateral axis of the distal femur is perpendicular to the longitudinal axis of the tibia. While this assumption may not occur physiologically (Kowalk et al., 1996), the model was found to be useful in describing relative differences within and

between groups. Future studies employing dynamic imaging of the arthrokinematics of the knee may provide additional insight into the relationship between load and alignment and the effect that TKR has on both. Assessment of the long term outcomes for frontal plane knee angle is also needed to ascertain if the surgical effect is susceptible to recurrent varus angulation (Prodromos et al., 1985), or whether the effect is robust to these changes (Hilding et al., 1995).

5. Conclusion

The significantly greater pre-operative TKR knee varus moment for level walking was restored to CON level post-operatively. This appears to be due, in part to the surgical realignment of the tibio–femoral joint, as the frontal knee angle and knee moment were found to be strongly correlated. Significantly less post-operative TKR knee varus moment compared to CON was also seen for stair climbing. The clinical WOMAC/VAS index was not significantly correlated to the frontal plane knee variables suggesting that the subjective measure and the objective measure captured different dimensions of the knee OA.

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