The Knee 26 (2019) 737–744

Contents lists available at ScienceDirect

The Knee

Residual varus alignment after total knee arthroplasty increases knee adduction moment without improving patient function: A propensity score-matched cohort study

Du Hyun Ro, Jong-Keun Kim, Do Weon Lee, Jangyun Lee, Hyuk-Soo Han, Myung Chul Lee *

Department of Orthopaedic Surgery, Seoul National University Hospital, Seoul, Republic of Korea

ARTICLE INFO

Article history:
Received 1 September 2018
Received in revised form 9 January 2019
Accepted 17 February 2019

Keywords:
Alignment
Total knee arthroplasty
Residual varus
Biomechanics
Motion capture system

ABSTRACT

Background: Targeting residual varus alignment in total knee arthroplasty may be functionally beneficial to preoperative varus patients.
Methods: Bilateral TKA patients were enrolled. According to the postoperative hip-knee-ankle axis, patients were allocated into residual varus ($3° \pm 1°$) alignment group or neutral ($0° \pm 1°$) alignment group. Then, 1:2 propensity score matching was used to match preoperative variables. Finally, matched neutral ($n = 45$) and varus groups ($n = 32$) were followed-up for two years and compared. The primary outcome was the Western Ontario & McMaster Universities Osteoarthritis Index (WOMAC). Secondary outcomes were range of motion (ROM), Knee Society knee score and function score, spatiotemporal gait parameters, dynamic alignment, knee flexion angle, knee adduction moment (KAM) and internal knee extension moment.
Results: At two years after surgery, the mean difference of WOMAC score was 0.3 (95% CI, [−3.1, 3.7]) between the two groups. All secondary outcomes, except KAM and dynamic alignment, showed no significant difference between the two groups. Residual varus alignment group showed increased KAM and maximum KAM was 19% higher ($P = 0.006$).
Conclusions: Residual varus alignment showed no clinical benefits, and both groups of patients had a functionally identical knee gait biomechanics, except for increased KAM and varus alignment. The authors consider that even in patients with varus alignment, the first principle is still achieving neutral alignment, which is helpful for reducing the KAM.
Level of evidence: III, retrospective cohort study.

1. Introduction

Total knee arthroplasty (TKA) is traditionally aimed at obtaining a neutral alignment in the coronal plane and symmetrical flexion and extension gap through a correct bone resection and meticulous soft tissue balancing [1,2]. Neutral alignment in the coronal plane showed excellent long-term implant survival in many studies, and was accepted as the gold standard [1–3]. Substantial healthcare resources have been devoted to the development and use of computer navigation and patient-specific instrumentation systems that achieve neutral mechanical alignment [2,4,5].

However, some authors have cast doubt on the long-held belief that neutral alignment yields lower revision rates [4,6,7]. Bellemans et al. have further fueled this debate as they showed that neutral alignment may not be desirable for everyone due to the concept of

* Corresponding author at: Department of Orthopaedic Surgery, Seoul National University Hospital, 101 Daehak-ro, Jongno-gu, Seoul 110-744, Republic of Korea.
E-mail address: leemc@snu.ac.kr (M.C. Lee).

https://doi.org/10.1016/j.knee.2019.02.006
0968-0160/

constitutional varus [8]. Thus, some authors challenged the concept of neutral alignment in TKA [9–11]. In addition, 20% of patients showed unsatisfactory results after surgery, suggesting that the neutral alignment might not be a rule [12–14].

At this point, it is particularly important whether we should leave residual varus in patients with preoperative varus. Questions such as "Does residual varus TKA recreate preoperative constitutional varus alignment?", and "Does it improve clinical outcome and function in patients?" are of current interest and under debate among arthroplasty surgeons [10,15–19].

However, current comparative studies regarding this subject are surprisingly scarce and inconclusive [10,15–20]. Moreover, conclusions regarding patient function are based on questionnaires or radiologic measurements. We consider that functional evaluation by knee gait biomechanics would provide objective information regarding this question.

We therefore investigated patient outcomes using conventional patient-reported questionnaires, radiologic measurements and knee gait biomechanics. In this study, we hypothesized that residual varus improved patient outcomes compared to neutral alignment TKA. The goals of this study were: (1) to evaluate whether residual varus improved patient outcomes compared to neutral alignment TKA, and (2) to compare the knee gait biomechanics between two groups.

2. Materials and methods

2.1. Study subjects

This study was approved by our Institutional Review Board. A total of 245 patients undergoing bilateral TKA with preoperative varus deformity were recruited (Figure 1). Bilateral staged TKA was performed at a one-week interval. The following exclusion criteria were applied: (1) primary diagnosis other than osteoarthritis; (2) male sex; (3) age <50 or >90 years; (4) postoperative complications; (5) postoperative mechanical axis difference between two limbs more than two degrees or valgus alignment more than two degrees; (6) prior hip or ankle replacement surgery; and (7) previous fracture surgery or deformity of the lower extremity. Therefore, 184 patients with preoperative varus deformity (mean varus, 10.8° (SD 4.1°); range, four to 23°) with a mean age of 68.1 (SD 6.1) years (range, 51–86 years) were eligible for the study. Patients were then divided into neutral alignment (0° ± 1°) and residual varus alignment (3° ± 1°) groups according to their mechanical axis (hip–knee–ankle axis) of the right limb (Figure 1). Patients not included in the neutral or varus alignment group were excluded from the analysis (i.e. valgus more than one degree (n = 1) or between varus one to two degrees (n = 49) or varus >4° (n = 2)). A pilot study performed on 30 patients (15 patients in each group) detected a tendency for varus to persist if the varus deformity was severe (varus >15°) before surgery. As it could be a significant confounding variable for the outcome, the propensity score matching was used. Matching was planned

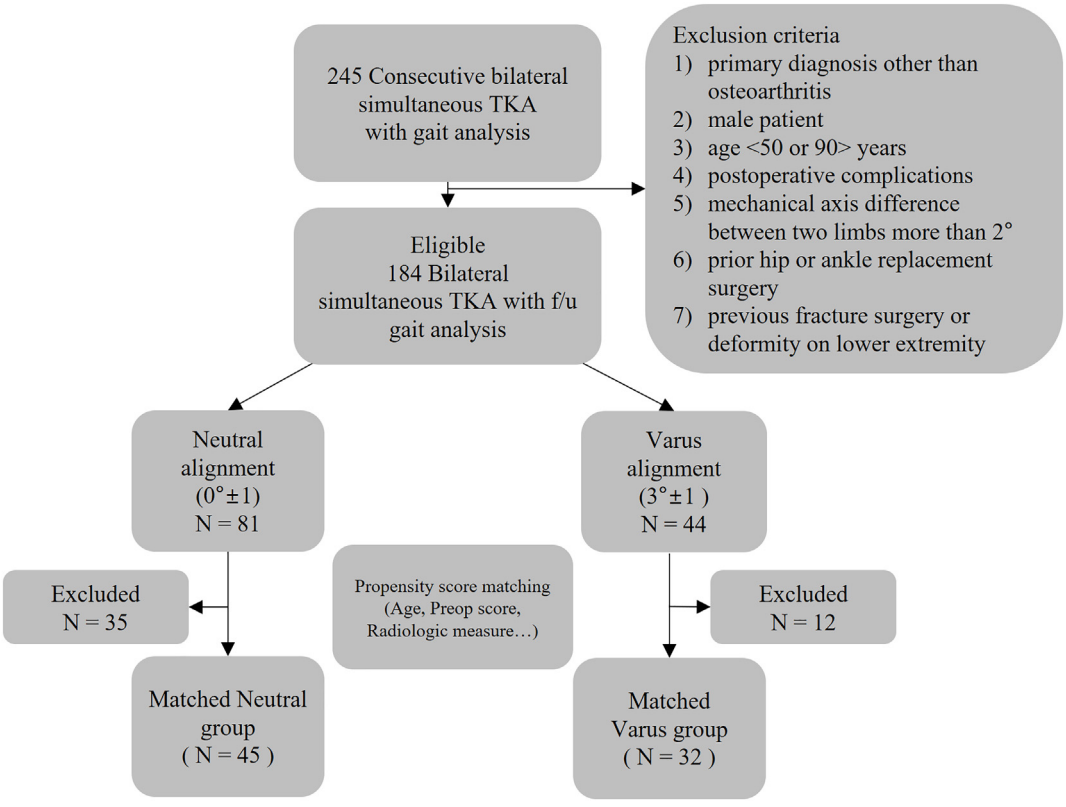

Figure 1. Study protocol.

for age, body mass index (BMI), range of motion (ROM), preoperative mechanical axis, femur rotation, ligament release, patella resurfacing, and preoperative clinical scores (Table 1).

Finally, 32 patients with residual varus TKA were matched with 46 patients with neutral TKA. The cohort was then followed up for two years. Primary outcome was the Western Ontario and McMaster Universities Arthritis Index (WOMAC). Secondary outcomes were ROM, Knee Society knee score and function score (KSKS and KSFS), spatiotemporal gait parameters, dynamic alignment, knee flexion angle, knee adduction moment (KAM) and internal knee extension moment (KEM).

2.2. Surgical/rehabilitation protocol

TKA was performed by a single surgeon with the same surgical/rehabilitation protocol. A medial parapatellar approach was used and both cruciate ligaments were resected in all cases. Routine release of deep medial collateral ligament was performed and additional semi-membranous release was performed in eight (10.4%) cases. TKA was performed with a goal of neutral mechanical alignment. Single posterior stabilized, fixed bearing implant was used (NexGen LPS-flex®; Zimmer Inc., Warsaw, IN, USA). Patella was resurfaced in all cases, except in the case of a thin patella (<20 mm) or intact cartilage (n = 21, 27.3%). All prostheses were fixed with cement. Postoperatively, active and passive ROM exercises were started 24 h after operation.

2.3. Radiologic measurement

The entire radiographic evaluation was independently performed by two authors (fellowship-trained in arthroplasty) blinded to other information. The inter-observer reliability of radiologic assessment was satisfactory (intra-class correlation coefficient 0.86–0.96). The average values measured by two observers were used in the analysis. Mechanical axis (hip–knee–ankle axis) was measured using standing full-limb radiography. All radiographic images were digitally acquired using a picture archiving and communication system (PACS) (Maroview 5.4, Infinitt, Seoul, South Korea), and assessments were performed using the PACS software.

To determine the rotational alignment of the femur, transverse computed tomography (CT) scans (Lightspeed Ultra®, GE Medical Systems, Milwaukee, WI, USA) were performed at one-millimeter intervals from the distal femur to the ankle joint before discharge. The Digital Imaging and Communications in Medicine (DICOM) files of CT scans were processed using a three-dimensional (3D) image reconstruction/analysis program (OnDemand3D™, CyberMed Inc., Irvine, CA, USA) to select the optimal image for measurement. The clinical trans-epicondylar axis (CEA) was defined as a line connecting the vertices of the medial and lateral epicondyles, while the posterior condylar axis as a line connecting the vertices of the articular surfaces on the medial and lateral posterior femoral condyles on a two-dimensional (2D) slice image. The angle between the CEA and posterior condylar axis was measured as the femur rotation. Internal rotation of the femur was considered as a negative value, and external rotation as a positive value.

2.4. Gait analysis protocol

Gait data were collected from the Human Motion Analysis Lab at our institution. The protocol used for gait analysis was the same as in our previous studies [21–23]. Participants were asked to perform an easy five-minute walk to warm up. After warming

Table 1
Study population.

		Total population (n = 125)			Propensity-matched population (n = 77)		
		Neutral (n = 81)	Varus (n = 44)	*P*	Neutral (n = 45)	Varus (n = 32)	*P*
		Mean ± SD	Mean ± SD		Mean ± SD	Mean ± SD	
Age		69.5 ± 5.5	70.4 ± 6.2	0.404	70.1 ± 5.4	69.7 ± 6.3	0.795
Body mass index (kg/m^2)		26.9 ± 3.4	26.6 ± 2.5	0.534	26.6 ± 3.5	26.3 ± 2.4	0.670
Range of motion		121 ± 13	114 ± 19	**0.018**	119 ± 14	113 ± 20	0.194
Preop radiologic measure	Mechanical axis (right)	8.7 ± 4.1	12.6 ± 5.1	<**0.001**	10.5 ± 4.1	11.2 ± 4.3	0.460
	Rotation (right)	5.2 ± 1.6	5.4 ± 1.8	0.505	5.6 ± 1.7	5.5 ± 1.7	0.826
	Mechanical axis (left)	9.3 ± 4.1	12.6 ± 5.5	<**0.001**	10.8 ± 4.2	10.8 ± 4.6	0.959
	Rotation (left)	5.1 ± 1.3	5.4 ± 1.7	0.271	5.3 ± 1.4	5.4 ± 1.8	0.735
Preop clinical scores	KSKS	53.7 ± 15.2	49.7 ± 13.4	0.141	50.9 ± 15.2	49.9 ± 14	0.766
	KSFS	41.8 ± 14.7	44 ± 14.9	0.444	43.6 ± 14.6	45.1 ± 15.5	0.670
	WOMAC	56.3 ± 19.7	55 ± 14.7	0.701	55.4 ± 20.1	55.3 ± 15.3	0.969
Semi-membranous insertion release	Yes	9	13	**0.014**	4	6	0.304
	No	72	31		41	26	
Patella resurfacing	Yes	22	14	0.680	33	23	1.000
	No	59	30		12	9	

Rotation: femur rotation (angle between clinical trans-epicondylar axis and posterior condylar axis). Positive value represents external rotation. KSFS, Knee Society function score; KSKS, Knee Society knee score; SD, standard deviation; WOMAC, Western Ontario & McMaster Universities Osteoarthritis Index.
Bold text indicates statistical significance.

up, reflection markers were placed on the subjects [24]. Then, the subjects were asked to walk at a self-selected speed along a nine-meter track.

Kinematic data were acquired at a sample rate of 120 Hz using 12 charge-coupled device cameras equipped with a 3D optical motion capture system (Motion Analysis, Santa Rosa, USA). Ground reaction force (kinetic) data were acquired at a sampling rate of 1200 Hz using three Advanced Mechanical Technology Inc. (AMTI, Watertown, MA, USA) force plates. The kinetic data were then normalized by height and weight (% body weight × height) [25].

We used Eva Real-Time software (Motion Analysis, Santa Rosa, USA), Microsoft Excel 2016 (Microsoft, Redmond, USA), and MATLAB R2017a (Mathworks, Natick, MA, USA) for real-time motion capture, post-processing and marker data tracking. The average of three representative strides from five or six separate trials was used for the analysis of each session [21–23]. Because the movement of both lower extremities is possibly dependent on each other, the right side is used as a representative (both radiological and gait data).

Kinetic and kinematics of the knee were investigated. These data were normalized to 101 data points over the gait cycle (waveform data). Coronal arc, which was defined as "the difference in angle between the maximum valgus angle and the maximum varus angle during the gait cycle" was extracted [24]. Maximum moment value and range of kinematic data were also extracted. Waveform pattern was recognized by principal component analysis and described in the Supplementary material [26].

2.5. Statistical analysis

The propensity score was calculated by binary logistic regression using R-packages with the covariates specified in Table 1. The criteria for propensity score matching were set using the greedy matching algorithm at a ratio of 1:2. As a first step, the match was performed with a propensity score that was identical to eight decimal places to the neutral alignment group. If no match was found, a match would be sought at seven decimal places; calculations were performed to one decimal place. The standardized difference was used as balance diagnostics, and differences of less than 10% were considered acceptable in the mean or prevalence of covariates between the groups.

Primary and secondary outcomes were compared using independent Student's *t*-test between varus and neutral alignment groups. For the categorical data, the Chi-squared test was used.

A power calculation performed prior to the study indicated that the sample had a power of 99% with alpha 0.05 to detect a difference of 10 points or greater on the average WOMAC scores [27]. $P < 0.05$ was considered statistically significant. Statistical analyses were performed using SPSS® ver. 19.0.1 for Windows (SPSS Inc., Chicago, IL, USA) and MatchIt and optmatch packages of R version 3.4.1 (Single Candle).

3. Results

After propensity score matching, covariates including demographics showed no significant difference between the groups (Table 1). The average WOMAC score of the neutral and varus alignment groups was 6.6 ± 7.8 and 6.3 ± 6.3, respectively. Mean difference was 0.3 (95% confidence interval (CI), −3.1, 3.7, $P = 0.864$) between the two groups. It showed sufficient power to conclude that no significant difference existed between the two groups ($\beta = 0.98$). Secondary outcomes also showed no significant difference between the two groups (Table 2). Spatiotemporal parameters including, gait speed, stride length, and cadence also showed no difference between the two groups.

With regard to the kinematics, sagittal ROM and coronal arc showed no difference between the two groups (Table 3). Kinematic waveform data showed identical gait patterns except overall varus alignment of knee joint (Figure 2, $P < 0.001$). Waveform data was quantitatively analyzed with Principal component analysis (see Supplementary data for the PCA analysis).

Table 2
Primary and secondary outcome measures.

	Neutral (n = 45)	Varus (n = 32)	Mean difference (95% CI)	*P*
	Mean ± SD	Mean ± SD		
Clinical scores				
WOMAC (primary outcome)	6.6 ± 7.8	6.3 ± 6.3	0.3 (−3.1 to 3.7)	0.864
KSKS	97.9 ± 4.7	98.2 ± 2.2	−0.2 (−2.0 to 1.6)	0.833
KSFS	90.0 ± 11.2	87.3 ± 11.9	2.8 (−2.5 to 8.1)	0.690
Range of motion	130 ± 8	128 ± 7	2.1 (−1.4 to 5.5)	0.234
Spatiotemporal data				
Cadence (steps/min)	108.7 ± 8.3	109 ± 12.2	−0.3 (−4.9 to 4.3)	0.904
Speed (cm/s)	92.3 ± 13.1	92.4 ± 20.3	−0.1 (−7.7 to 7.4)	0.970
Stride length (cm)	101.5 ± 11.2	100.5 ± 16	1.0 (−5.2 to 7.1)	0.761
Step width (cm)	10.7 ± 2.3	11 ± 2.7	−0.4 (−1.5 to 0.8)	0.533

CI, confidence interval; KSFS, Knee Society function score; KSKS, Knee Society knee score; SD, standard deviation; WOMAC, Western Ontario & McMaster Universities Osteoarthritis Index.

Table 3
Range of motion during gait cycle.

		Neutral (n = 45)	Varus (n = 32)	*P*
		Mean (range)	Mean (range)	
Sagittal ROM	Knee	53 (9–63)	54 (8–62)	0.466
	Hip	41 (−1 to 40)	42 (−4 to 38)	0.554
Coronal arc	Knee	3 (−2 to 1)	3 (1–4)	0.709
	Hip	9 (−3 to 6)	9 (−5 to 3)	0.722

ROM, range of motion.

For kinetics, maximum KAM was 19% higher in the varus group ($P = 0.006$) and this was the only significant difference between the groups (Table 4). Maximum KAM of the neutral group and varus group was 2.53 ± 0.73 (%Bw * Ht) and 3.01 ± 0.77 (%Bw * Ht), respectively. Kinetic waveform data showed that the overall magnitude of KAM was higher in the varus group, which is in concordance with maximum KAM (Figure 2, $P = 0.008$). Sagittal kinetic waveforms showed identical gait patterns (see Supplementary material for the PCA analysis).

4. Discussion

Important findings of this study were: (1) Residual varus alignment is not beneficial for WOMAC, KSKS, and KSFS scores; (2) KAM was increased in the varus group; and (3) other kinetic or kinematic data and gait speed showed no advantages for the varus group. Based on these data, we consider that neutral alignment should be targeted in patients with preoperative varus.

These results are in line with those of previous studies showing no difference in clinical outcomes in residual varus alignment [15,19,20]. Our data also showed no significant difference in gait speed, kinetics, and kinematics between the two groups. The results of this study are also consistent with those of previous studies showing no significant functional differences [15,19]. However, it was notable that only KAM increased in the varus group among the various gait parameters. In the stance phase of the gait, the knee is positioned relatively outward relative to the center of gravity. This causes a varus torque to the knee, which is

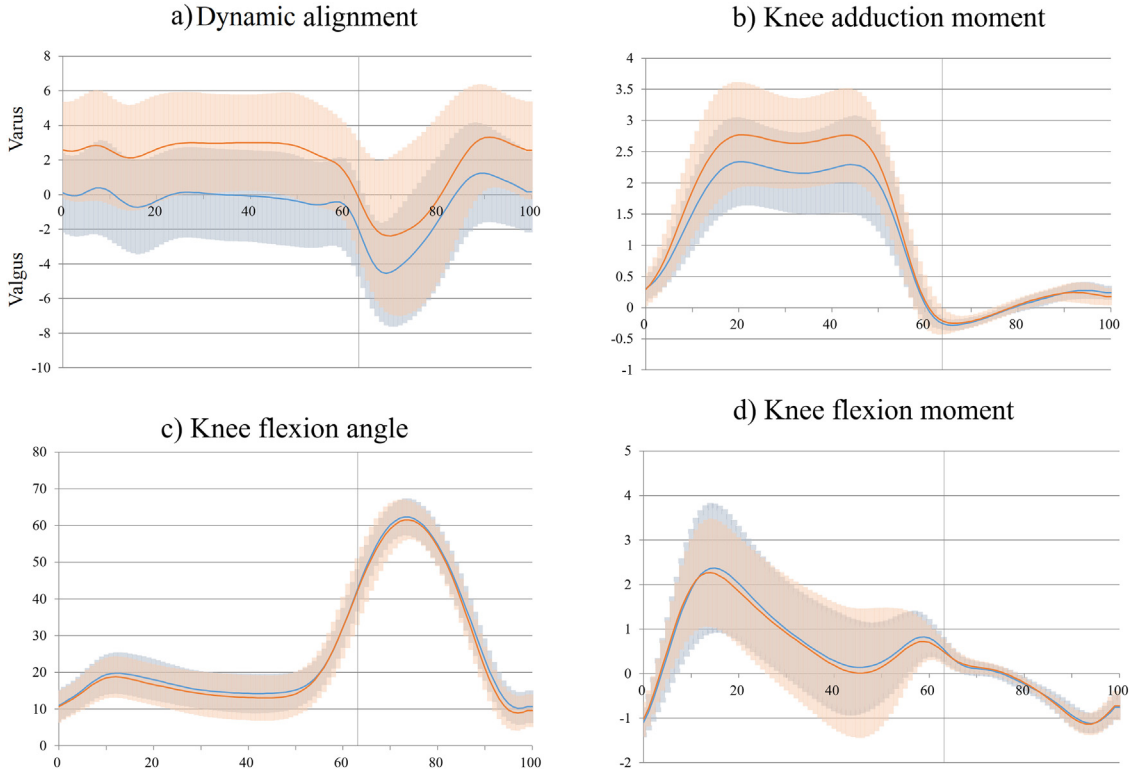

Figure 2. Kinetic and kinematic waveform data of residual varus (red) versus neutral (blue) alignment group. Kinematic data are presented in degrees. Kinetic data are presented as %BW × Ht. Shaded area represents ±1 standard deviation. Vertical line divides stance and swing phase. See Tables 3 and 4 for the statistical analysis. (a) Dynamic alignment: note the difference of overall alignment between two groups. (b) Knee adduction moment, increased knee adduction moment was observed at varus group. (c) Knee flexion angle, no difference. (d) Knee extension moment, no difference.

Table 4
Maximum moment value.

	Neutral (n = 45)	Varus (n = 32)	*P*
	Mean ± SD	Mean ± SD	
Knee flexion moment	2.58 ± 1.17	2.54 ± 1.09	0.861
Hip extension moment	3.2 ± 0.83	3.11 ± 0.98	0.654
Hip flexion moment	−2.81 ± 0.76	−2.92 ± 0.84	0.559
Knee adduction moment	2.53 ± 0.73	3.01 ± 0.77	**0.006**
Hip abduction moment	5.23 ± 0.81	5.08 ± 0.86	0.434

SD, standard deviation.

the definition of external KAM. Numerous literatures have shown that the KAM is correlated with the medial joint loading [28–36]. Considering the fact that KAM is a surrogate marker for medial joint loading [33,37–39] and that it may also be associated with implant loosening [40], we consider that residual varus can be disadvantageous for implant longevity. This finding suggesting that varus alignment is disadvantageous to longevity is also consistent with previous studies [1–3,20]. Increased polyethylene wear or stress of medial side is likely to occur. To our knowledge, this is the first study to compare kinetics and kinematics of residual varus versus neutral alignment in patients with preoperative varus.

However, the results of this study are inconsistent with those of previous studies showing that residual varus alignment results in poor outcomes [1–3,5,41], and that residual varus results in better outcomes [10,16]. These conflicting results regarding alignment have several implications and the authors consider that several factors are important for this difference. First, there may be differences in surgical technique and implant design [1–3,5,10,15,16,19,41]. The development of surgical techniques and modern implants can be tolerable in a certain range of mechanical axes. Modern implants with standard surgical technique were used in our study. Second, soft tissue release and patella resurfacing may be associated with surgical outcomes. Most of the above-mentioned studies did not report details regarding these important factors. Third, the lack of an analysis of preoperative alignment and the lack of preoperative patient matching may be another cause for a different conclusion. In fact, preoperative varus deformity often leads to residual varus, as obtaining neutral alignment can be challenging in case of substantial deformity [42]. Propensity score matching used in our study minimized the possible confounding effect. Fourth, femoral component rotation may also have an effect. We performed preoperative CT scans to optimize femoral component rotation for each patient and confirmed that proper femoral component rotation was achieved. Finally, there may be an inadequacy of the current questionnaire itself when evaluating these patients. WOMAC, KSKS and KSFS are appropriate for recognizing pre- and postoperative changes in patients with arthritis, but may be inadequate for detecting delicate changes such as functioning by alignment. The WOMAC score, KSKS, KSFS and other scores showed little difference or standard deviations were very large in the majority of studies [5,10,16,41]. Even if significant difference exists, it is also unclear from what degree the difference should be accepted as clinically meaningful in this particular situation [27]. Apart from the subjects of this study, we consider that the researcher should try to objectify patient evaluation. We think that gait analysis is part of this effort. It can precisely objectify the gait and indirectly predict the load applied to the implant. In this study, no difference was found between the two groups in most kinetic and kinematic data, including walking speed. Instead, only the alignment and differences of KAM were found. Based on this fact, the benefits of residual varus alignment were not detected, and both groups of patients had a functionally identical gait pattern, except for KAM and alignment. In addition, KAM was 19% higher in the varus-aligned group, suggesting that loosening is more likely to occur in the long-term follow-up.

This study had several limitations. First, a two-year follow-up was relatively short for a TKA study. Thus, this study is not appropriate to analyze the failure rate or to draw a conclusion regarding long-term results. However, as the primary goal of this study was to evaluate functional outcomes, the authors consider that two years is an acceptable follow-up period. Functionality after TKA improves during the first six months and reaches a plateau after two years [43]. Second, the number of subjects was relatively limited, as this study combined motion analysis. Motion analysis is a time- and money-consuming process and patients often refused to perform it. However, our data showed sufficient power for the primary outcomes and motion analysis data. A prospective study with large study subject should be performed to overcome this limitation. Third, males were excluded in the analysis because of sex differences of knee biomechanics [21]. Although we excluded males from the analysis, we think that our results can be applied to males for two reasons: (1) the same surgical principles are applied in both men and women [21]; and (2) the KAM difference is associated with the pelvic width and the step width, which is not directly affected during surgery. Thus, we think that it is reasonable to generalize our results to males. Finally, the study has a retrospective design, although data were collected prospectively as part of a joint registry at our institution. However, during the study period, analyzed data, including gait analysis, were collected by the same investigators. Thus, we do not anticipate the introduction of substantial bias with this limitation. In addition, we used propensity score matching to match several preoperative variables. We believe that this fact also limited possible biases.

5. Conclusions

In conclusion, no clinically significant differences were found between the residual varus alignment and neutral alignment groups. Moreover, no biomechanical difference, except varus alignment and the increase of KAM, was detected between these two groups. Therefore, the authors consider that even in patients with varus alignment, the first principle is still achieving neutral alignment, which is helpful for reducing the KAM.

Conflict of Interest

The authors certify that they have no commercial association that might pose a conflict of interest in connection with this article.

Acknowledgments

We appreciated to Seong Hyun Kim, Hye Sun Park, Hyo Jeong Yoo for the technical support in collecting and analyzing the kinematic data from the participants. We appreciate the statistical consultation provided by the Medical Research Collaborating Center at the Seoul National University College of Medicine. Also, Eun Soo Ahn is thanked for help in proofreading and correcting the manuscript. This study was supported by the Basic Science Research Program through the National Research Foundation of Korea (NRF), funded by the Ministry of Science (NRF-2015R1D1A1A01059785). The funding source did not influence the result of the study.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.knee.2019.02.006.

References

[1] Gromov K, Korchi M, Thomsen MG, Husted H, Troelsen A. What is the optimal alignment of the tibial and femoral components in knee arthroplasty? Acta Orthop 2014;85:480–7.
[2] Abdel MP, Oussedik S, Parratte S, Lustig S, Haddad FS. Coronal alignment in total knee replacement: historical review, contemporary analysis, and future direction. Bone Joint J 2014;96-B:857–62.
[3] Werner FW, Ayers DC, Maletsky LP, Rullkoetter PJ. The effect of valgus/varus malalignment on load distribution in total knee replacements. J Biomech 2005;38:349–55.
[4] Parratte S, Pagnano MW, Trousdale RT, Berry DJ. Effect of postoperative mechanical axis alignment on the fifteen-year survival of modern, cemented total knee replacements. J Bone Joint Surg Am 2010;92:2143–9.
[5] Choong PF, Dowsey MM, Stoney JD. Does accurate anatomical alignment result in better function and quality of life? Comparing conventional and computer-assisted total knee arthroplasty. J Arthroplasty 2009;24:560–9.
[6] Morgan SS, Bonshahi A, Pradhan N, Gregory A, Gambhir A, Porter ML. The influence of postoperative coronal alignment on revision surgery in total knee arthroplasty. Int Orthop 2008;32:639–42.
[7] Bonner TJ, Eardley WG, Patterson P, Gregg PJ. The effect of post-operative mechanical axis alignment on the survival of primary total knee replacements after a follow-up of 15 years. J Bone Joint Surg Br 2011;93:1217–22.
[8] Bellemans J, Colyn W, Vandenneucker H, Victor J. The Chitranjan Ranawat award: is neutral mechanical alignment normal for all patients? The concept of constitutional varus. Clin Orthop Relat Res 2012;470:45–53.
[9] Howell SM, Hodapp EE, Vernace JV, Hull ML, Meade TD. Are undesirable contact kinematics minimized after kinematically aligned total knee arthroplasty? An intersurgeon analysis of consecutive patients. Knee Surg Sports Traumatol Arthrosc 2013;21:2281–7.
[10] Howell SM, Howell SJ, Kuznik KT, Cohen J, Hull ML. Does a kinematically aligned total knee arthroplasty restore function without failure regardless of alignment category? Clin Orthop Relat Res 2013;471:1000–7.
[11] Howell SM, Papadopoulos S, Kuznik KT, Hull ML. Accurate alignment and high function after kinematically aligned TKA performed with generic instruments. Knee Surg Sports Traumatol Arthrosc 2013;21:2271–80.
[12] Choi YJ, Ra HJ. Patient satisfaction after total knee arthroplasty. Knee Surg Relat Res 2016;28:1–15.
[13] Bourne RB, Chesworth BM, Davis AM, Mahomed NN, Charron KD. Patient satisfaction after total knee arthroplasty: who is satisfied and who is not? Clin Orthop Relat Res 2010;468:57–63.
[14] Scott CE, Howie CR, MacDonald D, Biant LC. Predicting dissatisfaction following total knee replacement: a prospective study of 1217 patients. J Bone Joint Surg Br 2010;92:1253–8.
[15] Meneghini RM, Grant TW, Ishmael MK, Ziemba-Davis M. Leaving residual varus alignment after total knee arthroplasty does not improve patient outcomes. J Arthroplasty 2017;32:S171–6.
[16] Vanlommel L, Vanlommel J, Claes S, Bellemans J. Slight undercorrection following total knee arthroplasty results in superior clinical outcomes in varus knees. Knee Surg Sports Traumatol Arthrosc 2013;21:2325–30.
[17] Hatayama K, Terauchi M, Saito K, Higuchi H. Does residual varus alignment cause increasing varus laxity at a minimum of five years after total knee arthroplasty? J Arthroplasty 2017;32:1808–13.
[18] Fang DM, Ritter MA, Davis KE. Coronal alignment in total knee arthroplasty: just how important is it? J Arthroplasty 2009;24:39–43.
[19] Magnussen RA, Weppe F, Demey G, Servien E, Lustig S. Residual varus alignment does not compromise results of TKAs in patients with preoperative varus. Clin Orthop Relat Res 2011;469:3443–50.
[20] Park JK, Seon JK, Cho KJ, Lee NH, Song EK. Is immediate postoperative mechanical axis associated with the revision rate of primary total knee arthroplasty? A 10-year follow-up study. Clin Orthop Surg 2018;10:167–73.
[21] Ro DH, Lee DY, Moon G, Lee S, Seo SG, Kim SH, et al. Sex differences in knee joint loading: cross-sectional study in geriatric population. J Orthop Res 2017;35:1283–9.
[22] Ro DH, Han HS, Lee DY, Kim SH, Kwak YH, Lee MC. Slow gait speed after bilateral total knee arthroplasty is associated with suboptimal improvement of knee biomechanics. Knee Surg Sports Traumatol Arthrosc 2018;26:1671–80.
[23] Ro DH, Han HS, Kim SH, Kwak YH, Park JY, Lee MC. Baseline varus deformity is associated with increased joint loading and pain of non-operated knee two years after unilateral total knee arthroplasty. Knee 2018;25:249–55.
[24] Kadaba MP, Ramakrishnan HK, Wootten ME. Measurement of lower extremity kinematics during level walking. J Orthop Res 1990;8:383–92.
[25] Wannop JW, Worobets JT, Stefanyshyn DJ. Normalization of ground reaction forces, joint moments, and free moments in human locomotion. J Appl Biomech 2012;28:665–76.
[26] Deluzio KJ, Astephen JL. Biomechanical features of gait waveform data associated with knee osteoarthritis: an application of principal component analysis. Gait Posture 2007;25:86–93.
[27] Escobar A, Quintana JM, Bilbao A, Arostegui I, Lafuente I, Vidaurreta I. Responsiveness and clinically important differences for the WOMAC and SF-36 after total knee replacement. Osteoarthr Cartil 2007;15:273–80.
[28] Miyazaki T, Wada M, Kawahara H, Sato M, Baba H, Shimada S. Dynamic load at baseline can predict radiographic disease progression in medial compartment knee osteoarthritis. Ann Rheum Dis 2002;61:617–22.

[29] Bennell KL, Bowles KA, Wang Y, Cicuttini F, Davies-Tuck M, Hinman RS. Higher dynamic medial knee load predicts greater cartilage loss over 12 months in medial knee osteoarthritis. Ann Rheum Dis 2011;70:1770–4.
[30] Chehab EF, Favre J, Erhart-Hledik JC, Andriacchi TP. Baseline knee adduction and flexion moments during walking are both associated with 5 year cartilage changes in patients with medial knee osteoarthritis. Osteoarthr Cartil 2014;22:1833–9.
[31] Mahmoudian A, van Diesmall io RJH, Baert IAC, Bruijn SM, Faber GS, Luyten FP, et al. Changes in gait characteristics of women with early and established medial knee osteoarthritis: results from a 2-years longitudinal study. Clin Biomech (Bristol, Avon) 2017;50:32–9.
[32] Brisson NM, Wiebenga EG, Stratford PW, Beattie KA, Totterman S, Tamez-Pena JG, et al. Baseline knee adduction moment interacts with body mass index to predict loss of medial tibial cartilage volume over 2.5 years in knee osteoarthritis. J Orthop Res 2017;35:2476–83.
[33] Chang AH, Moisio KC, Chmiel JS, Eckstein F, Guermazi A, Prasad PV, et al. External knee adduction and flexion moments during gait and medial tibiofemoral disease progression in knee osteoarthritis. Osteoarthr Cartil 2015;23:1099–106.
[34] Thorp LE, Sumner DR, Wimmer MA, Block JA. Relationship between pain and medial knee joint loading in mild radiographic knee osteoarthritis. Arthritis Rheum 2007;57:1254–60.
[35] Alnahdi AH, Zeni JA, Snyder-Mackler L. Gait after unilateral total knee arthroplasty: frontal plane analysis. J Orthop Res 2011;29:647–52.
[36] Hatfield GL, Hubley-Kozey CL, Astephen Wilson JL, Dunbar MJ. The effect of total knee arthroplasty on knee joint kinematics and kinetics during gait. J Arthroplasty 2011;26:309–18.
[37] Kutzner I, Trepczynski A, Heller MO, Bergmann G. Knee adduction moment and medial contact force — facts about their correlation during gait. PLoS One 2013;8:e81036.
[38] Ogaya S, Naito H, Iwata A, Higuchi Y, Fuchioka S, Tanaka M. Knee adduction moment and medial knee contact force during gait in older people. Gait Posture 2014;40:341–5.
[39] Zhao D, Banks SA, Mitchell KH, D'Lima DD, Colwell Jr CW, Fregly BJ. Correlation between the knee adduction torque and medial contact force for a variety of gait patterns. J Orthop Res 2007;25:789–97.
[40] Astephen Wilson JL, Wilson DA, Dunbar MJ, Deluzio KJ. Preoperative gait patterns and BMI are associated with tibial component migration. Acta Orthop 2010;81:478–86.
[41] Longstaff LM, Sloan K, Stamp N, Scaddan M, Beaver R. Good alignment after total knee arthroplasty leads to faster rehabilitation and better function. J Arthroplasty 2009;24:570–8.
[42] Heyse TJ, Decking R, Davis J, Boettner F, Laskin RS. Varus gonarthrosis predisposes to varus malalignment in TKA. HSS J 2009;5:143–8.
[43] Nerhus TK, Heir S, Thornes E, Madsen JE, Ekeland A. Time-dependent improvement in functional outcome following LCS rotating platform knee replacement. Acta Orthop 2010;81:727–32.