European Journal of Orthopaedic Surgery & Traumatology (2019) 29:675–681
https://doi.org/10.1007/s00590-018-2318-4

ORIGINAL ARTICLE • KNEE - ARTHROPLASTY

Intraoperative kinematic analysis of posterior stabilized total knee arthroplasty with asymmetric helical post-cam design

Takatoshi Morooka[1] · Makiko Okuno[1] · Daisuke Seino[1] · Takuya Iseki[1] · Shigeo Fukunishi[1] · Syoji Kobashi[2] · Shinichi Yoshiya[1]

Received: 20 June 2018 / Accepted: 26 September 2018 / Published online: 22 October 2018
© Springer-Verlag France SAS, part of Springer Nature 2018

Abstract

Purpose To investigate intraoperative kinematics during passive flexion using a surgical navigation system for knees undergoing posterior stabilized (PS) total knee arthroplasty (TKA) with an asymmetric helical post-cam design using navigation system.

Methods In total, 45 knees with both pre- and postoperative kinematic data available were included in the study. Intraoperative kinematic measurements were performed during the course of surgery using the software incorporated in the navigation system. Measurements were performed at the following two time points: (1) before TKA procedure and (2) after TKA implantation. Among the kinematic parameters studied, anterior/posterior translation and axial rotation during flexion were subjected to the analysis.

Results Before surgery, physiologic anterior/posterior translational pattern of the tibia during flexion (rollback of the femur) was found in only 15.6% of the knees. After TKA implantation, postoperative kinematic measurement showed no significant change in the tibial translational during knee flexion. Similarly, with regard to rotation, non-physiologic external tibial rotation in early flexion was observed in the majority of the knees before surgery, and this abnormal kinematic pattern remained after the TKA procedure.

Conclusions The intraoperative three-dimensional motion analysis using a navigation system showed that the physiologic kinematic pattern (anterior translation and internal rotation of the tibia during flexion) of the knee was distorted in osteoarthritic knees undergoing TKA. The abnormal kinematic pattern before surgery was not fully corrected even after implantation of the PS TKA designed to induce natural knee motion; however, no clear relationship between the intraoperative kinematic pattern and knee flexion angle at one year was demonstrated, and the effect of knee kinematics on postoperative knee function and patient's satisfaction is still unclear.

Keywords Total knee arthroplasty · Surgical navigation · Posterior stabilized · Knee kinematics · Anterior–posterior translation · Internal–external rotation

Introduction

It has been reported that osteoarthritic knees undergoing total knee arthroplasty (TKA) exhibit non-physiologic knee kinematics [1], and the surgical outcomes are better when kinematics of the operated knee more closely resemble a physiologic motion pattern [2, 3]. Therefore, it is clinically important to examine the kinematics of the TKA-implanted knee and see how the normal kinematics are restored in the postoperative condition.

To date, a number of studies dealing with kinematics of TKA-implanted knees have been conducted using a variety of methods. Among them, the most frequently used methodology is image analysis by matching the two-dimensional (2D) image of the fluoroscopic image with a three-dimensional (3D) computer-assisted design (CAD) image of the implant (2D/3D image registration) [4–7]. However, this analytical methodology requires substantial

✉ Takatoshi Morooka
morooka0818@gmail.com

[1] Department of Orthopaedic Surgery, Hyogo College of Medicine, 1-1 Mukogawa-cho, Nishinomiya City, Hyogo 663-8501, Japan

[2] Graduate School of Engineering, University of Hyogo, 2167 Syosya, Himeji, Hyogo 671-2280, Japan

time and additional radiological exposure and does not allow for intraoperative assessment.

An alternative method for 3D kinematic analysis is the use of a computer navigation system. There have been a number of studies that examined intraoperative kinematics using a navigation system [8–15]. In general, these studies showed non-physiologic kinematic patterns in osteoarthritic knees undergoing TKA and the postoperative kinematics were influenced by the preoperative motion pattern. Therefore, physiologic kinematics could not be restored even after TKA implantation. Regarding the effect of knee kinematics on postoperative knee function, reported results are variable [10–12] and clinical significance of intraoperative kinematic measurement has not been clarified.

Since July 2014, we have been using a posterior stabilized (PS) type TKA (Vega, B/Braun, Germany). The design concept of this implant system is to induce physiologic knee flexion kinematics with posterior femoral rollback and internal tibial rotation beyond 40° of flexion by contact between the post and cam of the asymmetrical helical design (Fig. 1). Although this concept is theoretically reasonable, it has not been confirmed whether the knees implanted with this implant exhibit physiologic motion pattern in vivo.

The purpose of this study was to intraoperatively evaluate the 3D knee flexion kinematics during the sequence of TKA procedure using the Vega implant system. It was hypothesized that knees with osteoarthritis undergoing TKA lose physiologic motion pattern, and TKA with the aforementioned implant system would restore normal kinematics.

Fig. 1 Implant system used in the study

Materials and methods

The study protocol was approved by the Institutional Review Board, and a written informed consent was obtained from all the patients.

Study subjects

The study subjects were comprised of a consecutive series of patients who underwent primary TKA with PS-type TKA (Vega) from July 2014 to August 2015. This implant system (Vega) was the primary option for osteoarthritic knees except for those with severe instability or bony deficiency. During the study period, in total, 75 TKAs were performed by the principle investigator of this study (T.M.), and TKA of this type (Vega) was indicated for 51 of those 75 knees. A CT-free navigation (OrthoPilot Version 4.2) system was used in the surgery.

Among the 51 knees, sequential kinematic data were not fully available in 6 of the 51 knees. Consequently, kinematic data derived from the remaining 45 knees (in 45 patients) were subjected to the analysis of this study. There were 9 males and 36 females, and the mean age of patients at the time of surgery was 73.6 years (range 57–83 years). In all knees, preoperative weight-bearing radiograph showed varus osteoarthritis with radiological changes corresponding to Kellgren–Lawrence Grade III or IV.

Surgical procedure

The surgeries were conducted in all patients by the same surgeon (T.M.) under general anesthesia. The surgical technique of the navigation surgery was in accordance with the procedure instructed by the supplier.

First, the tracker pins were inserted and fixed to the femur and tibia. Subsequently, registration was performed by obtaining kinematic data of the hip, knee, and ankle joints, as well as the location of the anatomic bony landmarks. The knee was approached through the medial parapatellar arthrotomy.

In the TKA procedure, following assessment of integrity of the anterior and posterior cruciate ligaments (ACL/PCL) on macroscopic examination [16], the ACL and PCL were resected. Then, the initial osteotomy was conducted for the proximal tibia ("tibia-first" technique). After the soft tissue balancing, planning for the osteotomy on the femoral side was made so that the extension and flexion gaps could meet. Based on the planning, the distal/anterior/posterior femoral osteotomies were performed. The

rotational position of the tibial component was determined by relying on the Akagi line as an index [17]. Femoral and tibial components were fixed with cement, while the patella was not replaced in any knees during the study period.

Kinematic analysis using the navigation system

Intraoperative kinematics were analyzed using the software incorporated in the navigation system. The computer navigation system (OrthoPilot, B/Brown, Germany) used in our practice is equipped with software (Kobe version) that enables intraoperative 3D motion analysis. In the 3D kinematic assessment, the coordinate systems were established for the femur and tibia based on the kinematic and anatomic registration data following the formula incorporated in the navigation system [1, 8, 12]. For determining translation in the anterior/posterior direction and angle of internal/external rotation during flexion, the coordinate system (anterior/posterior and medial/lateral axes) on the horizontal plane of the femur was projected onto the tibial articular plane vertical to the longitudinal axis of the tibia, and measurement and calculation for anterior/posterior translation and internal/external rotation during extension/flexion motion were conducted.

3D flexion kinematics were measured before TKA procedure (Pre-op) and after implantation of the prostheses (Post-TKA). At the time of the kinematic measurement, the joint capsule was tentatively sutured and closed. The knee kinematics were recorded for non-weight-bearing passive flexion in a supine position. During the measurement, the knee was taken through range of motion from the maximum extension to maximum flexion while the calcaneal region was lifted by the surgeon without constraint and the thigh was held by the assistant with the hip kept at a 90° flexion position (Fig. 2a).

The 3D spatial relationship between the femur and tibia during the range from maximum extension to maximum flexion was recorded with an increment of 10° of knee flexion (Fig. 2b). Regarding the analytical parameters, anterior/posterior translation and internal/external rotation of the femur in relation to the tibia during the flexion sequence were calculated and analyzed.

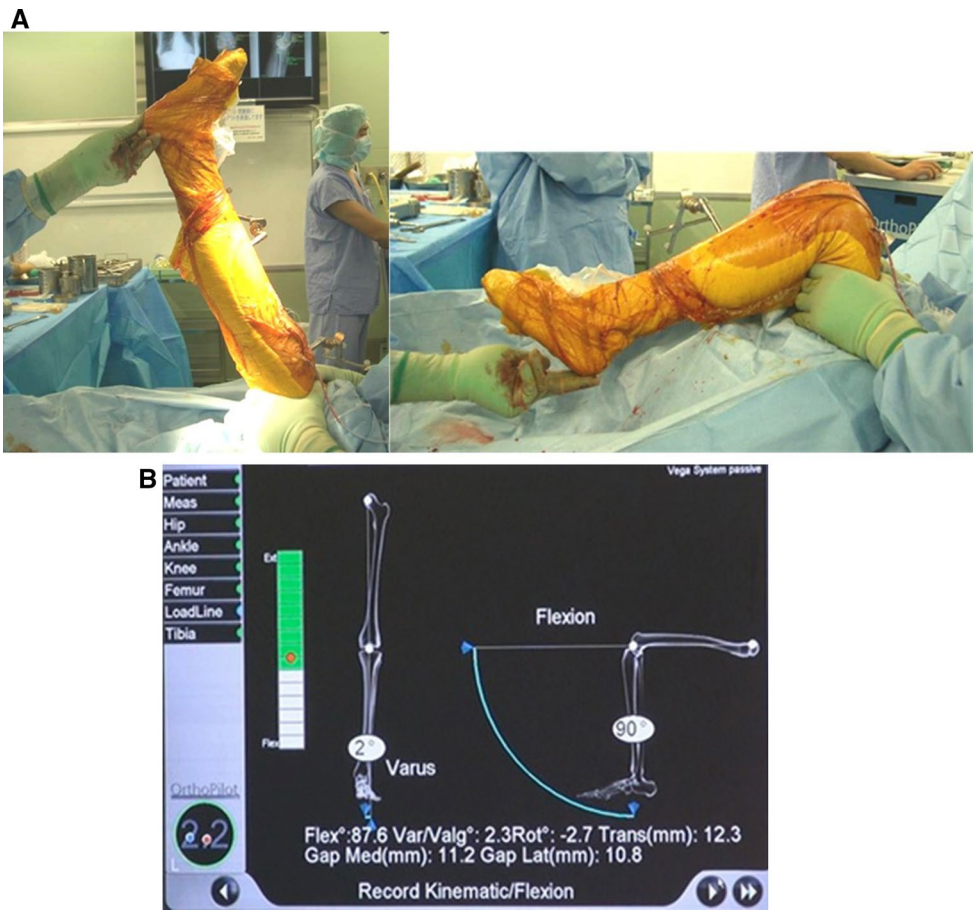

Fig. 2 Intraoperative kinematic measurement using the navigation. **a** The knee is flexed from maximum extension to maximum flexion without constraint while keeping the hip position at 90° of flexion. **b** Six-degree-of-freedom motion of the femur/tibia is recorded with an increment of 10° of flexion angle using the navigation system

Data analysis

In order to classify the patterns of flexion kinematics among the study subjects, a hierarchical cluster analysis was applied to the obtained data. In the analytical process, kinematic data at 10° increments from 10° to 100° were subjected to the analysis because there were deficits in kinematic data outside of this motion range (< 10° and > 100°) in some subjects due to contracture. Similarity between each of the cases was assessed using averaged squared distance, and the Ward's method was employed as the criterion in the agglomerative hierarchical clustering [18]. R version 3.3.0 was used for the analysis. Difference in kinematic pattern between the subgroups based on ACL status was analyzed using the Chi-squared test. For comparison between pre- and postoperative kinematic results, the Mann–Whitney U-test was used for the analysis. In the comparison of pre- versus postoperative kinematic results, the tibial translation and rotation values beyond 40° of flexion (after the post-cam engagement) were subjected to the analysis. A post hoc power analysis was performed for the pre- and postoperative comparison. Consequently, the statistical power was calculated to be 99% for a sample size of 45 to detect the significant difference with α level of 0.05. In addition, the effect of intraoperative kinematics on postoperative knee function was examined by assessing the correlation between the range of translation/rotation during flexion and flexion angle of the knee at 1 year based on Spearman's rank correlation. $P < 0.05$ was considered statistically significant. The analysis was performed using SPSS (version 19, SPSS Inc.).

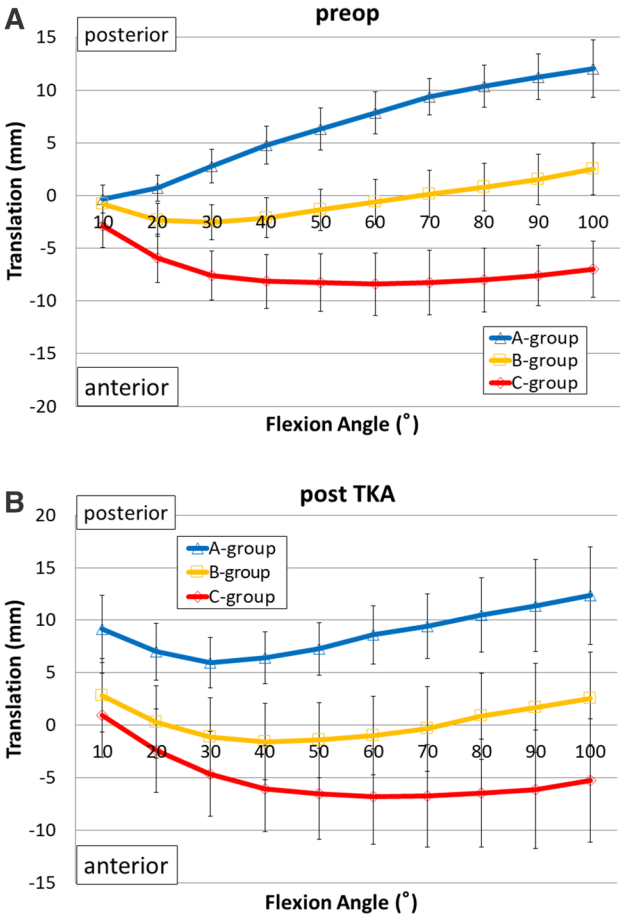

Fig. 3 Anterior/posterior femoral translation associated with knee flexion. The motion pattern in the anterior/posterior translation during passive flexion before the intra-articular surgical procedure was classified into the following three groups using hierarchical cluster analysis: Group A with gradual posterior femoral translation with flexion (physiologic pattern), Group B with reversed translational pattern in the initial phase of flexion with posterior translation during the late flexion phase, and Group C with initial reversed translational pattern without appreciable anterior/posterior motion during the subsequent flexion. **a** Before intra-articular surgical invasion (Pre-op). **b** After implantation of the prosthesis (Post-TKA)

Results

Anterior–posterior translation

(1) Pre-op (Fig. 3a).

Motion pattern in the anterior/posterior translation during passive flexion before intra-articular surgical procedure could be classified into the following three groups using the hierarchical cluster analysis.

Group A, where the femur translated posteriorly in relation to the tibia from the initial period of flexion (i.e., physiologic posterior femoral rollback associated with flexion was observed);
Group B, where the femur exhibited reversed translational pattern in the initial flexion phase followed by posterior femoral rollback.
Group C, where the femur translated anteriorly in the initial flexion phase without appreciable anterior/posterior motion during the subsequent flexion.
Group A, B and C included 7, 18 and 20 knees, respectively. Consequently, group A knees with physiologic translational motion pattern accounted for 15.6% of all subjects (7 of the 45 knees), while non-physiologic motion patterns in groups B and C knees were identified in 40% and 44.4% of the study subjects.

(2) Post-TKA

Following TKA procedure, all knees in group A exhibited translation pattern similar to that in group B with early reversed motion (anterior femoral translation) followed by gradual posterior femoral rollback during the subsequent flexion phase. By contrast, there was no appreciable change in translational pattern following TKA procedure in group B and C knees (Fig. 3b).

In the comparison of pre- versus postoperative translational results, the amount of posterior femoral translation during late flexion (beyond theoretical post-cum engagement at 40° of flexion) was not significantly altered by TKA implantation with *P* values ranging from 0.31 to 0.82 in each group.

Axial rotation (Fig. 4).

(1) Pre-op

With regard to internal/external rotation, in the pre-TKA stage, the intraoperative motion assessment showed mild internal rotation of the femur in the initial stage of flexion followed by external femoral rotation with further flexion in 40 of the 45 knees (88.9%). Since this motion pattern was observed in the majority of the knees, classification of the motion pattern was not feasible for axial rotation.

(2) Post-KTA

After the implantation of the prostheses, coupled rotation during flexion exhibited a similar pattern to that of the preoperative condition with mild internal femoral rotation in the initial stage of flexion followed by external femoral rotation with further flexion. In the comparison of pre- versus postoperative rotational results, the amount of external femoral translation during late flexion beyond 40° of flexion was not significantly altered by TKA implantation with *P* values ranging from 0.13 to 0.85 in each group.

Status of the ACL/PCL and its correlation with flexion kinematics

On gross examination at surgery, the ACL appeared to be functional in 36 knees (80%) and non-functional in 9 knees (20%), while the PCL appeared intact in all knees. Regarding the effect of ACL status on knee kinematics, all knees in group A with physiologic femoral rollback had functional ACL; however, statistical analysis showed no significant correlation between the status of the ACL and translational pattern during flexion (Table 1)

Correlation between intraoperative kinematics and postoperative flexion angle

Assessment was conducted for correlation between translation/rotation values during flexion and flexion angle of the

Table 1 Relationship between kinematic pattern and ACL status

	A group (*n*: 7)	B group (*n*: 18)	C group (*n*: 20)	*P* values
ACL functional	7	16	13	
Non-functional	0	2	7	$P = 0.065$

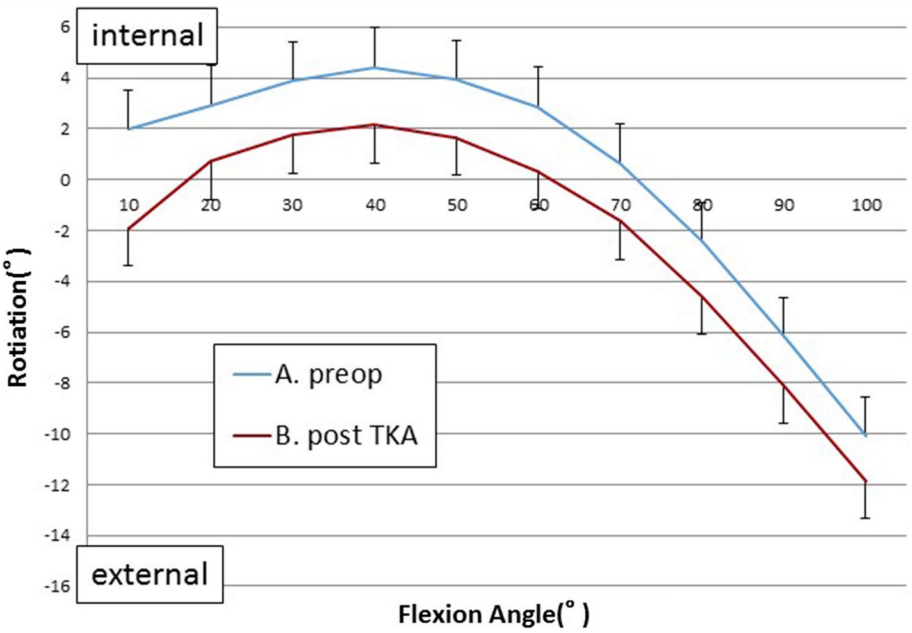

Fig. 4 Internal/external femoral rotation associated with knee flexion before intra-articular surgical invasion (Pre-op) and after implantation of the prosthesis (Post-TKA)

knee at 1 year. In this analysis, range of translation/rotation values between 10° and 100° were adopted as kinematic parameters. Consequently, no significant correlation was demonstrated ($\rho = 0.89$ and 0.74 for translation and rotation, respectively) between intraoperative kinematics and postoperative flexion.

Discussion

Previous biomechanical studies for physiologic knee motion have shown that the posterior femoral translation (posterior femoral rollback) and external femoral rotation in relation to the tibia occur associated with increasing flexion [19–22]. The present study revealed that this physiologic flexion kinematics were lost in the majority of knees with advanced osteoarthritis undergoing TKA. Regarding anterior/posterior translation during flexion, the normal pattern (posterior femoral rollback) was retrained only in 15.6% of the knees before surgery. Even after implantation of the PS TKA system specifically designed for induction of natural knee motion, physiologic translational motion pattern was not fully restored after surgery. Similarly, the majority of the knees exhibited an abnormal rotational pattern during the early flexion phase before surgery, and this motion pattern remained following the TKA procedure.

The 3D kinematics of the knee are thought to be determined by the tension of the soft tissues of the knee as well as the surface geometry at the joint contact area. Although the surface geometry is optimized and PCL function is substituted by the PS TKA implantation, those changes were not enough to restore the physiologic flexion kinematics.

In the present study, an implant of novel design aiming to reproduce physiologic kinematics was used; however, contrary to the study hypothesis, the implantation of TKA of this type failed to fully normalize the kinematic pattern. Whether improvement in surgical procedure and prosthetic design can accomplish reproduction of physiologic motion pattern for osteoarthritic knees with substantial deformity and destruction needs to be further investigated in future studies.

There have been several studies reporting the results of intraoperative kinematic assessment during TKA procedure using a navigation system [1, 9–15, 23–25]. Siston et al. investigated the flexion kinematics of knees implanted with PS TKA, and showed abnormal anterior (paradoxical) femoral translation until 60° of flexion and reduction of screw-home motion after surgery [1]. Casino et al. conducted the intraoperative kinematic assessment for PS rotating platform TKA and reported abnormal femoral translation up to 60° and no appreciable postoperative change in rotational kinematics [23]. In addition, several studies compared the kinematics of PS TKA and TKAs of other types [9, 12, 24]. These studies have shown that knees implanted with PS TKA with post-cam mechanism exhibited more anterior–posterior translation compared to posterior cruciate-retaining TKA. In general, those previous studies have shown paradoxical anterior femoral translation up to 60°–70° of flexion and non-physiologic rotational pattern with flexion after TKA. In addition, close correlation between pre- and postoperative kinematics is a common feature depicted in those studies. The results of the present study agreed with those previous study results. Although the PS prosthesis used in the study was designed to induce physiologic flexion kinematics, the intention of the design concept was not fully attained.

There are several limitations included in this study. First, the kinematic measurement of the knee was performed in non-physiologic conditions such as under general anesthesia, use of a tourniquet, and non-weight-bearing motion with the patient in a supine position. Therefore, kinematics during postoperative activities under weight bearing, such as walking, were not reproduced in this measurement condition. Second, the software used in the study for kinematic analysis has not been fully validated. Although there have been a number of studies reporting kinematics of TKA-implanted knees based on navigation assessment, accuracy and reproducibility of this measurement system are yet to be confirmed. In addition, several factors, such as errors involved in the intraoperative registration, may affect the measurement consistency and accuracy [26]. Third, the sample size of each group was small and variation of the results among the study subjects was large. Therefore, it was difficult to conduct a reasonable statistical analysis. A larger sample size seems required to draw a statistically validated conclusion. Fourth, subject grouping based on the kinematic pattern was performed using a hierarchical cluster analysis. Although application of an objective statistical method to grouping is a strength of this study, grouping using this method is specific to each data set (i.e., preoperative or postoperative data set). Consequently, postoperative changes from one category (preoperative) to another category (postoperative) could not be assessed with this analytical design. Finally, this study lacks data presentation for detailed clinical outcomes, though it is important to examine the effect of the intraoperative kinematic pattern on postoperative knee function and patient's satisfaction.

Conclusions

The intraoperative 3D motion analysis using a navigation system showed that physiologic kinematic pattern (anterior translation and internal rotation of the tibia during flexion) of the knee was substantially distorted in osteoarthritic knees undergoing TKA. The abnormal kinematic pattern before surgery was not fully corrected even after implantation of

the PS TKA designed to induce natural knee motion; however, no clear relationship between the intraoperative kinematic pattern and knee flexion angle at one year was demonstrated, and the effect of knee kinematics on postoperative knee function and patient's satisfaction is still unclear.

Compliance and ethical standards

Conflict of interest The authors declare that they did not receive and will not receive any benefits or funding from any commercial party related directly or indirectly to the subjects of this article.

Ethical standard All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional research committee and with the 1964 Declaration of Helsinki and later amendments or comparable ethical standards.

References

1. Siston RA, Giori NJ, Goodman SB et al (2006) Intraoperative passive kinematics of osteoarthritics knee before and after total knee arthroplasty. J Orthop Res 24(8):1607–1614
2. Nishio Y, Onodera T, Kasahara Y et al (2014) Intraoperative medial pivot affects deep knee flexion angle and patient-reported outcomes after total knee arthroplasty. J Arthroplast 29(4):702–706
3. Victor J, Bellemans J (2006) Physiologic kinematics as a concept for better flexion in TKA. Clin Orthop Rel Res 452:53–58
4. Banks SA, Hodge WA (1996) Accurate measurement of three-dimensional knee replacement kinematics using single-plane fluoroscopy. IEEE Trans Biomed Eng 43(6):638
5. Hoff WA, Komistek RD, Dennis DA et al (1998) Three-dimensional determination of femoral-tibial contact positions under in vivo conditions using fluoroscopy. Clin Biomech 13:455
6. Dennis DA, Komistek RD, Mahfouz MR, Haas BD, Stiehl JB (2003) Multicenter determination of in vivo kinematics after total knee arthroplasty. Clin Orthop Relat Res 416:37
7. Banks SA, Hodge WA (2004) Implant design affects knee arthroplasty kinematics during stair-stepping. Clin Orthop Relat Res 426:187
8. Delp SL, Stulberg D, Davies B et al (1998) Computer assisted knee replacement. Clin Orthop Relat Res 354:49–56
9. Fritzsche H, Beyer F, Postler A et al (2018) Different intraoperative kinematics, stability, and range of motion between cruciate substituting ultracongruent and posterior-stabilized total knee arthroplasty. Knee Surg Sports Traumatol Arthrosc 26(5):1465–1470
10. Ishida K, Shibanuma N, Matsumoto T et al (2016) Navigation-based femorotibial rotation pattern correlated with flexion angle after total knee arthroplasty. Knee Surg Sports Traumatol Arthrosc 24:89–95
11. Ishida K, Shibanuma N, Matsumoto T et al (2015) Factors affecting intraoperative kinematic patterns and flexion angles in navigated total knee arthroplasty. Knee Surg Sports Traumatol Arthrosc 23(6):1741–1747. https://doi.org/10.1007/s00167-015-3572-1
12. Kim TW, Lee SM, Seong SC et al (2016) Different intraoperative kinematics with comparable clinical outcomes of ultracongruent and posterior stabilized mobile-bearing total knee arthroplasty. Knee Surg Sports Traumatol Arthrosc 24(9):3036–3043
13. Matsumoto T, Takayama K, Muratsu H et al (2015) Semimembranosus release reduces tibial internal rotation and flexion angle in cruciate-retaining total knee arthroplasty. J Arthroplast 30(9):1537
14. Seito N, Onodera T, Kasahara Y et al (2017) Preoperative knee deformity and kinematics impact postoperative knee kinematics in total knee arthroplasty. Knee 124(6):1462–1468
15. Seon JK, Park JK, Jeong MS, Jung WB et al (2011) Correlation between preoperative and postoperative knee kinematics in total knee arthroplasty using cruciate retaining designs. Int Orthop 35(4):515–520. https://doi.org/10.1007/s00264-010-1029-1
16. Allain J, Goutallier D, Voisin MC (2001) Macroscopic and histological assessments of the crusiate ligaments in arthrosis of the knee. Acta Orthop Scand 72(3):266–269
17. Akagi M, Mori S, Nishimura S et al (2005) Variability of extraarticular tibial rotation references for total knee arthroplasty. Clin Orthop Relat Res 436:172
18. Kaufman L, Rousseeuw PJ (1990) Finding groups in data: an introduction to cluster analysis. Wiley, New York
19. Iwaki H, Pinskerova V, Freeman MA (2000) Tibiofemoral movement 1: the shapes and relative movements of the femur and tibia in the unloaded cadaver knee. J Bone Joint Surg Br 82(8):1189–1195
20. Freeman MA, Pinskerova V (2005) The movement of the normal tibio-femoral joint. J Biomech 38(2):197–208
21. Dennis DA, Mahfouz MR, Komistek RD, Hoff W (2005) In vivo determination of normal and anterior cruciate ligament-deficient knee kinematics. J Biomech 38(2):241–253
22. Kurosawa H, Walker PS, Abe S, Garg A, Hunter T (1985) Geometry and motion of the knee for implant and orthotic design. J Biomech 18(7):487–499
23. Casino D, Zaffagnini S, Martelli S et al (2009) Intraoperative evaluation of total knee replacement: kinematic assessment with a navigation system. Knee Surg Sports Traumatol Arthrosc 17(4):369
24. Baier C, Springorum HR, Götz J et al (2013) Comparing navigation-based in vivo knee kinematics pre- and postoperatively between a cruciate-retaining and a cruciate-substituting implant. Int Orthop 37(3):407
25. Young KL, Dunbar MJ, Richardson G et al (2015) Intraoperative passive knee kinematics during total knee arthroplasty surgery. J Orthop Res 33(11):1611
26. Jenny JY, Boeri C (2004) Low reproducibility of the intra-operative measurement of the transepicondylar axis during total knee replacement. Acta Orthop Scand 75(1):74