Patients with no functional improvement after total knee arthroplasty show different kinematics

Jörg Lützner · Stephan Kirschner ·
Klaus-Peter Günther · Melinda K. Harman

Received: 31 March 2012 / Accepted: 13 May 2012 / Published online: 29 May 2012
© Springer-Verlag 2012

Abstract

Purpose As many as 20 % of all patients following total knee arthroplasty are not satisfied with the result. Rotational alignment is one factor thought to affect clinical outcome. The purpose of this study was to assess relationships between prosthesis rotational alignment, function score and knee kinematics after TKA.

Methods In 80 patients a cemented, unconstrained, cruciate-retaining TKA with a rotating platform was implanted. Rotational alignment was measured using CT-scans. Kinematics was assessed using fluoroscopy images.

Results Seventy-three patients were available for follow-up after two years. Nine patients had more than 10° rotational mismatch between the femoral and tibial component in the postoperative CT scans. These patients showed significantly worse results in the function score. While the normal patients with less than 10° rotational mismatch improved from a mean pre-operative 55 points to a mean 71 points at follow-up, the group with more than 10° mismatch deteriorated from a mean 60 points pre-operatively to a mean 57 points at follow-up. The pattern of motion during passive flexion from approximately 0° to 120° was quite different. While external rotation steadily increased with knee flexion in the normal group, there was internal rotation between 30°

and 80° of flexion in the group with more than 10° rotational mismatch.

Conclusion Rotational mismatch between femoral and tibial components exceeding 10° resulted in different kinematics after TKA. It might contribute to worse clinical results observed in those patients and should therefore be avoided.

Introduction

Although 90 % of patients after total knee arthroplasty (TKA) report satisfaction with their general result [1–3], as many as 20 % are not satisfied with their improvement in physical function [2]. With an increasing number of more active and more demanding patients, this is not sufficient. Different reasons are thought to affect clinical outcome, such as leg alignment, rotational alignment, soft tissue-balancing, the femoro-patellar joint, and patient-related factors. It also has been suggested that knee kinematics associated with specific prosthesis designs affect patient satisfaction after TKA [4–6].

Knee kinematics during weight-bearing activities are different after TKA compared to the normal knee [7–10]. However, indicators of knee kinematics are difficult to discern during surgery and may not be predictive of function after TKA. Unlike evaluations of alignment and ligament balancing that are routinely included in the intra-operative surgical procedure, quantitative measures of knee kinematics that exist during intra-operative trialing are rare [11]. Furthermore, relationships between the kinematic performance of TKA during intraoperative trialing and subsequent functional outcome have not been established.

Subjective assessments of intra-operative knee kinematics are commonly used by surgeons to gain some understanding of the complex relationships between component

J. Lützner (✉) · S. Kirschner · K.-P. Günther
Department of Orthopaedic Surgery,
University Hospital Carl Gustav Carus,
Medical Faculty of the Technical University of Dresden,
Fetscherstr. 74,
01307 Dresden, Germany
e-mail: Joerg.Luetzner@uniklinikum-dresden.de

M. K. Harman
Department of Bioengineering,
Rhodes Engineering Research Center, Clemson University,
Clemson, SC, USA

rotational alignment and knee axial rotation, which are known to have considerable impact on knee function. As little as 3–7° of internal rotational alignment of the femoral and tibial components has been linked with suboptimal extensor mechanism function after TKA [12, 13]. TKA with external femoral component rotation have different kinematics compared to TKA with neutral or internal femoral rotation, resulting in atypical magnitudes of knee axial rotation [14, 15]. However, it is not clear that intra-operative trialing is suitably sensitive to detect such differences or is predictive of TKA functional performance after the patient has successfully completed rehabilitation and is performing dynamic activities. Therefore, it is important to ascertain whether measured kinematics during intra-operative trialing correspond to functional outcome.

This study assesses the relationship between femoro-tibial component rotational alignment and kinematics obtained in the immediate postoperative period and the patients' clinical outcome at two-years follow-up. Patients from a previous prospective, randomized study [16] of component alignment after mobile-bearing TKA were contacted for physical and radiological follow-up. It was hypothesized that differences in rotational alignment of the femoral and tibial components and associated altered kinematics would correspond to differences in functional outcomes.

Methods

The study protocol for the initial study (Clinical Trials NCT01022099), including intra-operative fluoroscopy and postoperative CT scans, was approved by the local independent ethics committee in March, 2005 and for the follow-up in January, 2008. Eighty subjects met all surgical inclusion criteria and provided written informed consent to participate, as previously described in detail [16]. In all patients a cemented, unconstrained, cruciate-retaining TKA with a rotating platform (Scorpio™ PCS, Stryker Orthopaedics, Mahwah, NJ, FDA-approved) was implanted. No patellar resurfacing was performed.

Rotational alignment of the femoral and tibial component relative to bone landmarks and the mismatch between both components was measured from CT scans obtained within the first week after the arthroplasty. Three quantitative descriptors of the components' rotational alignment were measured (ID.PACS 3.6, Image Devices, Idstein, Germany), including rotational alignment of the femoral and tibial components relative to bony landmarks as previously described in detail [16], and relative angular divergence (rotational mismatch) of the femoral component relative to the tibial component.

TKA axial rotation kinematics during passive knee flexion were measured from fluoroscopic images (4–8 images/knee) acquired during postoperative trialing immediately after wound closure with the surgeon moving the knee joint

from full extension to approximately 120° of flexion. The three-dimensional position and orientation of femoral, tibial and polyethylene bearing components were determined by one observer (MKH) using model-based shape matching techniques [17–21]. Error due to image distortion and matching was 0.3° for rotations and 1.0 mm for translations in the image plane. *Total knee axial rotation* was defined as relative internal-external motion between the femoral component and metal tibial baseplate in the transverse plane. *Articular axial rotation* was defined as relative motion occurring at the articular surface between the femoral component and the polyethylene bearing. *Bearing axial rotation* was defined as relative motion occurring at the distal back-side surface between the polyethylene bearing and the tibial baseplate. Positive axial rotation values corresponded to femoral internal rotation (tibial external rotation) and negative axial rotation values corresponded to femoral external rotation (tibial internal rotation). Thirteen patients were excluded from the kinematic analysis of prosthesis motion due to errors during image acquisition.

Seventy-three of the initial group of 80 patients were available for follow-up after a mean of 21 months postoperatively. Two patients died before initiation of the follow-up study. One patient had undergone revision for a pre-operatively unknown metallic hypersensitivity with persistent swelling. One patient had a Girdlestone resection following total hip infection on the same leg. Three patients refused to attend the follow-up examination. Patients were interviewed by a local study nurse using the Knee Society score [22] and the EuroQol questionnaire (release EQ-5D) [23]. Data description was based on means and standard deviation (SD) for continuous values and on absolute and relative frequencies for categorical values, respectively. Comparisons between groups were based on two sample Wilcoxon tests for continuous values and on Fisher's exact tests for categorical values, respectively. Results of these exploratory significance tests were summarized in p-values, where $p < 0.05$ indicates statistically significant differences between groups. All analyses were performed using SPSS® software (release 16.0 for Windows®).

Results

Differences in relative angular divergence between the femoral and tibial components (rotational mismatch) corresponded to differences in functional outcomes. In contrast, rotational alignment of the individual components relative to bone landmarks showed no influence on functional outcome or quality of life at follow-up. Out of 73 patients available for follow-up, nine patients had 10° or more rotational mismatch (Outlier Group) on the postoperative CT scans and 64 patients had less than 10° rotational mismatch (Nominal Group). Pre-operative data of these two groups showed no differences (Table 1).

Table 1 Demographic data, functional outcome and quality of life for patients with a rotational mismatch between the femoral and tibial components of less than 10° and 10° or more (mean ± SD)

Rotational mismatch	Nominal group <10° (n=64)	Outlier group ≥10° (n=9)	<i>p</i>
Pre-operative data			
Age at operation (years)	68 (9)	67 (10)	n.s.
Gender (% female)	69 %	56 %	n.s.
BMI (kg/m ²)	31 (5)	29 (4)	n.s.
Postoperative data			
Follow-up (months)	21 (3)	22 (4)	n.s.
Knee Society knee score			
Pre-operative	44 (16)	52 (17)	n.s.
Follow-up	82 (15)	89 (5)	n.s.
Improvement	38 (22)	37 (18)	n.s.
Knee Society function score			
Pre-operative	55 (11)	60 (10)	n.s.
Follow-up	71 (16)	57 (14)	<i>p</i> =0.02
Improvement	16 (17)	-3 (6)	<i>p</i> =0.001
EQ 5D VAS			
Pre-operative	52 (17)	51 (11)	n.s.
Follow-up	67 (15)	59 (10)	n.s.
Improvement	15 (21)	8 (19)	n.s.

Patients in the outlier group were not different from the nominal group in the Knee Society knee score (89 ± 5 vs 82 ± 15 points at follow-up) and EuroQuol 5D visual analogue scale (59 ± 10 vs 67 ± 15 points at follow-up), but showed significantly different results in the Knee Society function score. While the patients in the nominal group had improved function scores from pre-

operative 55 ± 11 points to 71 ± 16 points at follow-up, the function scores for patients in the outlier group deteriorated from 60 ± 10 points pre-operatively to 57 ± 14 points at follow-up ($p=0.02$; Table 1). Only one of the nine patients in the outlier group improved in the KSS function score (Table 2).

These two groups of patients with different rotational alignment and functional outcomes showed altered knee kinematics during intra-operative passive flexion motion (Table 3). While there was no significant difference in the average range of total axial rotation achieved in these groups, the magnitudes of maximum and minimum axial rotation were significantly different ($p<0.05$). The patterns of motion during knee flexion were considerably different between the groups, with significantly less femoral external rotation achieved in the outlier group (Fig. 1). Moreover, in the outlier group, there was femoral internal rotation with increasing knee flexion until approximately 70°, largely due to internal rotation of the polyethylene bearing on the tibial baseplate (Fig. 1).

The kinematics of the individual patients in the outlier group revealed a consistent trend in the motion patterns of the femoral component moving on the polyethylene bearing, evidence of the articular conformity at that interface (Fig. 2). However, the CT alignments of femoral and tibial alignment do not correspond very closely with the kinematics. All patients had well aligned femoral components (within 3.5°), but tibial alignment varied widely by approximately 37° (Table 2), with large variance toward tibial internal rotation in some patients (#1, #4, #26, #60) and toward tibial external rotation in other patients (#29, #32). Such bias in the initial alignment is evident in the offset between the curves generated from patients with altered kinematics and poor functional outcomes (outlier group) and those

Table 2 Details of patients with a rotational mismatch between femoral and tibial component of 10° or more (outlier group)

Study #	Rotational alignment in degrees			Kinematic analysis	KSS function score ^d		
	Femur ^a	Tibia ^b	Mismatch ^c		Preop.	Follow-up	Difference
1	-0.9	17.8	11.8	No	60	55	-5
4	-1.1	10.6	14.4	Yes	60	50	-10
26	0.1	20.9	10.9	Yes	45	45	0
29	3.5	-9.2	-13.3	Yes	60	60	0
32	1.7	-14.9	-12.1	Yes	80	80	0
36	3.1	8.3	-16.2	No	60	50	-10
47	1.7	-2.2	10.6	Yes	70	80	10
60	0.8	17.8	14.1	Yes	55	50	-5
65	3.2	0.0	12.7	Yes	50	45	-5

^a Rotational alignment of the femoral component. Positive values indicate internal rotation of the femoral component relative to the trans-epicondylar axis

^b Rotational alignment of the tibial baseplate. Positive values indicate internal rotation of the tibial baseplate relative to the medial third of the tibial tuberosity

^c Rotational mismatch between femoral and tibial component. Positive values indicate femoral internal rotation relative to the tibia

^d Knee Society function score in points between 0 and 100

Table 3 Alignment groups and average range of axial rotation

Rotational mismatch	n (% total)	Range of axial rotation (mean $\pm$ SD)	Maximum axial rotation ^a (mean $\pm$ SD)	Minimum axial rotation ^a (mean $\pm$ SD)
Nominal (within $\pm 10^\circ$)	64 (90 %)	$8.5^\circ \pm 6.3^\circ$	$-0.5^\circ \pm 6.8^\circ$	$-9.0^\circ \pm 5.6^\circ$
Outliers (beyond $\pm 10^\circ$)	7 (10 %)	$8.0^\circ \pm 4.5^\circ$	$4.7^\circ \pm 8.0^\circ$ ^b	$-3.4^\circ \pm 8.4^\circ$ ^b

^a Positive axial rotation corresponds to femoral internal rotation (tibial external rotation) and negative axial rotation corresponds to femoral external rotation (tibial internal rotation)

^b The magnitudes of maximum and minimum axial rotation were significantly different for the outlier group compared to the nominal group (t-test, $p < 0.05$)

patients with nominal alignment (Fig. 2). The motion pattern for the only patient who showed improvement in function at the two-year evaluation (#47) does not appear different from the other subset patients.

Discussion

In this study femoro-tibial rotational alignment and knee kinematics obtained during immediate postoperative trialing

corresponded with the patients' performance in the Knee Society function score after short-term follow-up. Patients presenting with deterioration of function scores had rotational mismatch of 10° or more and significantly less femoral external rotation during passive flexion (Tables 1 and 2).

It has been demonstrated that knee kinematics is different after TKA [19] with decreased femoral external rotation [24] and altered patellar tracking [25]. Previous studies have demonstrated a link between component alignment and outcome [26–31]. Recent studies have demonstrated that internal rotation of the tibial component is frequent in painful and stiff TKA [32, 33] and that rotational mismatch between the components might have a negative influence on the postoperative outcome [33]. However, there are no data documenting acceptable ranges of rotational mismatch between the femoral and tibial component. Furthermore, there are no quantitative studies linking intra-operative kinematic performance of TKA with subsequent functional outcome. In the present study, TKA with greater than 10° degrees of mismatch between the femoral and tibial components experienced significantly poorer functional outcomes, with no improvement in the Knee Society function score. Knee kinematics during passive flexion were significantly

Fig. 1 Axial rotation kinematics were different for patients with less than 10° (nominal group) and 10° or more (outlier group) tibial-femoral mismatch, including axial rotations at the articular surface (femur on polyethylene bearing) and at the backside surface (polyethylene bearing on tibia)

Fig. 2 Axial rotation kinematics for patients with 10° or more (outlier group) rotational mismatch. The total rotation reflects the axial rotations due to articular motion (femur on polyethylene bearing) and due to backside motion (polyethylene bearing on tibia)

Total Axial Rotation between the femoral component and tibial baseplate

Axial Rotation due to Articular Surface Motion (femoral component moving on polyethylene bearing)

Axial Rotation due to Backside Surface Motion (polyethylene bearing moving on tibial baseplate)

different in patients with mismatch, corresponding to the subsequent poor outcomes. While it is recognized that absolute alignment of the femoral and tibial component relative to bony landmarks is important, these data suggest that the coupled alignment of the femoral and tibial component is also critical for achieving good functional outcome.

These findings are especially interesting as mobile-bearing TKA designs have been developed to allow rotational freedom. The ability to self-align according to soft-tissue strains is thought to compensate for rotational malalignment [34–37], but such compensation may not be beneficial in general and may occur only within certain ranges

which are smaller than previously thought [38]. In the present study, TKA in both groups showed very consistent motion for the femoral component moving on the articular surface of the polyethylene bearing, with similar ranges of total axial rotation (Table 3). Therefore, even TKA with rotational mismatch in the outlier group could at least immediately postoperative sufficiently compensate for the differences in component alignment to achieve the necessary range of rotation and accomplish the passive flexion movement. However, motion of the polyethylene bearing was considerably different for the two groups (Fig. 1). In the nominal group, there was progressively increasing external

rotation with increasing flexion, primarily due to external rotation of the polyethylene bearing on the tibial baseplate from 0° to 80° and combined bearing rotation and femoral component external rotation beyond 80°. In contrast, the outlier group showed internal rotation of the polyethylene bearing throughout the flexion range, with opposite rotation motions occurring at the articular surface and backside surface of the polyethylene bearing in the higher flexion range (>80°). Such incongruous behaviour may have consequences for knee stability perceived by the patients and be a factor contributing to the observed poor function scores.

This study has some limitations. It is an analysis of data from a study designed for a different question [16] (component alignment in navigated and conventional TKA) although the subjects and data was registered prospectively. The kinematic analysis was performed postoperatively immediately following wound closure with the patient still under anaesthesia without muscle contraction or weight-bearing. This was done in an effort to minimize variability due to patient habitus, dynamic activity and possible pain. Furthermore, using slow and controlled movement of the knee eliminated measurement difficulties that can occur with motion blur in the image frames [20]. Finally, although the Knee Society score is frequently used to evaluate TKA outcome, it is recognized that the function score can be influenced by other joint pain and/or general health problems.

This study demonstrated that femoro-tibial rotational alignment is important for knee function after TKA and rotational mismatch leads to altered kinematics. Since femoro-tibial mismatch of 10° or more resulted in significantly worse results in the Knee Society function score, even with a mobile-bearing TKA design, efforts to prevent this magnitude of rotational mismatch could prove beneficial to function.

Standard surgical practice for TKA includes passive range of motion when the prosthesis trial components are in place. Such trialing provides the surgeons feedback about soft tissue tension, rotational orientation of the tibial component and patellar tracking. The final rotational orientation of the tibial component is still a matter of debate. It can be done using anatomical landmarks, such as the tibial tuberosity or the second metatarsal bone. Unfortunately these anatomic landmarks are variable among patients [34–37] and the consequence might be a rotational mismatch between femoral and tibial component [39]. Alternatively the “self-seeking method” can be used with tibial rotational orientation according to the position which is achieved after trialing. This “self-seeking method” achieves a good femoro-tibial rotational alignment in terms of a minimized mismatch between the components but implies the risk of transferring a possible femoral malrotation to the tibia with the consequence of problems with patellar tracking.

Based on the data of this study, we suggest the following approach for assessing rotational alignment in TKA. We recommend establishing rotational alignment of the tibial component using the border between the medial and the middle third of the tibial tuberosity, as this most likely produces a femoro-tibial rotational mismatch of less than 10° [39]. Additionally, during trial reduction, we recommend that surgeons make note of any forced changes in the rotational alignment of the tibial component due to soft-tissue strains. If this orientation is considerably different from the medial third of the tibial tuberosity, then rotational alignment of the femoral component should be double-checked and if patellar tracking is good and soft-tissue balancing has been well performed this rotational orientation should be used.

Conflict of interest The institution of one or more of the authors (JL, SK, MKH) has received funding from Stryker Orthopaedics.

References

- Dunbar MJ (2001) Subjective outcomes after knee arthroplasty. *Acta Orthop Scand Suppl* 72:1–63
- Nilsdotter AK, Toksvig-Larsen S, Roos EM (2009) Knee arthroplasty: are patients' expectations fulfilled? A prospective study of pain and function in 102 patients with 5-year follow-up. *Acta Orthop* 80:55–61
- Nunez M, Lozano L, Nunez E, Segur JM, Sastre S, Macule F, Ortega R, Suso S (2009) Total knee replacement and health-related quality of life: factors influencing long-term outcomes. *Arthritis Rheum* 61:1062–1069
- Andriacchi TP, Galante JO, Fermier RW (1982) The influence of total knee-replacement design on walking and stair-climbing. *J Bone Joint Surg Am* 64:1328–1335
- Kim YH, Yoon SH, Kim JS (2009) Early outcome of TKA with a medial pivot fixed-bearing prosthesis is worse than with a PFC mobile-bearing prosthesis. *Clin Orthop Relat Res* 467:493–503
- Pritchett JW (2004) Patient preferences in knee prostheses. *J Bone Joint Surg Br* 86:979–982
- Andersson GB, Andriacchi TP, Galante JO (1981) Correlations between changes in gait and in clinical status after knee arthroplasty. *Acta Orthop Scand* 52:569–573
- Banks SA, Markovich GD, Hodge WA (1997) In vivo kinematics of cruciate-retaining and -substituting knee arthroplasties. *J Arthroplasty* 12:297–304
- Hatfield GL, Hubley-Kozey CL, Astephen Wilson JL, Dunbar MJ (2011) The effect of total knee arthroplasty on knee joint kinematics and kinetics during gait. *J Arthroplasty* 26:309–318
- Kitagawa A, Tsumura N, Chin T, Gamada K, Banks SA, Kurosaka M (2010) In vivo comparison of knee kinematics before and after high-flexion posterior cruciate-retaining total knee arthroplasty. *J Arthroplasty* 25:964–969
- Markovich GD, Banks SA, Hodge WA (1998) Comparison of active and passive knee replacement kinematics. *Orthop Trans* 21:810–811
- Barrack RL, Schrader T, Bertot AJ, Wolfe MW, Myers L (2001) Component rotation and anterior knee pain after total knee arthroplasty. *Clin Orthop Relat Res* 392:46–55

13. Berger RA, Crossett LS, Jacobs JJ, Rubash HE (1998) Malrotation causing patellofemoral complications after total knee arthroplasty. *Clin Orthop Relat Res* 356:144–153
14. DesJardins JD, Banks SA, Benson LC, Pace T, LaBerge M (2007) A direct comparison of patient and force-controlled simulator total knee replacement kinematics. *J Biomech* 40:3458–3466
15. Rhoads DD, Noble PC, Reuben JD, Tullos HS (1993) The effect of femoral component position on the kinematics of total knee arthroplasty. *Clin Orthop Relat Res* 286:122–129
16. Lützner J, Krummenauer F, Wolf C, Günther KP, Kirschner S (2008) Computer-assisted and conventional total knee replacement: a comparative, prospective, randomised study with radiological and CT evaluation. *J Bone Joint Surg Br* 90:1039–1044
17. Banks SA, Hodge WA (1996) Accurate measurement of three-dimensional knee replacement kinematics using single-plane fluoroscopy. *IEEE Trans Biomed Eng* 43:638–649
18. Banks SA, Hodge WA (2004) 2003 Hap Paul Award Paper of the International Society for Technology in Arthroplasty. Design and activity dependence of kinematics in fixed and mobile-bearing knee arthroplasties. *J Arthroplasty* 19:809–816
19. Banks SA, Hodge WA (2004) Implant design affects knee arthroplasty kinematics during stair-stepping. *Clin Orthop Relat Res* 426:187–193
20. Fantozzi S, Leardini A, Banks SA, Marcacci M, Giannini S, Catani F (2004) Dynamic in-vivo tibio-femoral and bearing motions in mobile bearing knee arthroplasty. *Knee Surg Sports Traumatol Arthrosc* 12:144–151
21. Incavo SJ, Mullins ER, Coughlin KM, Banks S, Banks A, Beynnon BD (2004) Tibiofemoral kinematic analysis of kneeling after total knee arthroplasty. *J Arthroplasty* 19:906–910
22. Insall JN, Dorr LD, Scott RD, Scott WN (1989) Rationale of the Knee Society clinical rating system. *Clin Orthop Relat Res* 248:13–14
23. Oppe M, Rabin R, de Charro F (2011) EQ-5D user guide. www.euroqol.org. Accessed 21 May 2012
24. Seon JK, Park JK, Jeong MS, Jung WB, Park KS, Yoon TR, Song EK (2011) Correlation between preoperative and postoperative knee kinematics in total knee arthroplasty using cruciate retaining designs. *Int Orthop* 35:515–520
25. Kainz H, Reng W, Augat P, Wurm S (2012) Influence of total knee arthroplasty on patellar kinematics and contact characteristics. *Int Orthop* 36:73–78
26. Berend ME, Ritter MA, Meding JB, Faris PM, Keating EM, Redelman R, Faris GW, Davis KE (2004) Tibial component failure mechanisms in total knee arthroplasty. *Clin Orthop Relat Res* 428:26–34
27. Hofmann S, Romero J, Roth-Schiffl E, Albrecht T (2003) Rotational malalignment of the components may cause chronic pain or early failure in total knee arthroplasty. *Orthopade* 32:469–476
28. Jeffery RS, Morris RW, Denham RA (1991) Coronal alignment after total knee replacement. *J Bone Joint Surg Br* 73:709–714
29. Lotke PA, Ecker ML (1977) Influence of positioning of prosthesis in total knee replacement. *J Bone Joint Surg Am* 59:77–79
30. Ritter MA, Faris PM, Keating EM, Meding JB (1994) Postoperative alignment of total knee replacement. Its effect on survival. *Clin Orthop Relat Res* 299:153–156
31. Romero J, Stahelin T, Binkert C, Pfirrmann C, Hodler J, Kessler O (2007) The clinical consequences of flexion gap asymmetry in total knee arthroplasty. *J Arthroplasty* 22:235–240
32. Bedard M, Vince KG, Redfern J, Collen SR (2011) Internal rotation of the tibial component is frequent in stiff total knee arthroplasty. *Clin Orthop Relat Res* 469:2346–2355
33. Nicoll D, Rowley DI (2010) Internal rotational error of the tibial component is a major cause of pain after total knee replacement. *J Bone Joint Surg Br* 92:1238–1244
34. Akagi M, Mori S, Nishimura S, Nishimura A, Asano T, Hamanishi C (2005) Variability of extraarticular tibial rotation references for total knee arthroplasty. *Clin Orthop Relat Res* 436:172–176
35. Eckhoff DG, Metzger RG, Vandewalle MV (1995) Malrotation associated with implant alignment technique in total knee arthroplasty. *Clin Orthop Relat Res* 321:28–31
36. Huddleston JI, Scott RD, Wimberley DW (2005) Determination of neutral tibial rotational alignment in rotating platform TKA. *Clin Orthop Relat Res* 440:101–106
37. Uehara K, Kadota Y, Kobayashi A, Ohashi H, Yamano Y (2002) Bone anatomy and rotational alignment in total knee arthroplasty. *Clin Orthop* 402:196–201
38. Wasielewski RC, Komistek RD, Zingde SM, Sheridan KC, Mahfouz MR (2008) Lack of axial rotation in mobile-bearing knee designs. *Clin Orthop Relat Res* 466:2662–2668
39. Lützner J, Krummenauer F, Günther KP, Kirschner S (2010) Rotational alignment of the tibial component in total knee arthroplasty is better at the medial third of tibial tuberosity than at the medial border. *BMC Musculoskelet Disord* 11:57