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Influence of tibial rotation in total knee arthroplasty on knee kinematics and retropatellar pressure: an in vitro study

Arnd Steinbrück · Christian Schröder · Matthias Woiczinski · Tatjana Müller · Peter E. Müller · Volkmar Jansson · Andreas Fottner

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Abstract

Purpose Although continuous improvements have been made, there is still a considerable amount of unsatisfied patients after total knee arthroplasty (TKA). A main reason for this high percentage is anterior knee pain, which is supposed to be provoked by post-operative increased retropatellar peak pressure. Since rotational malalignment of the implant is believed to contribute to post-operative pain, the aim of this study was to examine the influence of tibial component rotation on knee kinematics and retropatellar pressure.

Methods Eight fresh-frozen knee specimens were tested in a weight-bearing knee rig after fixed-bearing TKA under a loaded squat from 20° to 120° of flexion. To examine tibial components with different rotations, special inlays with 3° internal rotation and 3° external rotation were produced and retropatellar pressure distribution was measured with a pressure-sensitive film. The kinematics of the patella and the femorotibial joint were recorded with an ultrasonic-based motion analysis system.

Results Retropatellar peak pressure decreased significantly from 3° internal rotation to neutral position and 3° external rotation of the tibial component (8.5 ± 2.3 vs. 8.2 ± 2.4 vs. 7.8 ± 2.5 MPa). Regarding knee kinematics femorotibial rotation and anterior–posterior translation, patella rotation and tilt were altered significantly, but relative changes remained minimal.

Conclusion Changing tibial rotation revealed a high in vitro influence on retropatellar peak pressure. We recommend the rotational alignment of the tibial component to the medial third of the tibial tuberosity or even more externally beyond that point to avoid anterior knee pain after TKA.

Keywords Total knee arthroplasty · Rotational malalignment · Retropatellar pressure · Tibial component · Knee kinematics · Anterior knee pain

Introduction

Since decades, total knee arthroplasty (TKA) is the surgical therapy of choice for advanced-stage knee osteoarthritis [2, 6]. Although continuous improvements concerning surgical technique, implant design and materials have been made, there are still up to 18 % of unsatisfied patients after TKA [11, 28, 41]. Besides the patient expectations, the extent of information given to the patient, preoperative functional status and extra-articular causes, there are also several surgical factors of influence for the outcome of TKA [1, 29].

A. Steinbrück (✉) · C. Schröder · M. Woiczinski · T. Müller · P. E. Müller · V. Jansson · A. Fottner
Department of Orthopedic Surgery, Physical Medicine and Rehabilitation, University Hospital of Munich (LMU), Campus Grosshadern, Marchioninistr. 15, 81377 Munich, Germany
e-mail: arnd.steinbrueck@med.uni-muenchen.de

C. Schröder
e-mail: christian.schroeder@med.uni-muenchen.de

M. Woiczinski
e-mail: matthias.woicinski@med.uni-muenchen.de

T. Müller
e-mail: tatjana.mueller@med.uni-muenchen.de

P. E. Müller
e-mail: peter.mueller@med.uni-muenchen.de

V. Jansson
e-mail: volkmar.jansson@med.uni-muenchen.de

A. Fottner
e-mail: andreas.fottner@med.uni-muenchen.de

In addition to instability, polyethylene (PE) wear and aseptic loosening, anterior knee pain is the main surgical reason for post-operative pain [38, 40]. The incidence of peripatellar complications after TKA is up to 12 % [7]. Post-operative increase in the retropatellar pressure is supposed to provoke post-operative patella problems [12, 20, 37].

PE wear, loosening and instability are influenced by altered knee kinematics after TKA [24, 42]. Rotational malalignment of the implant is suspected to contribute to post-operative pain, excessive PE wear, loosening, instability and patellar maltracking as well as increased retropatellar pressure [9, 18, 22, 35]; especially, internal rotational error of the tibial component often comes along with especially anterior pain after TKA [27].

In vitro studies with cadaver knee specimens are a well-known method to analyse altered knee kinematics after TKA and implications on retropatellar pressure distribution [4, 10, 16, 39, 42]. There are studies confirming the positive effects of external rotation of the femoral component in terms of reducing retropatellar peak pressure and reproducing more natural kinematics of the patella [25, 36], but there is not much literature concerning the influence of tibial rotation on the kinematics of the patella [3, 26].

In terms of the rotation of the tibial component, it is believed that the best position may be achieved orientating the rotation to the medial border or the medial third of the tibial tuberosity [19, 23]. Even though there are several clinical studies suggesting a better outcome with the tibial component placed at medial part of the tibial tuberosity or even rotated externally beyond that point, there is a lack of cadaver studies examining the exact influence of the tibial component rotation on retropatellar pressure and kinematics in TKA. Therefore, the aim of this study was to evaluate the influence of tibial component rotation on retropatellar pressure and kinematics of the TKA using cadaver specimens mounted on a special knee rig. Tibial component rotation was simulated with a particular technique with specially produced inlays by the manufacturer to allow analysing even small amounts of component rotation in between the same specimen. Since increased retropatellar pressure is supposed to provoke anterior knee pain, the results of this study can give guidance of tibial component alignment intraoperatively.

Materials and methods

Eight fresh-frozen human knee specimens [age 58.9 ± 11.7 years (range 47–82); 3 female, 5 male; height: 176.9 ± 5.9 cm; weight: 81.5 ± 10.6 kg] were used for the experiments. Knees with serious valgus or varus deformity (≥10°) were excluded. The specimens were resected 20 cm proximal and 15 cm distal to the joint line. The soft tissue surrounding the knee joint (including capsule, ligaments and tendons) was preserved. Afterwards, the fibula head was fixed to the proximal tibia using a 4.5-mm screw, and metallic finger traps (Bühler-Instrumente Medizintechnik GmbH, Tuttlingen, Germany, Fig. 1) were connected to the tendons and fixation augmented using suture material (FibreWire, Arthrex, Munich, Germany) [35]. At the end, the tibia and the femur were embedded into metallic pots with epoxy casting resin (Rencast FC53, Huntsman, Basel, Switzerland).

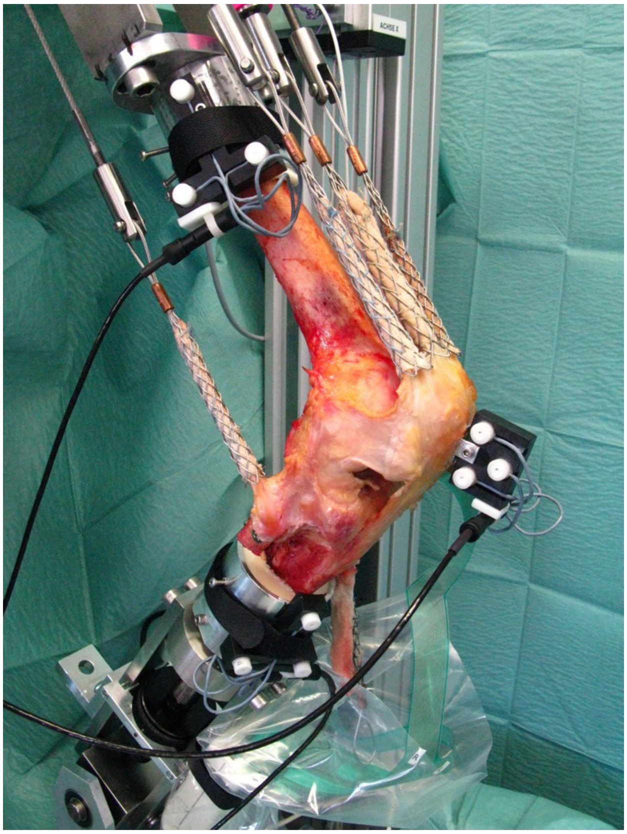

Fig. 1 Prepared knee specimen with miniature transmitters of femur, patella and tibia mounted in the knee rig

For the evaluation of the degree of osteoarthritis and to exclude knees with serious deformities, X-rays in anterior–posterior, sagittal and sunrise view were taken before implantation. The same X-rays were taken after TKA to ensure the correct implantation of the prostheses.

Implantation

For this in vitro study, a fixed-bearing, cruciate-retaining TKA (Columbus CR Aesculap, Tuttlingen, Germany) was chosen. Columbus knee system is a knee system which is on the market since 2003 with approximately 185,000 implantations and currently still used for total knee replacement [14]. The femoral component is a multi-radius design

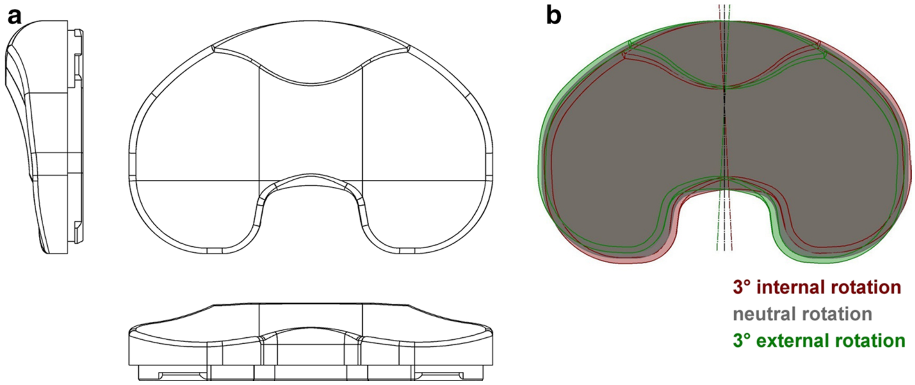

Fig. 2 **a** CAD-data of the inlay (*sagittal*, *top* and *posterior* view), **b** Top view of the three different inlays of a right knee in neutral, 3° internal rotation and 3° external rotation

with a relatively small dorsal femoral radius. The short posterior condyles enable high flexion up to 140°. The trochlea of the femoral component has a valgus direction of 7°, with an elevated antero-lateral femoral design to prevent patella luxation. The implantation was performed by the first author A.S. under supervision of the senior author A.F. using a subvastus approach to the knee and a tibia first technique for ligament balancing. According to the study of Lützner et al. [23], all tibial components were aligned to the medial third of the tibial tuberosity. In advance, the tibial tuberosity was divided into three parts, and the borders were marked with a surgical pen.

To achieve different rotations of the tibial component, different inlays using the CAD-data of the prosthesis and CAD-Software (Catia V5 R19, Dassault Systems, France) were constructed. Additional to the regular inlay (defined as neutral position), two variations with 3° of internal and external rotation were produced out of PE by the manufacturer (Fig. 2). This way, the articular surface of the inlays remained unchanged. With these variations, it was possible to examine the influence of different tibial rotations by only changing the inlays.

Biomechanical test setup

For the measurement of the retropatellar pressure distribution, the patella remained unresurfaced; only existing osteophytes on the circumference were removed. A pressure-sensitive film (K-Scan 4000, Tekscan Inc., Boston, USA) was sutured to the retropatellar surface using subcutaneous 1.0 suture material. To stabilise the attachment and to avoid shear forces, a 0.125-mm Teflon tape (PTFE-tape) was glued on the sensor before suturing. The sensor film has a total number of 572 sensels (62 sensels per cm^2) with a maximum pressure of 1,500 PSI (~10 MPa). For calibration of the sensor, a two-point load, as recommended by the manufacturer, was applied using a material testing machine (Z010, Zwick, Ulm, Germany). The patella ridge was landmarked on the sensor film for orientation and the following pressure distribution analysis.

The specimens were mounted on a 6° of freedom (DOF) knee rig [35, 36]. For the measurements, a loaded squat from 20° to 120° of flexion and back to 20° of extension was induced with a constant velocity of 3°/s by a linear drive (Driveset M150, Systec GmbH, Muenster, Germany). The position of the knee and the axial femorotibial rotation was measured by two angle sensors (8820 Burster, Gernsbach, Germany) in the upper "hip assembly" and the lower "ankle assembly". The quadriceps muscle force was simulated by another linear drive (Driveset M180, Systec GmbH, Muenster, Germany) and measured by a force sensor (8417-6002 Burster, Gernsbach, Germany) installed near the tendon. We restored the quadriceps muscle vectors anatomically: the rectus muscle was orientated to the femur shaft, vastus lateralis to the greater, vastus medialis to the lesser trochanter. Further muscles (medial vastus, lateral vastus, semitendinosus and biceps femoris muscle) were simulated using for each a 2-kg weight. In this constellation, the ground reaction force was measured under the "ankle assembly" by a six DOF force moment sensor (FN 7325-31 FGP Sensors, Cedex, France).

The two linear drives were controlled by a self-programmed LabVIEW code (Version 8.6, National Instruments, Austin, Texas, USA) on a personal computer using Real-Time and PID-Control Packages to achieve a constant ground reaction force of 50 N.

For recording of knee kinematics, an ultrasonic-based 3-dimensional motion analysis system (Zebris CMS 20, Isny, Germany) was used. Three miniature transmitters each were attached to the femur, the patella and the tibia (Fig. 1), providing the determination of the rotation and translation of the femur, the patella and the tibia with an accuracy of 0.1° and 0.1 mm. For the kinematics of the patella, the definitions of Bull et al. [8] (flexion, rotation, tilt and shift) were used (Fig. 3). Sufficient measurement reliability for kinematics and retropatellar pressure was assured by test–retest analysis; accuracy of the measurement system has been described in a former study [35]. This study was approved by the ethical committee of University of Munich (LMU).

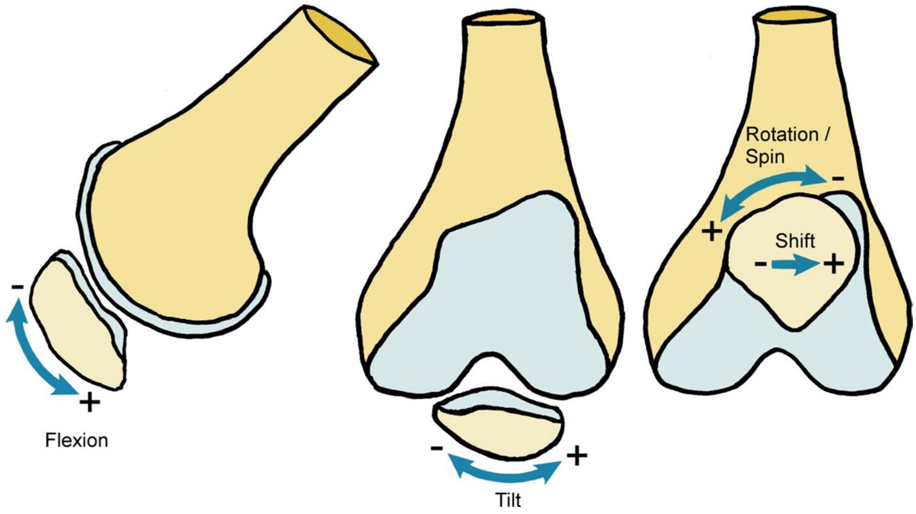

Fig. 3 Definition of patella kinematics (flexion, rotation, tilt and shift), lateral on the right side

Table 1 Regression coefficients out of the mixed-effects model analysis, mean and 95 % confidence interval are shown

Parameter	3° internal rotation	0° neutral	3° external rotation	Significance level
Quadriceps muscle force	−7.8 N (−14.9 N; −0.7 N)	0 N	5.5 N (−10.2 N; 4.0 N)	n.s.
Ground reaction force	0.2 N (−0.3 N; 0.6 N)	0 N	−0.03 N (−0.4 N; 0.4 N)	n.s.
Femorotibial rotation (+internal)	1.2° (0.9°; 1.45°)	0°	0.2° (−0.1°; 0.5°)	$p < 0.01$
Translation of the femur (+anterior)	−0.9 mm (−1.4 mm; −0.5 mm)	0 mm	0.4 mm (0.00 mm; 0.9 mm)	$p < 0.01$
Patella flexion	−0.03° (−1.9°; 1.9°)	0°	−0.1° (−2.0°; 1.8°)	n.s.
Patella rotation (+lateral)	0.2° (0.0°; 0.4°)	0°	−0.04° (−0.2°; 0.1°)	$p = 0.04$
Patella tilt (+lateral)	−0.1° (−0.3°; 0.16°)	0°	0.2° (0.02°; 0.5°)	$p = 0.02$
Patella shift (+lateral)	−0.01 mm (−0.2 mm; 0.2 mm)	0 mm	−0.1 mm (−0.2 mm; 0.1 mm)	n.s.
Retropatellar peak pressure	0.2 MPa (0.04 MPa; 0.4 MPa)	0 MPa	−0.3 MPa (−0.4 MPa; −0.10 MPa)	$p < 0.01$

Statistical analysis

Results for absolute values were presented in mean ± standard deviation. To compare different tibial rotations, the measured parameters were modelled using mixed-effect model with random intercept per knee specimen. Fixed effects were included in the model by the cosine of the flexion angle (FA in radian), the squared cosine of the FA, the cubed cosine of the FA, the different tibial rotations (external/neutral/internal) as well as flexion/extension of the knee. For this model, the results were displayed as regression coefficient with 95 % confidence interval. Analyses were performed using SPSS software (SPSS release 21.0, IBM, New York, USA). $p < 0.05$ was considered statistically significant.

Results

According to mixed-effect model, alteration of the rotation of the tibial component had a significant influence on the mean retropatellar peak pressure after TKA (Table 1). In neutral position, the retropatellar peak pressure was 8.2 ± 2.4 MPa. 3° of internal tibial rotation led to a clear increase in retropatellar peak pressure (8.5 ± 2.3 MPa), while 3° external rotation revealed a pronounced decrease in pressure (7.8 ± 2.5 MPa) ($p < 0.01$). Regarding the pressure distribution, the peak pressure was located at the medial part of the patella ridge (Fig. 4). The highest peak pressure differences were measured in high flexion angles (>80°). Quadriceps muscle force and ground reaction force did not alter significantly (Table 1).

Regarding the influence on the kinematic of the patella, there was a significant difference in patella rotation [rotation at 120° of flexion: neutral (3.1° ± 7.2°), internal (3.3° ± 7.2°), external (3.0° ± 7.2°) ($p = 0.04$) and patella tilt; tilt at 120° of flexion: neutral (4.1° ± 8.3°); internal (4.0° ± 8.3°); external (4.3° ± 8.4°) ($p = 0.02$)]. The changes in patella flexion and patella shift were not significant (Table 1).

Different rotations of the tibial component not only had an influence on the patella, there was also a significant alteration on the kinematics of the femorotibial joint (Table 1). 3° internal rotation of the tibial component led to a higher

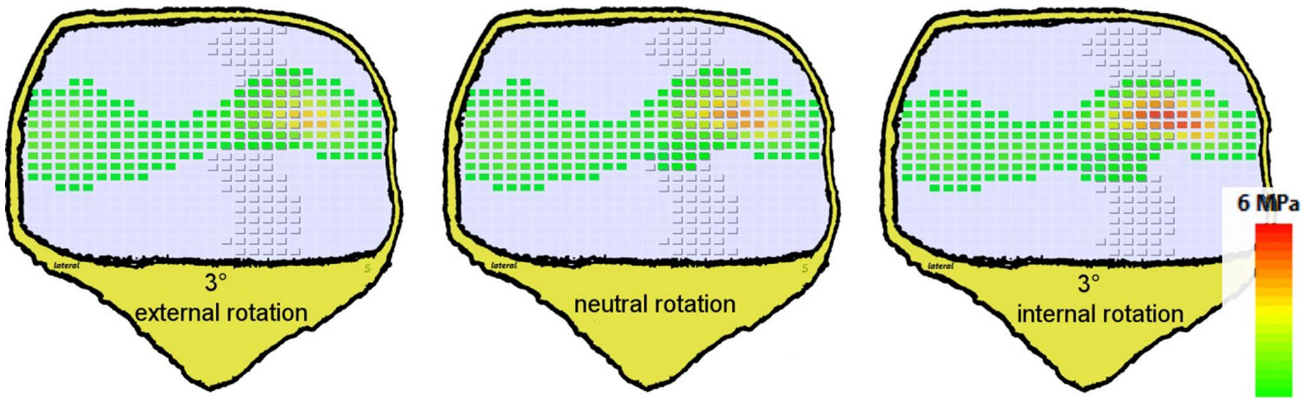

Fig. 4 Retropatellar pressure distribution in a flexion angle of 100° for different rotations of the tibial component. Patella ridge is *dotted in grey*

posterior translation of the femur. The opposite effect was seen using the inlay with 3° external rotation. Posterior translation of the femur at 120° of flexion was in neutral rotation −5.0 ± 3.9 mm, in internal rotation −5.6 ± 5.1 mm, in external rotation −4.9 ± 4.6 mm ($p < 0.01$).

Discussion

The most important finding of the present study was a significant influence of the rotation of the tibial component on retropatellar peak pressure. Looking at the pressure distribution, especially the peak pressure, on the medial part of the patella ridge was reduced by external rotation of the tibial component. This in vitro tendency might support clinical studies revealing less anterior knee pain after TKA with external rotation of the tibial component [23, 27]. Even though the mixed-effect model revealed a significant difference with alteration of only 3°, there is no threshold for the amount of reduction of retropatellar peak pressure and an effect on clinical symptoms like anterior knee pain. There are no standard guidelines for the rotational placement of the tibia component in TKA [19, 23, 32], and in clinical situations, malrotations of the tibial component are often much higher [13, 23]. Even if there would be a uniform ideal rotational position, it is hardly possible to place the tibial component within a range of 3° with conventional or patient-specific instrumentation or even computer-assisted surgery [15, 30, 33].

Even though there were significant differences regarding the regression coefficients of patella tilt and patella rotation between internal and external rotation of the tibial component, the influence on patella kinematics was rather marginal. The relatively small alteration of the patella rotation and patella tilt might not have a clinical impact. The alterations of the patella flexion and patella shift were even smaller and not significant.

A comparison with former in vitro studies examining the influence of tibial component rotation on patella kinematics is difficult due to different experimental set-ups [3, 26]. But in both referenced studies, the alteration of patella tilt, shift and rotation were also only marginal. Regarding external rotation of the tibial component, Anglin et al. [3] also found the tendency of a more lateral patella tilt in knee flexion compared with the position in extension.

The influence of the rotation of the tibial component on the kinematics of the femorotibial joint was also rather small. With internal rotation of the tibia, there was slightly more posterior translation of the femur, but a clinical impact of this difference is rather unlikely. The same applies for the femorotibial rotation. The difference of the mean values between 3° internal and 3° external rotation of the tibial component was statistically significant. Probably due to the low constraining force between the femur and tibial component in the used CR prosthesis, a rotation of the tibial component did not lead to a highly altered femorotibial rotation.

Comparing former in vitro studies with this experimental setup is complex, because different specimens with anatomical variability of the patella were used [35, 36]. But there seems to be a higher influence of the tibial rotation compared with the femoral rotation concerning retropatellar peak pressure. In a former study of Steinbrück et al. [36], the alteration of the femoral compartment of 3° internal rotation produced an increase in maximum retropatellar peak pressure of 0.01 MPa, and using the variant with 3° external rotation caused a decrease of 0.1 MPa compared with the neutral rotation. Compared with these data, 3° internal rotation of the tibial component led to a higher increase in the maximum retropatellar peak pressure by 0.2 MPa, as well as 3° external rotation revealed a higher decrease by 0.5 MPa. In the range of ±3° of rotation alteration, the influence on the maximum retropatellar peak pressure was five times higher for the tibial component compared with the femoral component (0.7 vs. 0.1 MPa). Only further external rotation of the femoral component by 6° caused a distinct decrease in mean retropatellar peak pressure of 1.1 MPa.

This study has a number of limitations to be considered. One limitation lies within the variety of the tibial tuberosity [17]. Especially in knees with varus deformity, the tibial tuberosity is not a reliable rotational landmark for the tibia component [5, 31]. On the other hand, Lawrie et al. [21] are certifying a good reliability of the tibial tuberosity on the flexion–extension axis. In our study, we used the tibial tuberosity for orientation since it is the main rotational landmark in clinical practice of TKA [23]. To reduce the amount of variety, specimens with serious valgus or varus deformity (≥10°) were excluded.

A challenge of all in vitro studies using cadaver specimens is the limited acquisition of samples. We tested all modifications of implantation in between one specimen, and due to paired observations, statistical significance is supported, although a higher number of specimens might have supported our results substantially. Due to technical reasons, it was only possible to produce altered inlays with 3° of internal or external rotation. In clinical situations, malrotations of the tibial component are often much higher [13, 23]. Another limitation with in a knee rig study lies within the constriction of simulation to a loaded squat. Many activities of daily living like walking, climbing stairs or rising from a chair cannot be simulated with this rig. But parts of the results may be transferred to in vivo activities.

Finally, these achieved results only apply for TKA with fixed-bearing inlays. The results cannot be transferred to TKA with mobile bearing inlays or rotation platform, because these inlays adjust independently to the rotation of the tibial component.

The results of our study highlight the importance of tibial component alignment especially in knee arthroplasty with fixed bearing. In patients with unexplained knee pain after TKA, a vast internal tibial malrotation should be radiologically excluded [27, 34].

Conclusion

A significant reduction of retropatellar pressure by rotating the tibial component externally could be confirmed by this in vitro study, while knee kinematics remained almost unchanged. Wide internal rotation of the tibial component should be avoided intraoperatively and might cause anterior knee pain according to clinical studies.

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Conflict of interest The authors declare that they have no conflict of interest.

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