ORIGINAL PAPER

Influence of tibial slope on extension and flexion gaps in total knee arthroplasty: increasing the tibial slope affects both gaps

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Abstract

Purpose Increasing the tibial slope is often performed if the flexion gap is narrower than the extension gap. The main hypothesis of this study is that increasing the tibial slope coincidentally enlarges the extension gap.

Methods Twenty formalin-fixed cadaveric knees were obtained for study. After CT in full extension and 90° flexion, the data of each specimen were entered into a standardized coordinate system and virtual bone cuts were performed with incrementally increasing the posterior slope. Gaps were measured at tibiofemoral contact points in 90°-flexion and full extension in the medial and lateral compartment.

Results Increasing the tibial slope did significantly widen both the extension and the flexion gaps ($p<0.001$). In extension, the opening rates, i.e. the gap increase per degree of slope increase, were equal medially and laterally (0.5 mm ±0.1) medial vs 0.6 mm (±0.0) lateral, whereas in flexion the lateral gap did open significantly more than the medial one (0.6 mm ±0.1) medial vs 0.9 mm (±0.1) lateral ($p<0.001$), resulting in a significantly greater flexion gap laterally.

Conclusions Increasing the tibial slope beyond the pre-operative planning in order to widen a tight flexion gap intra-operatively is not recommended as doing so will increase the extension gap simultaneously and will make the medial and lateral flexion gaps unequal.

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Introduction

In total knee arthroplasty (TKA), implant alignment in flexion and extension and correct sizing are essential for good ligament/soft-tissue tension and postoperative function [1]. Many surgeons strive to produce extension and flexion gaps that are of equal magnitude and/or symmetrical [2–5].

Krackow et al. [6] and Mihalko et al. [7] defined the tibiofemoral gap as it occurs under distraction of the adjacent soft-tissue mantle. The flexion and extension gaps are influenced by various factors, including deformities and osteolysis [4], contractures of the soft tissue mantle [8], operative approach [9], osteophytes [10, 11], and eversion of the patella [12, 13]. Even preparation of the flexion gap can influence the magnitude of the extension gap [14]. Finally, bony resection can affect capsular and ligamentous tension, and thus also the size of the gaps [15].

In a cadaveric study, Bellemans et al. [16] found that increasing the tibial slope improves knee flexion. Lombardi et al. [17] reported that in cases of a relatively tight flexion gap, equalizing flexion and extension gap can often be reached by increasing the tibial slope. This technique is implemented by surgeons in addition to the release of posterior ligaments assuming that "tibial roll-back" [18] during flexion prevents effects on the extension gap.

The medial and lateral tibiofemoral contact points can be used to measure the extent of roll-back. Wretenberg et al. [19] reported on the extent to which the tibiofemoral contact points of the medial and lateral compartments shift with increasing flexion. The actual extent of the roll-back mechanism in this scenario is likely overestimated.

The goal of the current study is to assess the magnitude of the extension and flexion gaps as tibial slope increases, considering physiological movements and using the tibiofemoral contact points for measurements. The main hypothesis is that increasing tibial slope also enlarges the bony part of the extension gap.

In comparison to conventional methods of measuring extension and flexion gaps, i.e. under distraction, this analysis considers only the bony portion of the gaps without distraction, similar to the measured resection technique. This gap is defined as the "osseous resection gap." The starting measure is the exact amount of bone that needs to be resected from the femur and tibia in order to implant the prosthetic components (Fig. 1).

Materials and methods

After approval by the Ethics Commission Beider Basel (EKBB) of Switzerland, 20 (ten left and ten right) formalin-fixed knee joint specimens from a university-level anatomy course were investigated. The average age of the donors was 81.9 years (± 12.4), the mean body weight was 67.4 kg (± 14.8), and the mean body height was 164.8 cm (± 10.2). Ten specimens were from male and ten from female donors.

In order to get a specimen with intact capsule and ligaments, the femur, tibia, and fibula were each dissected 150 mm proximally or by two 6-mm rods mounted in two drill holes that were 3 cm apart from each other in the coronal plane parallel to the knee joint axis. Skin, subcutaneous fat tissue, and muscle were predominantly resected.

Fig. 1 Osseous resection gaps. The red lines designate cuts necessary for implantation of prosthetic components

A customized frame was constructed to fix the specimen during CT scan. It was essentially made out of plastic and carbon to allow artefact-free data acquisition (Fig. 2).

For attachment to the frame, the femur was enclosed in a plastic sleeve, and a carbon rod was fixed through the 6-mm canal. The tibia was rigidly fixed to the frame by two 6-mm rods mounted in two drill holes that were 3 cm apart from each other in the coronal plane parallel to the knee joint axis.

Imaging was performed with a helical GE Lightspeed 16 row CT scanner (General Electric Healthcare Corporation, Waukesha, WI): 120 kV, slice thickness 0.625 mm, Voxel depth 0.5 mm, Voxel height 0.296875 mm, and Voxel width 0.296875 mm.

Two CT scans were performed per specimen, one in full extension and one at 90° flexion.

Adjustment of data using a standardized coordinate system

The DICOM data was analyzed using the visualization software VGStudio Max 2.1.1 (Volume Graphics GmbH, Heidelberg, Germany), which allows high-precision measurements by means of a CT-based coordinate measurement technology [20]. The data from the knee specimens were imported into a defined coordinate system. The coordinate system was based on the reports of Grood et al. [21] as well as McPherson et al. [22]. The coordinate system was initially defined in full extension, since tibiofemoral rotation is least in this position [18, 22]. Two-dimensional reconstructions of the data sets in the sagittal, frontal, and transverse planes as well as a three-dimensional reconstruction of the entire data volume per knee and axis were selected for monitor display. The transverse flexion-axis was determined by measuring movements of the
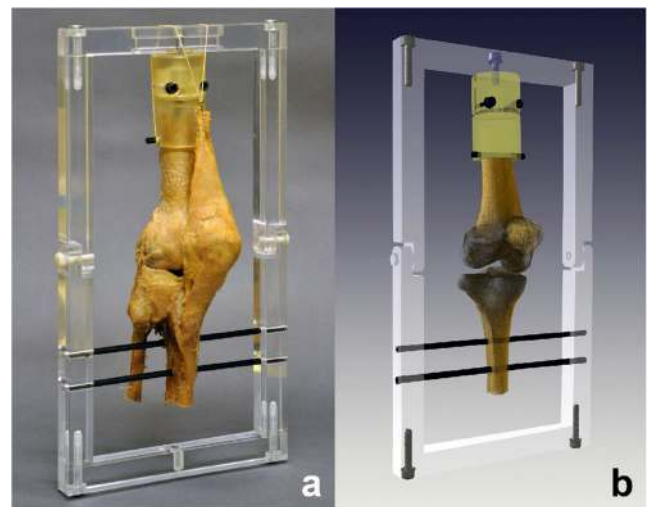

Fig. 2 Customized frame for CT scan. **a)** The frame was used for readings and the accurate positioning (motion) of the specimens. Although the frame does give the possibility to restrict the rotation of the femur, we did not use this option, in order to obtain a physiological movement. **b)** 3D CT reconstruction of the frame and specimen after CT scan

flexion facet center (FFC) on the posterior femoral condyle. It runs nearly parallel to the joint axis [23, 24].

In the sagittal plane, tibial reference points (tRP) were determined [22]. The tRP is the intersection between the three spatial axes at the most distal edge of the posterior tibia, defined at the level of the center of the proximal tibial drill canal. The FFC and tRP span the frontal plane. The coordinate system could be established from the frontal plane (primary reference), the axis through the FFC (secondary reference), and the tRP as the origin (tertiary reference). After arrangement of the data with the knee in extension, the corresponding data in flexion was aligned with exact stacked projection using a software-integrated function (Fig. 3a).

Determination of the tibiofemoral contact points

We determined the tibiofemoral contact points (tfCPs) of the medial and lateral joint compartments in full extension and with 90° of flexion according to the recommendations of Wretenberg et al. [19]. Because the tibiofemoral contact surfaces have a concave shape and thus, the tfCP is not located in the exact center of the contact surface, we selected the most inferior point of the medial and femoral condyles in the transverse plane, and included these in the calculation of the tfCP.

For each knee specimen, four tfCPs were determined, and for each of these, the distance to the transverse axis was measured. One each on the medial and lateral sides was measured in full extension, and again one each side in 90° of flexion (Fig. 3b).

Virtual bone resection and measurement

Virtual bone resections were performed according to the descriptions of Cheng et al. [25]. Resection of the tibia was carried out 6 mm distal to the deepest point of the medial tibial plateau parallel to the "horizontal plane" [25]. This tibial cut was defined as the 0° slope plane according to the standardized coordinate system. The distal femoral cut was made parallel to the tibial
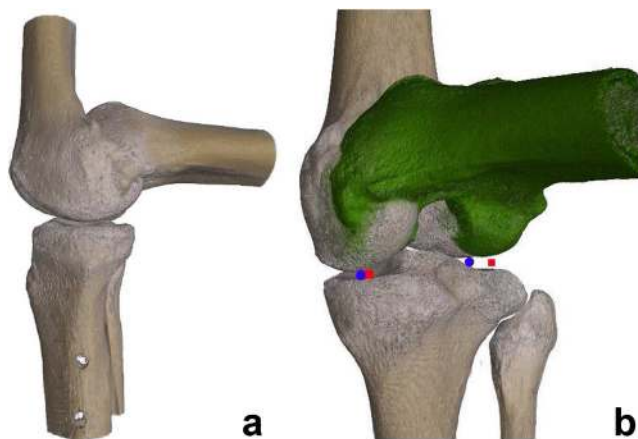
resection in full extension. Resection height was 9-mm proximal to the most distal point of the medial femoral condyle [25].

For the adjustment of the tibial slope, a pivot point was defined at the anterior edge of the tibial plateau. The longest mediolateral span of the tibial plateau was determined as the linear route. The route was halved, and the pivot point was set perpendicular to the midpoint along the anterior tibial border. The 0° slope plane of the tibial plateau was inclined towards distal posterior from this pivot point to 3.5°, 7°, and 10° to perform the further virtual cuts (Fig. 4).

Using a distance measuring gauge (caliper), the separation between the distal femoral cut and the tibial resection plane could be measured in extension and in flexion with progressing slopes of 0°, 3.5°, 7°, and 10° through the associated tfCPs. Sixteen measurements were produced per knee.

Statistical methods

A linear regression analysis was performed assuming the investigated variables were independent, i.e. the measurement of the distance between the femoral and tibial cuts through the corresponding tfCPs (in mm), motion (flexion vs. extension), and position (medial vs. lateral compartment).

We used a general estimating equation (GEE) regression model to obtain the desired independence of the respective measured variables in the identical knee. For each knee, a coefficient estimation was carried out using the Wald test [26]. Thus, we were able to ascertain whether the corresponding coefficient differed significantly from that with a 0° slope or not.

In an additional GEE model, the gap distance, i.e. the investigated or independent variable, was correlated to the dependent
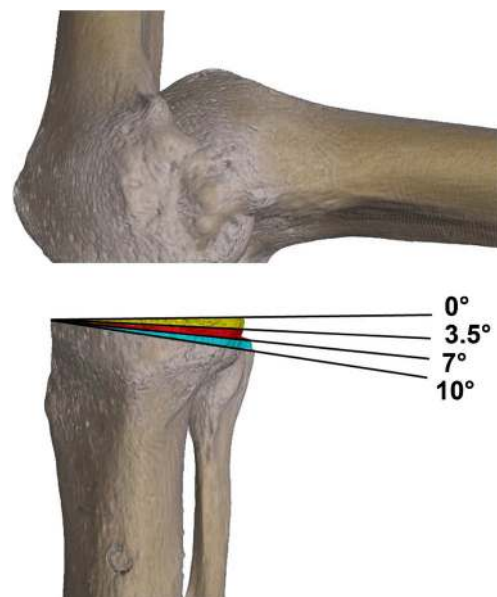

Fig. 3 Fusion of scans with specimen in extension and flexion. **a**) Exact stacking projection using the tibia to depict motion. **b**) Tibiofemoral contact point in extension (blue circle) and flexion (red square) in the medial (*left*) and lateral (*right*) compartments

Fig. 4 Depiction of virtual osseus resection with tibial slopes of 0°, 3.5°, 7° and 10°

single explanatory categorical variable reflected by all 16 groups to attain the resulting estimation of the standard deviation.

All calculations were performed with R (R Development Core Team 2011, version 2.13.0).

Results

All tibiofemoral contact points (tfCPs) in the medial and lateral compartments shifted posteriorly, inferiorly, and laterally during flexion. The extent of movement between the contact points of the medial and lateral compartments varied. Overall, the posterior shift of the lateral tfCPs was greater than that of the medial tfCPs. In the medial compartment, the tfCPs shifted an average 4.4 ($\pm$ 2.2) mm when flexing the knee from full extension to 90°, whereas the posterior shift of the lateral tfCPs averaged 16.3 ($\pm$ 5.0) mm.

The osseous resection gaps produced through the virtual osteotomy were equal for all knee specimens medially and laterally averaged 19.3 ($\pm$ 2.9 mm) with a tibial slope of 0°.

Overall, 320 readings were produced. Per knee, two readings per position, compartment, and slope angle were performed, i.e. in total 16 readings per knee specimen.

The averaged gap increases per slope angle are summarized in Table 1.

In this area, the osseous resection gaps increased almost linearly with increasing slope in each position and at each measuring point. The relative measured gap increases by 10 % from slope 0° to 3.5°, from 3.5° to 7° and from 7° to 10° in both the medial and the lateral compartment. Again, the lateral compartment opened about 30 % more in flexion than the other readings in each range (Fig. 5).

Calculation of average gap change according to slope increase in 1° increments indicated a significant prosthetic gap change of 0.6 mm ($p<0.001$). Increasing the tibial slope did widen the lateral compartment significantly more than the medial one in 90° of flexion ($p<0.001$). For each 1° increase of tibial slope, the osseous resection extension gaps increased 0.5 ($\pm$ 0.0) mm medially, and 0.6 ($\pm$ 0.0) mm laterally. In

flexion, the medial osseous resection gap also averaged 0.6 ($\pm$ 0.1) mm, but laterally it was 0.9 ($\pm$ 0.1) mm (Fig. 6).

Discussion

The aim of this study was to assess the influence of tibial resection on the osseous resection gaps in full extension and 90° flexion according to slope angle and joint compartment.

All bone cuts were carried out virtually in 3D CT scans, after the data from knee joint specimens were adapted using a standardized coordinate system. At 0° slope, the tibial cuts consisted only of the amount of bone necessary to allow prosthetic components to fill the space under load [27]. These gaps are differentiated from the typical extension and flexion gaps, which are defined under distraction of the knee joint [6, 7]. In the starting position (here at 0° tibial slope), all four gaps, i.e. medial and lateral each in flexion and extension, were equally sized due to the virtual resection. The mean gap size of all 20 specimens averaged 19.3 mm, with the accompanying standard deviation of ($\pm$ 2.9 mm) reflecting basically the varying cartilage thicknesses present. This can be explained because of the resection technique as described by Tigani et al. [27], in which bony reference points were used. A total knee prosthesis that is symmetric in the area of the contact points would thus exactly fill in this osseous resection gap, and distraction of the knee in this state would, neglecting changes in the capsule/ligaments caused by the resection itself, lead to the typical extension and flexion gaps. It can be expressed by the following simplified relationship:

Extension or flexion gap = elasticity of the soft tissue mantle + osseousresection gap

In cases of an "ideal" soft tissue mantle and optimal alignment of the components, adjustment of the leg axis, etc., the endoprosthesis perfectly fills the osseous resection gap in the area of the tibiofemoral contact points (tfCPs) during the complete range of flexion and extension. Thus, for this idealized case, the following can be assumed:
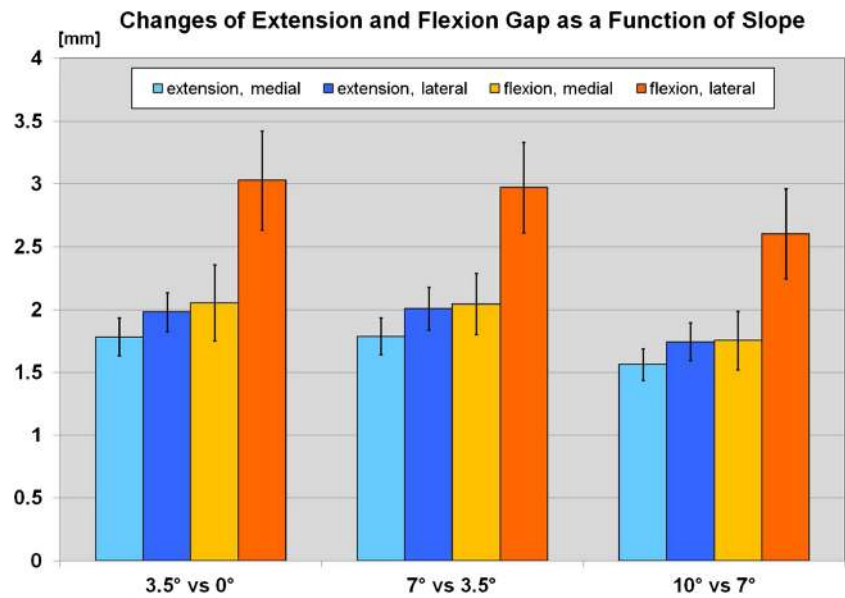
Osseous resection gap$_{ideal}$ = prosthetic gap

It is important to note that the prosthetic gap, according to the thickness of the prosthetic components, is thus always the

Table 1 Mean osseous resection gaps for motion (flexion vs. extension), and position (medial vs. lateral compartment) according to tibial slope

Slope [°]	Motion	Medial mean gap [mm]	Lateral mean gap [mm]
0.0	Full extension	19.3 (SD 0.66)	19.3 (SD 0.66)
3.5	Full extension	21.1 (SD 0.66)	21.3 (SD 0.67)
7.0	Full extension	22.9 (SD 0.67)	23.3 (SD 0.69)
10.0	Full extension	24.5 (SD 0.67)	25.1 (SD 0.71)
0.0	90° flexion	19.3 (SD 0.66)	19.3 (SD 0.66)
3.5	90° flexion	21.4 (SD 0.66)	22.4 (SD 0.68)
7.0	90° flexion	23.4 (SD 0.65)	25.3 (SD 0.70)
10.0	90° flexion	25.2 (SD 0.65)	27.9 (SD 0.73)

Fig. 5 Mean of osseous resection gaps for position and motion according to increasing tibial slope

same size under loading in the tfCP regions. If additional bone is resected from one area, the osseous resection gap collapses under load to the size of the prosthetic gap, with concomitant relaxation of the soft tissue mantle. Conversely, too little bone resection will overstretch the soft tissue mantle.

The main limitations of this study result from the fact that formalin-fixed knee joint specimens have been used. Additionally the frame could have influenced the motion, leading to a non-physiologically restricted guidance. Therefore, we focused on the kinematics of the specimens during motion.

Positional changes of the tibiofemoral contact points (tfCPs) are correspondingly very important for physiological movement. The tfCPs can be used to measure the extent of roll-back, i.e. the anteroposterior shift of the contact surfaces between the femur and the tibia that occurs with increasing knee flexion. In this study, the

tfCP acted as a reference point to measure the distance between the femoral and tibial resection planes in each position and with each form of movement. In our cadaver study, similar to previous studies [3, 24], the tfCPs shifted only minimally posteriorly (4.4 ± 2.2 mm) in the medial compartment from extension to flexion in 90°. However, the posterior shift in the lateral compartment was significantly larger (16.3 ± 5.0 mm).

These values are in the range of data from previous studies, as collected by Freeman and Pinskerova [18] in an extensive review of the literature. As shown before our knee specimens were almost moving physiologically, despite formalin fixation and restricted guidance. Even more so, only the bony part of the gaps have been looked at in this study. This of course does not correspond with the complex intra-operative procedure with distraction force.

Fig. 6 Mean of osseous resection gaps per increasing 1° increment of tibial slope
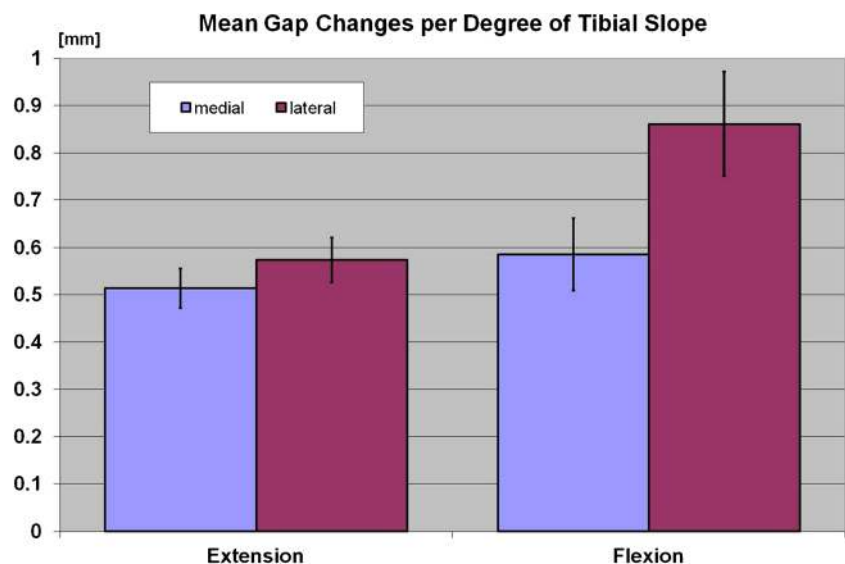
However, the bony part is of great importance for the postoperative alignment with weightbearing, and it is predictable by geometrical rules.

For each 1° of increased tibial slope, the osseous resection gap increased approximately 0.5–0.6 mm in extension both medially and laterally and in flexion medially. In contrast, the lateral osseous resection gap increased by about 0.9 mm in flexion.

This larger effect on the lateral osseous resection gap is due to the larger lateral femoral roll-back, as occurs with physiological motion. When controlling the total knee joint-movement, however, often non-physiological motion and even paradoxical movement is documented [28, 29].

In such cases, the effects on the osseous resection gaps in extension would be even larger in comparison, although in the overall context here many factors must be considered that influence the sequence of motion after TKA. The intra-operatively observable effect of releasing the flexion gap by increasing tibial slope is explained by the corresponding release of the posterior ligament structures, as reported by Lombardi et al. [17] und Krakow [30].

Conclusion

The results of this study confirm that increasing the tibial slope affects not only the osseous resection gap in flexion, but also the osseous resection gap in extension ($p<0.001$). Thus, we do not recommend equilibrating a narrow flexion gap by increasing the tibial slope in cases where the extension gap and the tibial slope are both appropriately adjusted with respect to leg-axis and tibial slope as planned. Instead, equilibration should be achieved via a ligament balancing procedure, without the use of additional bony resections.

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