RESEARCH ARTICLE

Robotic-arm Assisted Total Knee Arthroplasty: the Relationship between Bone Resection, Gap Balancing and Resultant Implant Alignment

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Abstract

Objectives: The primary aim was to assess the association between bone resection and the resultant flexion and extension gaps in the medial and lateral compartments of the knee when performing robotic-arm assisted total knee arthroplasty (rTKA). The secondary aims were to compare medial and lateral bone resections and the influence on limb alignment, and whether the amount of bone resection that resulted in equal gaps was predictable.

Methods: A prospective study of 22 consecutive patients with a mean age of 66 years undergoing rTKA was conducted. The femoral component was mechanically aligned, and the alignment of the tibial component was adjusted (+/-3degrees of the mechanical axis) to obtain equal extension and flexion gaps. All knees underwent soft tissue balancing using sensor-guided technology. The final compartmental bone resection, gaps, and implant alignment were obtained from the robot data archive.

Results: There was a correlation between bone resection and the resultant gap in the medial (r=0.433, p=0.044) and lateral (r=0.724, p<0.001) compartments of the knee. There were no differences in bone resection from the distal femur and posterior condyles in the medial (p=0.941) or lateral compartments (p=0.604) or for the resultant gaps (p=0.341 and p=0.542, respectively). There was more bone removed from the medial compartment compared to the lateral aspect: 0.9mm (p=0.005) in extension and 1.2mm (p=0.026) flexion. The differential bone resection changed the knee alignment by one degree of varus. There were no significant differences between the actual and predicted medial (difference 0.05, p=0.893) or lateral (difference 0.00, p=0.992) tibial bone resection.

Conclusion: There was a direct association between bone resection and resultant compartment joint gap when using rTKA, which was predictable. Gap balancing was achieved when less bone was resected from the lateral compartment which resulted in an estimated one-degree varus alignment of the knee.

Level of evidence: II

Keywords: Arthroplasty, Gap balancing, Knee, Measured resection, Robotic

Introduction

Robotic assisted total knee arthroplasty (rTKA) offers increased accuracy of implant positioning and is associated with improved patient reported outcomes.[1] rTKA also enables the surgeon to adjust positioning of the implants to facilitate joint gap balancing and preserves the periarticular soft tissues when compared to manual TKA.[2-4] Several techniques of aligning the implant to result in a balanced knee have been described.[5-8] There is likely to be a direct relationship between alignment and balance, as a malaligned knee may not demonstrate balance throughout a range of motion due to changes in ligament tension along the kinematic axis

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specific to that knee.[9] Furthermore, despite the numerous techniques described for aligning the prothesis there is no gold standard definition of what constitutes a balanced knee, with various methods of balancing being described.[8]

There are several different methods described for aligning TKA: mechanical, adjusted mechanical, anatomical, kinematic and restricted kinematic alignment,[5] and more recently functional alignment.[10] Commonly employed methods of balancing the knee are: measured resection, gap balancing, intra-compartmental pressure and natural (trapezoidal). A recent study by Chang et al[11]used rTKA to functionally align the prothesis, using intra-operative extension and flexion gap balancing, was shown to result balanced compartments, medial and lateral, throughout a range of knee flexion when using an intra-compartmental pressure-sensor. What is not clear from the current literature is the relationship between bone resection, gap balancing and implant alignment, and whether it is possible to predict the required amount of bone to be removed in the medial and lateral compartments to result in a gap balanced TKA. This would allow a greater understanding of the relationship between the required bone resection to result in a gap balanced TKA, and therefore aid decision making.

The primary aim of this study was to assess the association between bone resection and the resultant flexion and extension gaps in the medial and lateral compartments of the knee when performing rTKA. The secondary aims were to compare the femoral and tibial bone resections and the associated gaps in both the medial and lateral compartments of the knee in extension and flexion, whether these influenced component / limb alignment, and if bone resection that resulted in a gap balanced knee was predictable.

Materials and Methods

As part of an ongoing randomised controlled trail at the study centre a consecutive series of patients undergoing a rTKA were identified from this study cohort. Ethical approval was obtained by the Tyne & Wear South Research Ethics Committee, UK (reference 19/NE/0027). The study is sponsored by the Newcastle Hospitals NHS Foundation Trust (NUTH R&D: 8822). This study was conducted in accordance with the principles of the Declaration of Helsinki and conducted in full conformity with relevant regulations and with the ICH Guidelines for Good Clinical Practice (CPMP/ICH/135/95) July 1996.

Patients listed for a primary TKA for osteoarthritis of the knee by two participating surgeons (DJD, DJW) at the study centre were screened for inclusion. The inclusion criteria were: aged between 45 to 85 years, planned for routine primary cruciate retaining TKA, osteoarthritis of the knee as indication, and suitable candidate for a TKA. Exclusion criteria included: varus deformity of ≥20 degrees, not able to comply with the study protocol, know or planned pregnancy during the study period, needed patella resurfacing, not able to understand the information or provide written consent, not able to answer questionnaires for cognitive or language reasons, any other significant disease or disorder that may bias the results of the study.

All participants received a Triathlon (Stryker Mahwah, New Jersey, USA) TKA with a cruciate retaining polyethylene (X3) insert using a MAKO robotic-arm (Mako, Kalamazoo, Michigan, USA). A medial parapatellar approach was used in all cases. All patients required a preoperative CT scan as part of the planning process for positioning and sizing of the implants. The femoral implant was aligned to the mechanical axis of the femur the implant was then aligned to the bony contours of articular surface of the distal femur. Gap balancing was then performed, with the aim of achieving an equal extension and flexion gaps in both the medial and lateral compartments of the knee, which was the same as the overall thickness of the planned implant.[12] One surgeon (DJW) performed [12] TKA and planned for a 9mm tibial component (overall thickness 17mm) and the other surgeon (DJD) also perfomed [12] TKA but planned for an 11mm tibial component (overall thickness 19mm). The specified tibial bone cut was then performed using the robotic arm provided it was within +/- 3 degrees of the mechanical axis and a 3 degree slope.[12] When the implant was in place a Verasense™ (OrthoSensor Inc. Dania Beach, Florida, USA) insert was used to measure intraarticular pressures in both tibio-femoral compartments through a range of movement (extension to flexion). Further bone cuts were undertaken as required to balance the knee which was defined as a pressure difference of less than 15Ibs between the compartments.[13] The MAKO robotic-arm (Mako, Kalamazoo, Michigan, USA) system was used to capture data for final implant positioning, bone resection and the extension and flexion gaps.

Statistical Package for Social Sciences (SPSS) software (IBM, Inc., Armonk, New York, United States) version 17 was used for statistical analysis. An independent Student's t-test was used to assess continuous variables for significant differences between medial and lateral compartments. The association between bone resection and resultant joint gaps was assessed using a Pearson's correlation coefficient. Agreement between calculated and plotted actual and predicted bone resection from the tibia were assessed using a Bland and Altman plot, which illustrates the differences between the measures If no linear relationship is observed on the Bland and Altman plot this indicates that the statistical variation was similar for all degrees (mm) of bone resection required to balance the extension and flexion gaps. To enable an accurate assessment of bone resection and joint gaps (space between femur and tibia) adjusted resection and gap measures were made account for polyethylene thickness: converting to a 17mm overall thickness of component. A p-value of <0.05 was defined as statistically significant.

A power calculation was performed to detect a strong correlation (r=0.6)[14] between bone resection and the associated joint gap between, an alpha of 0.025 (Bonferroni corrected for multiple testing: medial and lateral compartments), two tailed Pearson's correlation and a power of 80% determined a minimum of 22 patients would be required.

Results

Twenty-two consecutive patients undergoing 22 rTKA were recruited to the study, with a mean age of 66 years

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of which 14 were female and 8 were male. There were 10 right and 12 left rTKA, all of which were cruciate retaining. The median femoral size was 4.5 (interquartile range (IQR) 3 to 6) and the median tibial baseplate size was 4.5 (IQR 3 to 5).

Primary aim: bone resection and gaps

There was a significant correlation between the thickness of bone resected and the resultant gap in the medial (r=0.433, 95% confidence interval (CI) 0.014 to 0.722, p=0.044) and lateral (r=0.724, 95% CI 0.435 to 0.878, p<0.001) compartments of the knee. Overall, there was a total 13.5mm of bone resected from both the medial compartment in extension and flexion, which were not significantly different (95% CI -1.2 to 1.3, p=0.941) [Table 1]. There was a total 12.3mm and 12.6mm of bone resected from the lateral compartment in extension and flexion, respectively, which were not significantly different (95% CI -0.9 to 1.5, p=0.604) [Table 1]. The medial extension gap was 19.0mm and the flexion gap was 18.9mm, which was not significantly different (95% CI -0.1 to 3.2, p=0.341) [Table 2]. The lateral extension gap was 19.0mm and then flexion gap was 19.2mm, which was not significantly different (95% CI -0.3 to 0.6, p=0.542) (Table 2). The differential in the bone resection and the associated gaps between the medial or lateral compartment were not significantly different between extension (0.1mm, 95% CI -1.3 to 1.4, p=0.929) and flexion (0.1mm, 95% CI -1.0 to 1.3, p=0.772) [Table 3].

Table 1. Bone resection from the femur and tibia, and total unadjusted and adjusted (implant thickness – for 17mm implant) resection in extension (distal femur and tibia) and flexion (femoral posterior condyles and tibia) for medial and lateral compartments of the knee

	Medial (mm)	**Lateral** (mm)	**Difference** (95% CI)	**p-values***
Region				
Femoral Distal (SD)	8.4 (1.3)	5.1 (1.9)	3.3 (2.7 to 4.0)	<0.001
Femoral Posterior (SD)	8.4 (2.1)	5.4 (1.7)	3.0 (2.1 to 3.9)	<0.001
Difference (95% CI)	0.0 (-1.2 to 1.3)	0.3 (-0.9 to 1.5)		
p-value*	0.941	0.604		
Tibia	5.1 (1.4)	7.2 (1.3)	2.1 (1.5 to 2.6)	<0.001
Unadjusted for implant				
Total Extension (SD)	13.5 (1.7)	12.3 (2.2)	1.2 (0.4 to 2.1)	0.005
Total Flexion (SD)	13.5 (2.4)	12.6 (2.1)	0.9 (0.1 to 1.7)	0.026
Difference (95% CI)	0.0 (-1.2 to 1.3)	0.3 (-0.9 to 1.5)		
p-value*	0.941	0.604		
Adjust for implant				
Total Extension (SD)	12.5 (1.6)	11.3 (2.0)	1.2 (0.4 to 2.1)	0.005
Total Flexion (SD)	12.5 (2.2)	11.6 (1.9)	0.9 (0.1 to 1.7)	0.026
Difference (95% CI)	0.0 (-1.2 to 1.3)	0.3 (-0.9 to 1.5)		
p-value*	0.941	0.604		

*unpaired t-test

Table 2. Extension and flexion gaps unadjusted and adjusted (implant thickness – for 17mm implant) for medial and lateral compartments of the knee

	Medial (mm)	**Lateral** (mm)	**Difference** (95% CI)	**p-values***
Unadjusted				
Total Extension (SD)	19.0 (1.1)	19.0 (1.3)	0.0 (-1.8 to 2.2)	0.834
Total Flexion (SD)	18.9 (1.1)	19.2 (1.2)	0.3 (0.0 to 0.5)	0.073
Difference (95% CI)	0.1 (-0.1 to 3.2)	0.1 (-0.3 to 0.6)		
p-value*	0.341	0.542		
Adjust for implant				
Total Extension (SD)	1.0 (0.9)	1.0 (1.0)	0.0 (-0.2 to 0.2)	0.834
Total Flexion (SD)	0.9 (0.9)	1.2 (1.0)	0.3 (0.0 to 0.5)	0.073
Difference (95% CI)	0.1 (-0.1 to 0.3)	0.1 (-0.3 to 0.6)		
p-value*	0.341	0.542		

*unpaired t-test

Table 3. The difference between then bone resection and the associated gaps in extension (distal femur and tibia) and flexion (femoral posterior condyles and tibia) for medial and lateral compartments of the knee

Difference between resection and gap	**Medial** (mm)	**Lateral** (mm)	**Difference** (95% CI)	**p-values***
Total Extension (SD)	5.5 (1.6)	6.7 (1.5)	1.3 (0.4 to 2.1)	0.005
Total Flexion (SD)	5.4 (2.2)	6.6 (2.1)	1.2 (0.4 to 1.9)	0.004
Difference (95% CI)	0.1 (-1.3 to 1.4)	0.1 (-1.0 to 1.3)		
p-value*	0.929	0.772		

*unpaired t-test

Secondary aim: bone resections in the medial and lateral compartments

There was significantly (p<0.001) more bone resected from the medial femoral condyle compared to the lateral femoral condyle, both distally and posteriorly [Table 1]. The converse was demonstrated for the proximal tibia where there was significantly more bone resected from the lateral plateau relative to the medial plateau [Table 1]. There was no significant difference in the overall bone resection in the medial (p=0.941) or lateral (p=0.604) compartments between extension and flexion, which remained the same when adjusting for implant thickness [Table 1]. Overall, there was more bone removed from the medial compartment of the knee relative to the lateral aspect, with 0.9mm (p=0.005) and 1.2mm (p=0.026) of extra bone being resection from the medial compartment in extension and flexion, respectively [Table 2].

Secondary aim: gaps in the medial and lateral compartments

There was no significant difference in the extension gap between the medial and lateral compartment in extension (p=0.834) or flexion (p=0.073), for unadjusted or adjusted for implant thickness [Table 2]. These equal medial and lateral gaps were achieved by unequal bone resection in the respective compartments, with more being resected from the lateral compartment in extension (1.3mm, p=0.005) and in flexion (1.2mm, p=0.004) [Table 3].

Secondary aim: component alignment

The mean femoral alignment was 0.5 (standard deviation (SD) 0.9) degrees of varus and the mean alignment of the tibial component was 1.1 (SD 1.4) degrees of varus [Figure 1], which resulted in an overall alignment of 1.6 degrees of varus. There was a mean external rotation of the femoral component of 0.7 (SD 0.9) degrees. The differential bone resection between the medial and lateral compartment of 1.3mm and 1.2mm, respectively, with equal extension and flexion gaps [Figure 1] suggested the alignment of the knee has changed by one degree [Figure 2]. This may account, in part, for the varus sagittal positioning of the tibial component.

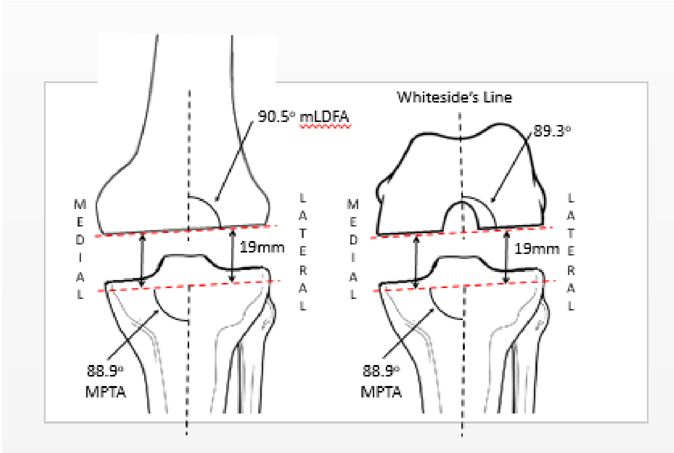

Figure 1. Illustration of the bone cuts according the mechanical axis (dashed lines) that resulted in equal medial and lateral joint gap in extension and flexion (in this case aiming for 19mm)

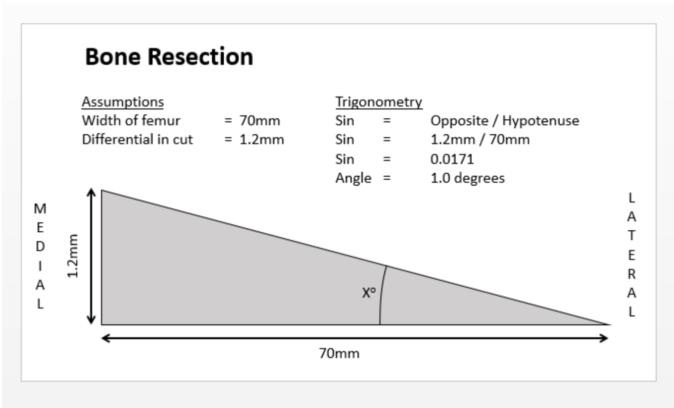

Figure 2. An illustration of the effect of a 1.2mm differential bone cut between medial (more) and lateral (less) compartments of the knee that results in a 1 degree change in alignment (varus)

Secondary aim: predicting tibial bone resection required to balance gaps

It was assumed that the bone resection from the distal and posterior femur in the medial and lateral compartment would be equivalent [Table 1]). Using the data from table 1 (bone resection) and table 3 (difference between gap and bone resection) the following equations were constructed to predict the tibial bone required to balance medial and lateral compartment gaps in extension and flexion:

Medial tibial resection = Implant thickness (mm) – Medial Femoral resection (mm) – 4.5mm

Lateral tibial resection = Implant thickness (mm) – Lateral Femoral resection (mm) – 5.7mm

Using these equations there was a significant correlation between the actual and predicted medial (r=0.561, p=0.007, Pearson's) and lateral (r=0.535, p=0.010, Pearson's) tibial bone resections. There was no significant difference between the actual and predicted medial (difference 0.05, 95% CI -0.65 to 0.74, p=0.893) or lateral (difference 0.00, 95% CI -0.91 to 0.90, p=0.992) tibial bone resection. However, the Bland-Altman plots demonstrated that the actual and predicted medial and lateral tibial bone resection varied by +/-3mm and +/- 4mm respectively.

Discussion

This study has shown that rTKA enables gap balancing to be performed, with equal amounts of bone being resected in extension and flexion within medial and lateral compartments, but there was more bone resected from the medial compartment compared to the lateral compartment to achieve equal compartment gaps. The unequal resection of bone from the medial (more) and lateral (less) compartments resulted in a one degree of varus alignment of the tibial component to balance the gaps when using the femur first technique. Once the orientation of the femoral component is affirmed the required bone resection of the proximal tibia was predictable to enable extension and flexion gaps to be balanced in the medial and lateral compartments.

There was a difference in the amount of bone resected and the resultant gap, which ranged from 5.4mm to 5.5mm in the medial compartments and 6.6mm to 6.7mm in the lateral compartments. This difference in part can be explained by the cartilage thickness in the knee, which is approximately 5mm thick in total (2mm femoral condyle and 3mm tibial plateau).[15] However, the reason for the differential bone resection between the compartments to achieve equal gaps is not clear. One possible explanation may relate to the natural laxity in the lateral compartment of knee, relative to the medial compartment, to potentially aid the medial pivot movement within the knee.[16] Therefore, when equal tension is applied to both compartments the lax lateral ligamentous structures will facilitate a greater opening of the joint, relative to the medial aspect, and less bone resection would be required to achieve equal medial and lateral gaps. Another, potential explanation may be due to intrinsic shortening of medial collateral structures and stretching of lateral tissues which is observed in knees with a varus deformity,[17] which was the only deformity included in the current study. This would therefore result a less bone resection in the lateral compartment being required to balance the gaps. The medial compartment of the knee is thought to function a ball and socket joint and in contrast the lateral compartment due to less constraint facilitates femoral roll back as the knee flexes and is associated with internal rotation of tibia.[18] A kinematic alignment study demonstrated that increased laxity in the lateral flexion gap following TKA was associated with better patient reported outcomes.[19] Therefore, despite the current study aiming for equal medial and lateral joint gaps, this may not be the optimal balance for the patient.

Insall[20] originally described mechanical alignment as bone cuts being made at 90 degrees to the mechanical axis of the lower limb, which was to limit outliers (greater than +/- 3 degrees) to avoid early failure of the TKA.[21,22] Navigation and robotic assisted surgery enables the implants to be aligned more precisely intraoperatively, within +/- 1 degree.[23] This has led to some surgeons to adopt other methods of implant alignment such as kinematic or functional alignment.[24] Kinematic alignment is associated with improved patient reported outcomes when compared to traditional mechanical alignement.[25] This may be related to improved balance within the knee which is observed in 80% of kinematically aligned knees and only 35% of mechanically aligned knees.[26] rTKA has been shown to result in a balanced TKA according to the VeraSense knee system (Orthosensor) when compared to manual TKA,[27] which is achieved 79% of the time with bone cuts alone.[28] Chang et al[11] demonstrated with functional component alignment and gap balancing in a cohort of 30 patients undergoing posterior stabilised rTKA resulted in a balanced knee, according to the VeraSense knee system (Orthosensor). Resection of the posterior cruciate ligament (PCL) is however associated with an extension/flexion mismatch in joint gaps, and an increased flexion gap relative to the extension gap of 1.1mm,[29] and may have resulted in a reduction in the bone resection from the posterior femoral condyles to balance the gaps. The current study retained the PCL and demonstrated equal amounts of bone resection of the distal and posterior condyles of the femur.

A novel aspect of the current study was to identify the correlation between bone resection and the resultant compartment gap. Furthermore, it was shown that the amount of bone resection from the tibia was predictable once the femoral alignment was fixed, using the formulae provided in the results. There was however a variation of +/-3mm in the 95% confidence interval of the predicted bone resection required. The results of the current study would need to be validated in a larger cohort, which may then reduce this observed wide 95% confidence interval. The authors suggest that the formulae presented may be employed as a basis of operative planned to balance the extension and flexion gaps and affirmed intraoperatively.

The major limitation of the current study was the absence of functional outcome data relating to the described cohort of patients and whether this is different to that observed after manual TKA. However, previous studies have shown a balanced TKA, according to intercompartmental pressures, is associated with the improved patient satisfaction. Furthermore, there were a limited number of patients in the study, which may have resulted in a type 2 error for some of the secondary outcomes, but the study was powered to the primary outcome. Only patients with a varus deformity of less than 20 degrees were included in the study cohort, therefore the findings may not be directly related to valgus and those patients with a greater deformity which would need to be affirmed in future studies. Inclusion of a typical varus deformity may also be a strength of the study, lending homogeneity to the study cohort and the findings that may not have been observed if differing knee deformities were included.

Conclusion

There was a direct association between bone resection and resultant compartment joint gap when using rTKA. Gap balancing was achieved when less bone was resected from the lateral compartment, which may be explained by the natural laxity within that compartment and resulted in an estimated one degree varus alignment of the tibial component. The required bone resection to result in equal extension and flexion gaps in the medial and lateral compartments of the knee were predictable.

Abbreviations

CI: Confidence intervals
CT: Computed tomography
SD: Standard deviation
SPSS: Statistical Package for Social Sciences
rTKA: Robotic total knee arthroplasty
TKA: Total knee arthroplasty

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