BJO

KNEE

Current concepts in total knee arthroplasty

MECHANICAL, KINEMATIC, ANATOMICAL, AND FUNCTIONAL ALIGNMENT

F. A. Begum,
B. Kayani,
A. A. Magan,
J. S. Chang,
F. S. Haddad

From University College Hospital, London, UK

Limb alignment in total knee arthroplasty (TKA) influences periarticular soft-tissue tension, biomechanics through knee flexion, and implant survival. Despite this, there is no uniform consensus on the optimal alignment technique for TKA. Neutral mechanical alignment facilitates knee flexion and symmetrical component wear but forces the limb into an unnatural position that alters native knee kinematics through the arc of knee flexion. Kinematic alignment aims to restore native limb alignment, but the safe ranges with this technique remain uncertain and the effects of this alignment technique on component survivorship remain unknown. Anatomical alignment aims to restore predisease limb alignment and knee geometry, but existing studies using this technique are based on cadaveric specimens or clinical trials with limited follow-up times. Functional alignment aims to restore the native plane and obliquity of the joint by manipulating implant positioning while limiting soft tissue releases, but the results of high-quality studies with long-term outcomes are still awaited. The drawbacks of existing studies on alignment include the use of surgical techniques with limited accuracy and reproducibility of achieving the planned alignment, poor correlation of intraoperative data to long-term functional outcomes and implant survivorship, and a paucity of studies on the safe ranges of limb alignment. Further studies on alignment in TKA should use surgical adjuncts (e.g. robotic technology) to help execute the planned alignment with improved accuracy, include intraoperative assessments of knee biomechanics and periarticular soft-tissue tension, and correlate alignment to long-term functional outcomes and survivorship.

Cite this article: ***Bone Jt Open*** **2021;2-6:397–404.**

Keywords: Knee alignment, Total knee arthroplasty, Functional alignment, Kinematic alignment, Anatomical alignment, Mechanical alignment

Introduction

Total knee arthroplasty (TKA) is an effective, cost-efficient treatment for patients with symptomatic end-stage knee osteoarthritis.[1] The procedure is undertaken in over 90,000 patients per year in the UK, and over the last decade, TKA has become the most commonly performed joint arthroplasty procedure worldwide.[2] Data extracted from various national joint registries has shown that TKA is associated with excellent long-term implant survivorship, with the ten-year revision rate for cemented, unconstrained, fixed-bearing TKA reported at 3%.[1-3] However, several recent studies have found that approximately 20% of patients undergoing an uncomplicated primary TKA are unsatisfied with the outcome of their surgery.[4-6] The aetiology of this is likely to be multifactorial but one important surgeon-controlled variable is limb coronal alignment, as this directly affects periarticular soft-tissue function, knee biomechanics through the arc of knee flexion, and implant survivorship following TKA.[5-12] Suboptimal limb alignment in TKA may lead to altered knee kinematics, increased component wear, poor functional outcomes, and premature implant failure requiring complex revision TKA.[5,7,8,13,14] Conceptually, an improved understanding and execution of the optimal alignment technique may help to increase patient satisfaction, improve

Correspondence should be sent to Ms Fahima A Begum; email: fahimabegum@doctors.org.uk

doi: 10.1302/2633-1462.26.BJO-2020-0162.R1

Bone Jt Open 2021;2-6:397–404.

functional outcomes, increase implant survivorship, and reduce complications following TKA.

There is currently no uniform consensus on the optimal coronal alignment technique for TKA. Traditional neutral mechanical alignment facilitates knee flexion and symmetrical component wear, but forces the limb into an unnatural position that alters knee biomechanics.[7,8,15,16] Kinematic alignment aims to restore native prearthritic alignment, but previous intraoperative techniques for executing this alignment have been limited by poor accuracy and reproducibility, and the acceptable safe ranges for limb alignment remain uncertain.[17-21] Anatomical alignment aims to restore predisease limb alignment and bone geometry, but it remains unknown how this technique translates to long-term functional outcomes and implant survivorship.[9,22] More recently, functional alignment has been introduced as a technique for providing patient-specific limb alignment within the safe ranges of mechanical alignment but the results of high-quality studies with long-term outcomes are still awaited.[23] This narrative review explores the principles of the various alignment techniques used for TKA, discusses the surgical guides and techniques used to execute each alignment method, explores their respective benefits and limitations, and identifies important clinical gaps within the existing literature for further research.

Mechanical alignment. Since the introduction of TKA in the 1970s, neutral mechanical alignment (NMA) has remained the most commonly adopted alignment technique for TKA.[24] The principle of NMA in TKA is to distribute load evenly across the components in the stance phase to promote symmetrical component wear, and increase component durability in TKA.[9] Intraoperatively, this is achieved by undertaking bone resections and placing implants perpendicular to the femoral and tibial mechanical axes, while externally rotating the femoral component, which also secondarily facilitates correct patella tracking.[25,26] Measured resections or gap balancing techniques are used to equalize flexion-extension gaps and achieve equipoise in mediolateral soft-tissue tension.[27] Traditionally, NMA is undertaken to achieve postoperative limb alignment to within 3° of neutral to the mechanical axis. Many orthopaedic surgeons consider this alignment technique as a dichotomous variable, in which an “aligned” limb falls within 3° of neutral alignment, whereas a “maligned” limb falls outside of this safe range.[28-30] However, questions pertaining to the safe range of NMA remain, and if the ideal alignment target is narrow and generic for all patients, or actually wider and more patient-specific.

Kim et al[31] conducted a prospective randomized study on 520 patients undergoing bilateral TKA, with NMA using computer navigation on one side and a conventional jig-based technique on the contralateral side. Mechanical axis on postoperative CT coronal plane was from 4.5° varus to 4.3° valgus for knees that underwent computer-navigated TKA, and from 5.3° varus to 5.3° valgus for knees that had conventional TKA ($p = 0.821$). Clinical outcomes were assessed using the Knee Society Score (KSS)[32] and Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC)[33] at three months, one year, and annually thereafter. The authors reported no difference between the two treatment techniques in relation to the range of motion, KSS, and WOMAC scores at each of the follow-up intervals and at mean follow-up of 10.8 years.[31] There was also no difference in implant survivorship between the two treatment techniques, and deviation of greater than 3° from the neutral mechanical axis did not increase the rate of component loosening or failure.

Bonner et al[28] performed a retrospective review of 501 patients undergoing conventional jig-based TKA with NMA, and assessed the effects of postoperative limb alignment on implant survivorship. Patients were classified as aligned if long-leg radiographs showed limb alignment within 3° of NMA and maligned if limb alignment deviated by more than 3° from NMA. Patients were followed up postoperatively at six months, one year, and annually thereafter. A total of 14 patients were excluded from the final analysis as postoperative alignment values were not recorded. At 15 years follow-up, 33 patients underwent revision TKA for aseptic loosening, including 11 patients (5%) from the aligned group and six patients (14%) from the maligned group ($p = 0.36$). The authors concluded that limb alignment greater than 3° outside of NMA did not increase the risk of implant loosening or failure compared to limb alignment within 3° of NMA following TKA.[28]

Parratte et al[29] reviewed outcomes in 292 patients undergoing primary conventional jig based TKA with NMA and correlated overall limb alignment to implant survivorship. The authors found that 27 patients underwent revision TKA for aseptic loosening, mechanical failure, component wear, or patellar maltracking, which included 27 patients (9.2%) with alignment within 3° of neutral limb alignment, compared to eight patients (7.5%) with alignment outside of this safe range ($p = 0.88$). The authors also concluded that implant positioning and limb alignment more than 3° outside of neutral alignment did not increase the risk of premature implant failure.[29]

Manjunath et al[27] performed a prospective study on 120 patients undergoing conventional jig-based TKA with NMA and examined the effects of limb alignment on functional outcomes. The study found that 96 patients had limb alignment within the 3° of NMA and 24 patients had limb alignment outside of these predefined safe ranges for limb alignment. At six weeks follow-up, patients within these predefined safe ranges had improved KSS scores ($p = 0.026$) compared to those outside of these safe ranges. The authors concluded that limb alignment within 3° of neutral alignment enabled better restoration of functional outcomes at short-term follow-up. However, the authors did not assess how this translates to longer-term functional outcomes or component survivorship.[27]

There are several limitations of these existing studies reporting on predefined safe ranges for limb alignment during TKA. Firstly, bone resections targets for achieving NMA in these patients were calculated using standard short knee radiographs, which may not accurately reflect the overall alignment of the limb. Secondly, several studies have reported outcomes using rudimentary TKA implant designs, and so the findings may not be directly transferable to outcomes with more modern condylar implant designs for TKA. Thirdly, limited assessments were made of implant positions in the axial plane while attempting to achieve overall neutral limb alignment. NMA remains the most commonly adopted alignment technique for TKA, but further research is needed into the accuracy with which this is achieved using conventional manual techniques, and the safe ranges for limb alignment in TKA based on individualized patient anatomy and knee kinematics.

Kinematic alignment. NMA offers an alignment target for maximizing implant durability but alters natural knee kinematics, which may compromise subjectively reported clinical and functional outcome scores. Native limb alignment within the general population follows a Gaussian (normal) distribution, with only 5% to 5.5% of patients having natural NMA.[24] Consequently, in most patients undergoing TKA with NMA, the knee is forced into an unnatural position, with changes to native knee orientation in all three dimensions.[7,8,15,16] This may lead to modifications in the natural femoral flexion axis, periarticular ligament tension, quadriceps function, patella tracking, and knee kinematics through the arc of motion.[7,8,34]

A recent multicentre study of 661 patients undergoing TKA reported that only 436 patients (66%) felt their knee was "normal", and 357 patients (54%) had residual knee symptoms.[35] The principles of TKA with kinematic alignment (KA) is to restore each patient's own native limb alignment and preserve their normal axes of rotation about the knee joint. Preservation of individualized limb alignment and knee biomechanics may conceptually help to improve these subjectively reported functional outcomes, and reduce complications such as aseptic loosening, instability, patella maltracking, stiffness, and common peroneal nerve palsy, which are associated with forcing the limb into NMA for TKA.[7] Some studies have shown improved clinical outcomes in TKA with KA compared to mechanical alignment at short-term follow-up, while other systematic reviews and meta-analyses have shown no difference in clinical or functional outcomes between the two alignment techniques for TKA.[10,17,19,36–41]

Hutt et al[36] performed a prospective study on 100 consecutive patients undergoing TKA with KA. Preoperative long-leg radiographs were used to calculate coronal femoral and tibial bone resection angles to restore the native joint line obliquity and height, and intraoperative computer navigation was used to execute the planned implant positioning and limb alignment within each patient.[36] The authors reported that there was no difference in the pre- and postoperative lateral distal femoral angle and mean proximal tibial angle, suggesting that the native femoral flexion axis was preserved. At mean 2.4 years follow-up, the study found improvements in the WOMAC[33] and Knee Injury and Osteoarthritis Outcome Score (KOOS)[42] compared to preoperative values. The authors reported that four patients with severe varus alignment and one patient with severe valgus alignment required additional ligament releases, and two further patients with moderate valgus alignment required lateral retinacular release for patella maltracking.[36]

Young et al[43] performed a randomized controlled trial (RCT) comparing 50 patients undergoing TKA with NMA versus 49 patients receiving TKA with KA. NMA was achieved using preoperative radiological planning and intraoperative computer navigation, while kinematic alignment was achieved using preoperative MRI planning and intraoperative patient-specific cutting blocks. Postoperative limb alignment was assessed using CT scans in both treatment groups. At two years follow-up, there was no difference between the two treatment groups in relation to Oxford Knee Scores (OKS),[44] Forgotten joint Scores (FJS),[45] and WOMAC[33] scores. Postoperative limb alignment was also comparable between patients undergoing NMA versus KA (mean 0.4° (standard deviation (SD) 3°) varus vs 0.7° (SD 2°) varus respectively; $p = 0.6$). There was no difference in complication rates between the two groups over this follow-up period.[43]

Waterson et al[10] performed a RCT comparing functional outcomes in 35 patients undergoing TKA with NMA versus 36 patients undergoing TKA with KA. Preoperative MRI scans were used to guide bone resections and implant positioning, and intraoperative computer navigation then executed the planned implant positioning and alignment in both treatment groups. Postoperative plain hip-knee-ankle radiographs showed that the planned alignment was achieved in 28 patients (78%) undergoing TKA with KA and 27 patients (77%) receiving TKA with NMA. The study showed that patients undergoing TKA with KA had improved American Knee Society Scores (AKSS)[32] compared to those undergoing TKA with NMA at six weeks ($p = 0.05$), three months ($p = 0.09$), and six months ($p = 0.62$) follow-up, but no significant difference at one

Table I. Comparison of different alignment techniques used for total knee arthroplasty.

Author	Study design/patients	Alignment technique	Main findings	Complications reported
Kim et al[31]	Prospective randomized study, 520 patients	NMA with computer navigation vs NMA using conventional jig-based technique	No difference in ROM, KSS/WOMAC scores, or implant survivorship at a mean follow-up of 10.8 years	10 revisions due to aseptic loosening (6 computer and 4 with conventional) 26 cases of anterior femoral notching in navigation group, 6 in conventional group 5 cases of excessive resection in navigation group 2 deep infections in navigation group
Bonner et al[28]	Retrospective comparative review, 501 TKAs (in 396 patients)	Jig-based NMA (± 3°) vs malaligned group (> 3°)	Weak trend towards improved survival with more accurate alignment of the mechanical axis at 15 years follow-up	33 TKAs (7.2%) were revised due to aseptic loosening
Parratte et al[29]	Clinical and radiological retrospectives study, 292 patients	Jig-based NMA (± 3°) vs malaligned group (> 3°)	After adjusting for age and BMI, having an outlier beyond 3° of the MA was not associated with increased risk of revision at 15-year follow-up	45 (15.4%) revisions in the NMA group (aseptic loosening, mechanical failure, wear, patellar problems) 14 (13%) in the outlier group
Manjunath et al[27]	Prospective study, 120 TKAs in 80 patients	Jig-based NMA (± 3°) vs malaligned group (> 3°)	Patients in alignment within 3° of NMA has improved KSS scores, but no difference in functional scores at 6 weeks follow-up	Not available
Hutt et al[36]	Prospective study, 100 TKAs in 95 patients	KA with computer navigation	Preserving the native femoral flexion axis resulted in improved mean WOMAC and KOOS scores at a mean follow-up 2.4 years	5 patients with severe pre-op varus/valgus alignment required additional ligament releases 2 patients with moderate valgus alignment required lateral retinacular release for patella maltracking
Young et al[43]	RCT, 99 patients	NMA vs KA	No difference in OKS/FJS/WOMAC score or revision rates at 2 years	3 revisions in KA group (including patella dislocation, infection, and 2 MUAs for stiffness) 4 revisions in MA (including periprosthetic fracture, infection, recurrent haemarthrosis, and traumatic patellar dislocation)
Waterson et al[10]	RCT, 71 patients	NMA vs KA	KA group had improved AKSS at 6 weeks and 6 months but no difference at 1 year	Patients with complications were excluded from the assessment of function
Dossett et al[19]	Prospective RCT, 82 patients	NMA vs KA	KA group had better ROM, WOMAC, OKS, and KSS scores at 6 months	4 complications in KA group (including 1 evacuation of haematoma, 2 MUA, 1 patellar subluxation) 3 complications in MA group (including 1 local debridement for haematoma and skin sloughing, 1 evacuation of haematoma, 1 ORIF for patella fracture)
Woon et al[47]	Meta-analysis of 4 RCTs, 458 patients	KA with patient specific instruments vs NMA with conventional jig-based technique	No different in WOMAC or KSS scores at 1 year	Not available
Incavo et al[51]	Cadaveric study, 7 specimens	NMA vs AA	NMA balanced throughout flexion	Not applicable
Matziolis et al[52]	RCT, 60 patients	NMA using traditional balancing technique vs AA reversed gap technique	AA with reverse gap technique associated with reduced soft tissue tension and significantly lower degree of midflexion instability	Not available

AA, anatomical alignment; AKSS, American Knee Society Score; FJS, Forgotten Joint Score; KA, kinematic alignment; KOOS, Knee injury and Osteoarthritis Outcome Score; KSS, Knee Society Score; MA, mechanical alignment; MUA, manipulation under anaesthesia; NMA, neutral mechanical alignment; OKS, Oxford Knee Score; ORIF, open reduction internal fixation; RCT, randomized controlled trial; ROM, range of motion; TKA, total knee arthroplasty; WOMAC, Western Ontario and McMaster Universities Osteoarthritis Index.

year ($p = 0.84$). TKA with KA marginally improved functional outcomes at six weeks for some of the outcome measures after surgery compared to NMA, but there were no differences between the two groups at one-year follow-up, suggesting that there are some comparable short term results between the two groups but no significant differences mid- to long-term.[10]

Dossett et al[19] undertook a prospective RCT comparing 41 patients undergoing TKA with NMA versus 41 patients undergoing TKA with KA. NMA was executed using plain radiographs and conventional alignment jigs, while KA was undertaken using preoperative CT scanograms and patient-specific cutting blocks.[19] All radiological outcomes were assessed using long-leg CT scanograms. The study found that TKA with KA was associated with better range of knee motion, and improved WOMAC, OKS, and combined KSS scores, as compared with TKA using NMA at six months follow-up. In patients undergoing TKA with

KA, the angle of the femoral component was 2.4° more valgus ($p < 0.001$) and the angle of the tibial component was 2.3° more varus ($p < 0.001$) than in patients undergoing TKA with NMA, but there was no difference in the overall hip-knee-ankle angle (0.3° difference; p = 0.69) and anatomical angle of the knee (0.8° difference; p = 0.13) between the two treatment groups. KA was associated with a more naturally-aligned TKA, and therefore produced better outcome scores compared to NMA at six months after TKA. However, follow-up data were limited to six months after surgery and the risk of alignment-related TKA failures remained similar in both treatment groups.[19]

Woon et al[46] performed a meta-analysis comparing outcomes in TKA with NMA versus TKA with KA. The study included four RCTs with 229 patients undergoing TKA with KA performed using patient-specific instrumentation versus 229 patients with NMA undertaken using conventional jig-based techniques. The study found no difference in WOMAC scores, KSS function scores, or KSS combined scores between the two groups at one-year follow-up.[46] Subgroup analysis showed the there was no correlation in preoperative limb alignment and postoperative WOMAC and KSS combined scores at one-year follow-up.[47]

Overall, KA aims to restore individualized predisease limb alignment and preserve native knee kinematics through the arc of flexion. However, there are a number of limitations within existing studies assessing the effects of TKA with KA on functional outcomes, component survivorship, and long-term complications. Studies have used heterogeneity in the preoperative imaging methods for surgical planning, and executed the planned alignment using techniques with limited accuracy and reproducibility such as conventional alignment jigs, 3D cutting blocks, patient-specific implants, and computer navigation. Furthermore, KA aims to preserve native periarticular soft-tissue and restore predisease ligamentous tension, but existing studies have not objectively assessed intraoperative soft-tissue tension or gap measurements with KA. The recent evolution of robotic technology may offer an avenue for accurately executing KA while helping to record intraoperative flexion-extension gaps, mediolateral soft-tissue tension, and range of motion in future studies.[21,30] This technology enables improved precision for performing the planned bone resections, implant positioning and limb alignment, which may help to better define the safe ranges for limb alignment in TKA. Future studies should focus on the safe thresholds for executing patient-specific alignment and restoring individualized knee biomechanics to optimize functional outcomes, while respecting the boundaries for mechanical alignment to preserve long-term implant durability.[23,48–51] Table I summarizes individual studies comparing different alignment techniques, highighting the key findings and complications reported.

Anatomical alignment. Anatomical alignment (AA) aims to recreate native knee anatomy and geometry, while accounting for the natural varus angulation of the proximal tibial plateau. Initial proponents of AA in TKA advocated for 3° of varus in the proximal tibial resection and 3° of valgus in the distal femoral resection to restore the natural mechanical axis and joint line. TKA with AA has been subsequently modified to 2° of varus in the proximal tibial resection, instead of 3°, but the principles of restoring native alignment and respecting the native angulation of the joint line remain unchanged. Preliminary studies have reported AA for TKA improves patella tracking, reduces tension in the lateral retinaculum ligament, and facilitates more equal load distribution in the tibial component, with a reduced incidence of radiolucent lines compared to NMA.[52,53] However, the main drawback of AA is that inadvertent over-resection of the 3° proximal tibial varus cut may lead to varus tibial implant position and varus limb alignment, which is associated with premature component failure in TKA.[9,22] In order to overcome this, several studies on AA in TKA have used robotic technology to accurately execute the planned bone resections and limb alignment.[21,30,54]

Incavo et al[51] performed a cadaveric study on seven lower limb specimens undergoing TKA with NMA on one side versus AA on the contralateral side. Each joint was stripped at a level 15 cm from the joint line, preserving the joint capsule, quadriceps muscle, hamstring tendons, and ligamentous structures. Fixed trackers were placed in the femur, tibia, and medial and lateral joint spaces to assess knee kinematics and periarticular soft-tissue tension through the arc of flexion during simulated squatting. The study found that TKA with AA balanced mediolateral soft tissue tension at 0° and 90° knee flexion, but lateral joint gaps were wider than medial joint gaps at 60° knee flexion, and medial joint gaps wider than later joint gaps at 150° knee flexion. In contrast, TKA with NMA produced balanced mediolateral joint gaps though the full arc of knee flexion. The findings suggest that TKA with AA enables better restoration of the native knee pivot movement and more accurate recreation of native periarticular soft tissue tension during knee flexion.[51]

Matziolis et al[52] performed a RCT aiming to present a soft-tissue-preserving gap technique for AA that optimizes mid-flexion stability. The study included 30 patients undergoing TKA with NMA using the traditional gap-balancing technique versus 30 patients receiving TKA using a reversed gap technique. In the traditional gap-balancing technique group, 15 patients (50%) required additional soft-tissue releases to balance flexion-extension gaps, with nine of these patients (15%) requiring “extensive” soft-tissue releases of more than two knee stabilizers to balance the knee. Appropriate distal femoral resection, femoral component size, and rotation were then selected to achieve balanced flexion-extension gaps and equal mediolateral soft-tissue tension. In TKA with AA using the reverse gap technique, preoperative MRI was used to determine bone resection, femoral implant size, and femoral implant position relative to the transepicondylar axis, and an intraoperative computer navigation system helped to execute this plan accurately. In this group, additional soft tissue releases were performed in 13 cases (43%) to balance flexion-extension gaps and only four patients (7%) required "extensive" soft-tissue releases. Furthermore, 16 patients (53%) with TKA using the traditional gap technique with NMA showed instability of more than 2 mm at 5°, 30°, or 60°, compared with eight patients (27 %) undergoing TKAs using the reverse gap technique ($p = 0.035$).[52] The authors concluded that TKA with AA achieved using the reverse gap technique enables satisfactory balance of flexion-extension gaps, with reduced need for intraoperative soft-tissue releases and decreased mid-flexion instability compared to TKA with NMA using the gap-balancing technique.[52]

The main limitations of studies reporting on AA for TKA include the short-term clinical outcomes, and lack of long-term data on functional outcomes and implant survivorship. Many studies also exclude patients with pre-existing bony deformities, severe arthritis, and valgus deformities. AA in TKA has fallen out of favour and is not commonly used in routine arthroplasty practice. However, these studies have highlighted the importance of using 3D preoperative imaging to create patient-specific surgical plans when using AA, and that intraoperative robotic technology helps to accurately execute the planned implant positions and limb alignment in TKA.

Functional alignment. Functional alignment (FA) has been proposed as a novel technique that aims to restore the native plane and obliquity of the joint, as dictated by the soft-tissue envelope.[23] The procedure is preoperatively planned to achieve NMA with component positions perpendicular to the axes of the femur and tibia. Surgical aids such as computer navigation or robotic technology are then used to assess resection thickness, flexion-extension gaps, and limb alignment during surgery.[23] Following removal of osteophytes, varus or valgus strains are applied to restore native periarticular soft-tissue tension and correct the coronal plane deformity. Computer software is used to virtually adjust the component positions with potential changes in limb alignment, flexion-extension gaps, and range of motion displayed on-screen.[21,30,51,53,54] Valgus correction may be applied to the distal femoral resection and varus correction to the tibial resection to restore the native obliquity of the joint line. The joint line height is preserved which increases knee flexion, aids patella tracking, and improves mid-flexion stability. This technique aims to execute individualized physiological limb alignment within the 0° to 3° safe zone of coronal alignment and achieve patient-specific knee kinematics while limiting any soft-tissue releases.[23] Any fixed deformities may require ligamentous releases to balance flexion-extension gaps, although the extent and frequency of such releases is smaller when compared with the standard NMA technique.

Initial studies have shown that robotic TKA with functional alignment reduces the need for controlled soft-tissue releases and periarticular soft-tissue injury compared to conventional jig-based TKA with NMA. Robotic TKA with FA may also enable improved postoperative functional rehabilitation, reduced analgesia requirements, and earlier time to hospital discharge compared to conventional TKA with NMA.[23] However, there are no existing studies assessing the effects of TKA with functional alignment on long-term functional outcomes, implant survivorship, and complications. A recent protocol has been published for a prospective randomized control with 100 patients comparing robotically aligned mechanical alignment versus robotically aligned functional alignment for assessing patient satisfaction, clinical outcomes, gait, cost-effectiveness, component survivorship, and complications between these treatment techniques.[23] The results of further studies comparing TKA with functional alignment to TKA with traditional alignment techniques are currently awaited.

In conclusion, optimizing limb alignment in TKA is important as it affects periarticular soft-tissue tension, knee biomechanics, and implant survivorship. Several alignment techniques have been proposed for TKA. NMA facilitates knee flexion and symmetrical component wear but forces the limb into an unnatural position that alters native biomechanics through the arc of knee flexion. KA aims to restore native knee alignment within predefined safe ranges but surgical techniques for assessing and executing this alignment have had limited accuracy and reproducibility. AA aims to restore predisease alignment and knee geometry but existing studies using this technique are based on cadaveric specimens or clinical trials with limited follow-up times. FA aims to restore the native plane and obliquity of the joint by manipulating implant positioning while limiting soft tissue releases but the results of high-quality studies with long-term outcomes are still awaited.

There is limited correlation between the planned alignment technique and postoperative functional outcomes, which is likely to be multifactorial. Firstly, as highlighted above, the surgical techniques to execute the planned limb alignments have limited accuracy and reproducibility. Therefore, we cannot be certain that the planned alignment for each patient has been accurately achieved. Furthermore, only alignment in the coronal plane has been assessed, with very limited data on the impact of sagittal and axial alignment on outcomes.

Thirdly, several potential confounders such as obesity, previous surgery, extent of preoperative deformity, or neurological compromise have not been matched or accounted for in the statistical analyses. Fourthly, the majority of studies do not have a prospectively randomized control group undergoing surgery with the same implant design, surgical approach, soft-tissue releases, or rehabilitation programme. Further studies on alignment in TKA should use surgical adjuncts (e.g. robotic technology) to help execute the planned alignment with improved accuracy, prospectively randomize patients to their treatment groups, assess intraoperative knee biomechanics, and correlate alignment to long-term patient-reported functional outcomes and survivorship. The majority of research has been undertaken on alignment in the coronal plane, with limited evidence on the impact of the planned surgical technique on sagittal or axial alignments. Alignment should ideally be considered as a triad of all three planes to optimize bone resections and implant positioning. Additional research is required on the safe ranges of alignment with modern TKA implant designs to achieve the balance between restoring patient-specific kinematics for improving functional outcomes, while respecting the safe boundaries of NMA to optimize implant durability.

References

1. **Font-Rodriguez DE**, **Scuderi GR**, **Insall JN**. Survivorship of cemented total knee arthroplasty. *Clin Orthop Relat Res*. 1997;345:79–86.
2. **Gill GS**, **Joshi AB**, **Mills DM**. Total condylar knee arthroplasty. 16- to 21-year results. *Clin Orthop Relat Res*. 1999;367:210–215.
3. **Rodricks DJ**, **Patil S**, **Pulido P**, **Colwell CW**. Press-fit condylar design total knee arthroplasty. fourteen to seventeen-year follow-up. *J Bone Joint Surg Am*. 2007;89-A(1):89–95.
4. **Baker PN**, **van der Meulen JH**, **Lewsey J**, **Gregg PJ**, **National Joint Registry for England and Wales**. The role of pain and function in determining patient satisfaction after total knee replacement. data from the National joint Registry for England and Wales. *J Bone Joint Surg Br*. 2007;89-B(7):893–900.
5. **Bourne RB**. Measuring tools for functional outcomes in total knee arthroplasty. *Clin Orthop Relat Res*. 2008;466:2634–2638.
6. **Noble PC**, **Conditt MA**, **Cook KF**, **Mathis KB**. The John Insall Award: Patient expectations affect satisfaction with total knee arthroplasty. *Clin Orthop Relat Res*. 2006;452:35–43.
7. **Almaawi AM**, **Hutt JRB**, **Masse V**, **Lavigne M**, **Vendittoli P-A**. The impact of mechanical and restricted kinematic alignment on knee anatomy in total knee arthroplasty. *J Arthroplasty*. 2017;32(7):2133–2140.
8. **Bellemans J**, **Colyn W**, **Vandenneucker H**, **Victor J**. The Chitranjan Ranawat award: is neutral mechanical alignment normal for all patients? The concept of constitutional varus. *Clin Orthop Relat Res*. 2012;470(1):45–53.
9. **Cherian JJ**, **Kapadia BH**, **Banerjee S**, **Jauregui JJ**, **Issa K**, **Mont MA**. Mechanical, anatomical, and kinematic axis in TKA: Concepts and practical applications. *Curr Rev Musculoskelet Med*. 2014;7(2):89–95.
10. **Waterson HB**, **Clement ND**, **Eyres KS**, **Mandalia VI**, **Toms AD**. The early outcome of kinematic versus mechanical alignment in total knee arthroplasty: a prospective randomised control trial. *Bone Joint J*. 2016;98-B(10):1360–1368.
11. **Kayani B**, **Konan S**, **Horriat S**, **Ibrahim MS**, **Haddad FS**. Posterior cruciate ligament resection in total knee arthroplasty. *Bone Joint J*. 2019;101-B(10):1230–1237.
12. **Kayani B**, **Konan S**, **Ahmed SS**, **Chang JS**, **Ayuob A**, **Haddad FS**. The effect of anterior cruciate ligament resection on knee biomechanics. *Bone Joint J*. 2020;102-B(4):442–448.
13. **Kayani B**, **Konan S**, **Tahmassebi J**, **Pietrzak JRT**, **Haddad FS**. Robotic-arm assisted total knee arthroplasty is associated with improved early functional recovery and reduced time to hospital discharge compared with conventional jig-based total knee arthroplasty: a prospective cohort study. *Bone Joint J*. 2018;100-B(7):930–937.
14. **Kayani B**, **Konan S**, **Pietrzak JRT**, **Haddad FS**. Iatrogenic bone and soft tissue trauma in Robotic-Arm assisted total knee arthroplasty compared with conventional Jig-Based total knee arthroplasty: a prospective cohort study and validation of a new classification system. *J Arthroplasty*. 2018;33(8):2496–2501.
15. **Eckhoff DG**, **Bach JM**, **Spitzer VM**, **et al**. Three-Dimensional mechanics, kinematics, and morphology of the knee viewed in virtual reality. *J Bone Joint Surg Am*. 2005;87 Suppl 2:71.
16. **Eckhoff D**, **Hogan C**, **DiMatteo L**, **Robinson M**, **Bach J**. Difference between the epicondylar and cylindrical axis of the knee. *Clin Orthop Relat Res*. 2007;461:238–244.
17. **Dossett HG**, **Estrada NA**, **Swartz GJ**, **LeFevre GW**, **Kwasman BG**. A randomised controlled trial of kinematically and mechanically aligned total knee replacements: Two-year clinical results. *Bone Joint J*. 2014;96-B(7):907–913.
18. **Howell SM**, **Howell SJ**, **Kuznik KT**, **Cohen J**, **Hull ML**. Does a kinematically aligned total knee arthroplasty restore function without failure regardless of alignment category? *Clin Orthop Relat Res*. 2013;471(3):1000–1007.
19. **Dossett HG**, **Swartz GJ**, **Estrada NA**, **LeFevre GW**, **Kwasman BG**. Kinematically versus mechanically aligned total knee arthroplasty. *Orthopedics*. 2012;35(2):e160-9.
20. **Howell SM**, **Papadopoulos S**, **Kuznik K**, **Ghaly LR**, **Hull ML**. Does varus alignment adversely affect implant survival and function six years after kinematically aligned total knee arthroplasty? *Int Orthop*. 2015;39(11):2117–2124.
21. **Kayani B**, **Haddad FS**. Robotic total knee arthroplasty. *Bone Joint Res*. 2019;8(10):438–442.
22. **Choong PF**, **Dowsey MM**, **Stoney JD**. Does accurate anatomical alignment result in better function and quality of life? comparing conventional and computer-assisted total knee arthroplasty. *J Arthroplasty*. 2009;24(4):560–569.
23. **Kayani B**, **Konan S**, **Tahmassebi J**, **Oussedik S**, **Moriarty PD**, **Haddad FS**. A prospective double-blinded randomised control trial comparing robotic arm-assisted functionally aligned total knee arthroplasty versus robotic arm-assisted mechanically aligned total knee arthroplasty. *Trials*. 2020;21(1):194.
24. **Hood B**, **Blum L**, **Holcombe SA**, **et al**. Variation in optimal sagittal alignment of the femoral component in total knee arthroplasty. *Orthopedics*. 2017;40(2):102–106.
25. **Rivière C**, **Iranpour F**, **Auvinet E**, **et al**. Alignment options for total knee arthroplasty: a systematic review. *Orthop Traumatol Surg Res*. 2017;103(7):1047–1056.
26. **Oussedik S**, **Abdel MP**, **Victor J**, **Pagnano MW**, **Haddad FS**. Alignment in total knee arthroplasty. *Bone Joint J*. 2020;102-B(3):276–279.
27. **Manjunath KS**, **Gopalakrishna KG**, **Vineeth G**. Evaluation of alignment in total knee arthroplasty: a prospective study. *Eur J Orthop Surg Traumatol*. 2015;25(5):895–903.
28. **Bonner TJ**, **Eardley WGP**, **Patterson P**, **Gregg PJ**. The effect of post-operative mechanical axis alignment on the survival of primary total knee replacements after a follow-up of 15 years. *J Bone Joint Surg Br*. 2011;93-B(9):1217–1222.
29. **Parratte S**, **Pagnano MW**, **Trousdale RT**, **Berry DJ**. Effect of postoperative mechanical axis alignment on the fifteen-year survival of modern, cemented total knee replacements. *J Bone Joint Surg Am*. 2010;92-A(12):2143–2149.
30. **Kayani B**, **Konan S**, **Ayuob A**, **Onochie E**, **Al-Jabri T**, **Haddad FS**. Robotic technology in total knee arthroplasty: a systematic review. *EFORT Open Rev*. 2019;4(10):611–617.
31. **Kim Y-H**, **Park J-W**, **Kim J-S**. Computer-navigated versus conventional total knee arthroplasty a prospective randomized trial. *J Bone Joint Surg Am*. 2012;94-A(22):2017–2024.
32. **Insall JN**, **Dorr LD**, **Scott RD**, **Scott WN**. Rationale of the knee society clinical rating system. *Clin Orthop Relat Res*. 1989;248:13–14.
33. **Bellamy N**, **Buchanan WW**, **Goldsmith CH**, **Campbell J**, **Stitt LW**. Validation study of WOMAC: a health status instrument for measuring clinically important patient relevant outcomes to antirheumatic drug therapy in patients with osteoarthritis of the hip or knee. *J Rheumatol*. 1988;15(12):1833–1840.
34. **Hollister AM**, **Jatana S**, **Singh AK**, **Sullivan WW**, **Lupichuk AG**. The axes of rotation of the knee. *Clin Orthop Relat Res*. 1993;290:259–268.
35. **Parvizi J**, **Nunley RM**, **Berend KR**, **et al**. High level of residual symptoms in young patients after total knee arthroplasty. *Clin Orthop Relat Res*. 2014;472(1):133–137.
36. **Hutt JRB**, **LeBlanc M-A**, **Massé V**, **Lavigne M**, **Vendittoli P-A**. Kinematic TKA using navigation: surgical technique and initial results. *Orthop Traumatol Surg Res*. 2016;102(1):99–104.
37. **Jeremić DV**, **Massouh WM**, **Sivaloganathan S**, **Rosali AR**, **Haaker RG**, **Rivière C**. Short-Term follow-up of kinematically vs. mechanically aligned total knee arthroplasty with medial pivot components: a case-control study. *Orthop Traumatol Surg Res*. 2020;106(5):921–927.

38. **Howell SM**, **Papadopoulos S**, **Kuznik KT**, **Hull ML**. Accurate alignment and high function after kinematically aligned TKA performed with generic instruments. *Knee Surg Sports Traumatol Arthrosc*. 2013;21(10):2271–2280.
39. **Matsumoto T**, **Takayama K**, **Ishida K**, **Hayashi S**, **Hashimoto S**, **Kuroda R**. Radiological and clinical comparison of kinematically *versus* mechanically aligned total knee arthroplasty. *Bone Joint J*. 2017;99-B(5):640–646.
40. **Yeo J-. H**, **Seon J-. K**, **Lee D-. H**, **Song E-. K**. No difference in outcomes and gait analysis between mechanical and kinematic knee alignment methods using robotic total knee arthroplasty. *Knee Surg Sports Traumatol Arthrosc*. 2019;27(4):1142–1147.
41. **Sappey-Marinier E**, **Pauvert A**, **Batailler C**, **et al**. Kinematic versus mechanical alignment for primary total knee arthroplasty with minimum 2 years follow-up: a systematic review. *Sicot J*. 2020;6:18.
42. **Roos EM**, **Roos HP**, **Lohmander LS**, **Ekdahl C**, **Beynnon BD**. Knee injury and osteoarthritis outcome score (KOOS)--development of a self-administered outcome measure. *J Orthop Sports Phys Ther*. 1998;28(2):88–96.
43. **Young SW**, **Walker ML**, **Bayan A**, **Briant-Evans T**, **Pavlou P**, **Farrington B**. The Chitranjan S. Ranawat Award : No Difference in 2-year Functional Outcomes Using Kinematic versus Mechanical Alignment in TKA: A Randomized Controlled Clinical Trial. *Clin Orthop Relat Res*. 2017;475(1):9–20.
44. **No authors listed**. Guidance of the Routine Collection of Patient Reported Outcome Measures (PROMS). Department of Health, London. 2008. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/216651/dh_128447.pdf (date last accessed 15 June 2021).
45. **Behrend H**, **Giesinger K**, **Giesinger JM**, **Kuster MS**. The "forgotten joint" as the ultimate goal in joint arthroplasty: validation of a new patient-reported outcome measure. *J Arthroplasty*. 2012;27(3):430-436.
46. **Klatt BA**, **Goyal N**, **Austin MS**, **Hozack WJ**. Custom-fit total knee arthroplasty (OtisKnee) results in malalignment. *J Arthroplasty*. 2008;23(1):26–29.
47. **Woon JTK**, **Zeng ISL**, **Calliess T**, **et al**. Outcome of kinematic alignment using patient-specific instrumentation versus mechanical alignment in TKA: a meta-analysis and subgroup analysis of randomised trials. *Arch Orthop Trauma Surg*. 2018;138(9):1293–1303.
48. **Srivastava A**, **Lee GY**, **Steklov N**, **Colwell CW Jr**, **Ezzet KA**, **D'Lima DD**. Effect of tibial component varus on wear in total knee arthroplasty. *Knee*. 2012;19(5):560–563.
49. **Ritter MA**, **Davis KE**, **Meding JB**, **Pierson JL**, **Berend ME**, **Malinzak RA**. The effect of alignment and BMI on failure of total knee replacement. *J Bone Joint Surg Am*. 2011;93(17):1588–1596. Volume.
50. **Yim J-H**, **Song E-K**, **Khan MS**, **Sun Zhui**, **Seon J-K**, **Sun Z**. A comparison of classical and anatomical total knee alignment methods in robotic total knee arthroplasty. *J Arthroplasty*. 2013;28(6):932–937.
51. **Incavo SJ**, **Schmid S**, **Sreenivas K**, **Ismaily S**, **Noble PC**. Total knee arthroplasty using anatomic alignment can produce mid-flexion laxity. *Clin Biomech*. 2013;28(4):429–435.
52. **Matziolis G**, **Brodt S**, **Windisch C**, **Roehner E**. The reversed gap technique produces anatomical alignment with less midflexion instability in total knee arthroplasty: a prospective randomized trial. *Knee Surg Sports Traumatol Arthrosc*. 2016;24(8):2430–2435.
53. **Kayani B**, **Konan S**, **Huq SS**, **Tahmassebi J**, **Haddad FS**. Robotic-arm assisted total knee arthroplasty has a learning curve of seven cases for integration into the surgical workflow but no learning curve effect for accuracy of implant positioning. *Knee Surg Sports Traumatol Arthrosc*. 2019;27(4):1132–1141.
54. **Kayani B**, **Konan S**, **Pietrzak JRT**, **Haddad FS**. Iatrogenic bone and soft tissue trauma in Robotic-Arm assisted total knee arthroplasty compared with conventional Jig-Based total knee arthroplasty: a prospective cohort study and validation of a new classification system. *J Arthroplasty*. 2018;33(8):2496–2501.

Author information:

- F. A. Begum, MBBS, BMSc, MRCS(Eng), BSc(Hons), Specialist Registrar in Trauma and Orthopaedics
- B. Kayani, MBBS, MRCS(Eng), BSc(Hons), Specialist Registrar in Trauma and Orthopaedics
- A. A. Magan, BM BSc(Hons), MRCS(Eng), FRCS, Senior Clinical Fellow
- J. S. Chang, MBBS, MRCS, FRCSC, Senior Clinical Fellow
- F. S. Haddad, BSc MD(Res) MCh(Orth) FRCS(Orth) FFSEM, Professor of Orthopaedic Surgery

Department of Trauma and Orthopaedic Surgery, University College Hospital, London, UK; Department of Orthopaedic Surgery, The Princess Grace Hospital, London, UK.

Author contributions:

- F. A. Begum: Performed the literature search, Collected the data, Devised, wrote, and edited the manuscript.
- B. Kayani: Collected the data, Edited the manuscript.
- A. Magan: Collected the data, Wrote the manuscript.
- J. Chang: Edited the manuscript.
- F. S. Haddad: Developed the concept of the paper, Devised and edited the manuscript.

Funding statement:

- No benefits in any form have been received or will be received from a commercial party related directly or indirectly to the subject of this article.

ICMJE COI statement:

- F. S. Haddad reports editorial board membership by *The Bone & Joint Journal* and the Annals of the Royal College Of Surgeons, consultancy and royalties from Smith & Nephew, Corin, MatOrtho, and Stryker, and payment for lectures from Smith & Nephew and Stryker, all of which are unrelated to this article