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TKA SYMPOSIUM (P SANCHETI, SECTION EDITOR)

Mechanical, Anatomical, and Kinematic Axis in TKA: Concepts and Practical Applications

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Abstract Successful total knee arthroplasty (TKA) has often been based on the restoration of the knee to neutral alignment postoperatively. Numerous reports have linked malaligned TKA components to increased wear, poor functional outcomes, and failure. There have been many different alignment philosophies and surgical techniques that have been established to attain the goal of proper alignment, which includes such techniques as computerized navigation, and custom cutting guides. In addition, these methods could potentially have the added benefit of leading to improved functional outcomes following total knee arthroplasty. In this report, we have reviewed and analyzed recent reports concerning mechanical, anatomic, and kinematic axis/alignment schemes used in total knee arthroplasty.

Keywords Alignment · Total knee arthroplasty · Mechanical axis · Kinematic axis · Anatomic axis

Introduction

One aim for total knee arthroplasty is to achieve excellent alignment of the femoral, tibial, and patellar components, with ultimate restoration of the patient's lower extremity to neutral [1]. Proper alignment of the knee is considered to be one of the most influential factors in determining the long-term outcomes after TKA [2], and is believed to decrease both the mechanical and shear stresses placed on the bearing surfaces, as well as the bone/prosthesis interfaces [3–5]. In addition, proper alignment aids to balance the forces transmitted through the soft-tissue envelope, which is crucial for suitable functioning of the joint [4]. Furthermore, when total knee arthroplasties are poorly aligned this can result in decreased implant survivorship, as well as being implicated as a cause for increased wear, poor functional outcomes, and early failure leading to component loosening with older polyethylene and implant designs [3, 5–10].

There are various different alignment strategies and surgical techniques that have been utilized to attain this goal [11]. Classical alignment has been commonly used for TKA using either the measured resection or gap balancing techniques [11]. In contrast, anatomic alignment sought to try to closely match the true anatomy of the femur and tibia to allow the joint line to be parallel to the ground during the normal stance phase of gait [12••].

In many international joint registries, approximately one-fifth to one-quarter of all patients have been found to be dissatisfied following their total knee arthroplasty [13, 14]. The development of various technologies, including computer navigation and patient-specific instrumentation, has intended to help the surgeon to better replicate the neutral mechanical axis of the knee [15–18]. However, even though these technologies have sometimes led to improved radiographic alignment and fewer axis outliers, these innovations have not necessarily led to improved clinical outcomes [19, 20].

The purpose of this review various alignment schemas used to implant TKA's specifically mechanical, anatomic, and kinematic axes. This report will specifically review: (1) various definitions of alignment axes, (2) historical concepts of knee alignment, (3) various alignment schemes, and (4) recent evidence on outcomes with the use of mechanical and kinematic alignment.

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Alignment Axes

Vertical Axis

On normal weight bearing anteroposterior radiographs, a vertical line that extends distally from the center of the pubic symphysis is known as the vertical axis [4]. This axis is used as a reference axis/line from which the other axes are determined.

Mechanical Axis

The mechanical axis of the lower extremity is determined by drawing a line from the center of the femoral head to the center of the ankle joint, which corresponds to an approximately 3° slope compared with that of the vertical axis [21]. This can be subdivided into the femoral mechanical axis, which runs from the head of the femur to the intercondylar notch of the distal femur, and the tibial mechanical axis, which extends from the center of the proximal tibia to the center of the ankle [21] (Fig. 1). The medial angle formed between the mechanical axis of the femur and the mechanical axis of the tibia is called the hip–knee–ankle angle, which represented the overall alignment of the lower extremity and is usually slightly less than 180° in normal knees [22–24]. The position of the mechanical axis causes it to usually pass just medial to the tibial spine, but this can vary widely based on the patient height and pelvic width (increased pelvic width as in females and decreased height results in increased axis deviation) [10].

Anatomic Axis

The anatomic axis of the lower extremity is an axis in relation to the intramedullary canals [21]. There are 2 methods that are used to define the anatomic axis of the femur. The first is a line drawn proximal to distal in the intramedullary canal bisecting the femur in one-half, whereas the second method is a point at the femoral shaft center to a point 10 centimeters above the knee joint located at an equal distance between the medial and lateral cortex [21] (Fig. 1). The anatomic axis of the tibia is created by a line drawn proximal to distal in the intramedullary canal bisecting the tibial in half [21] (Fig. 1). On anteroposterior evaluation, the mechanical, and anatomic axes of the tibia commonly correspond exactly with one another. However, the anatomic axis of the femur has an approximate 5°–7° of inclination difference than the mechanical axis. Moreover, the anatomic axis can deviate markedly depending on femoral or tibial deformities, as well as the patient's hip angle [4]. On a weight-bearing radiograph, the lateral angle between the anatomic axes of the femur and the tibia is called the femorotibial angle (FTA) [21]. The average femorotibial angle is approximately 178° in men, and 176° and 174° in Asian and Caucasian women, respectively [21].

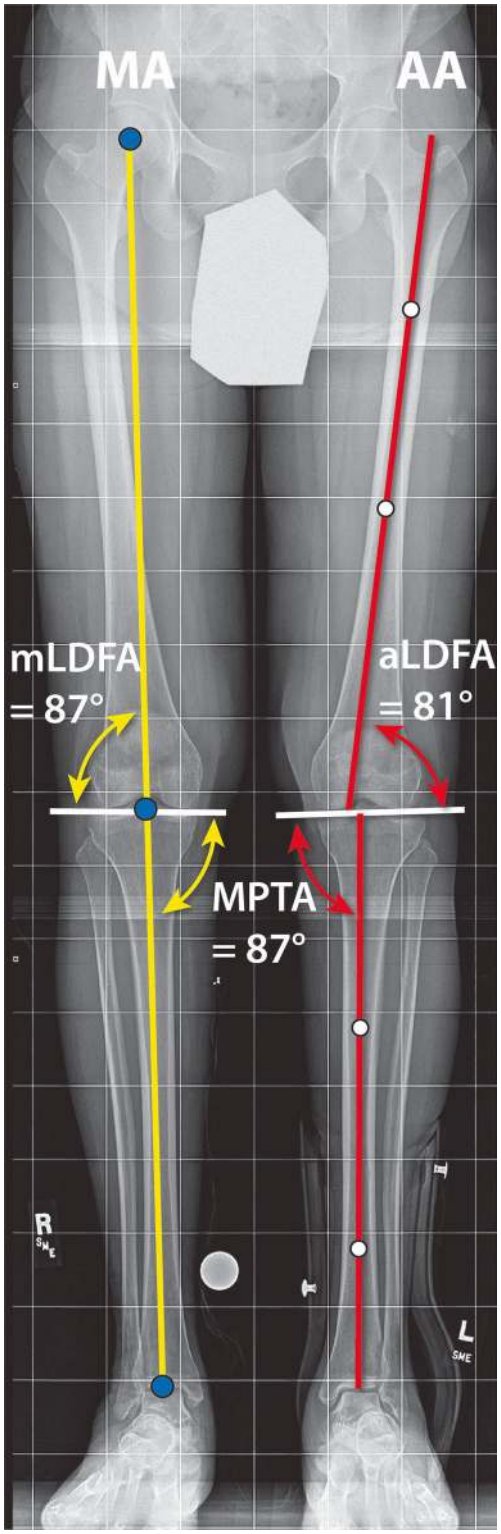

Fig. 1 Long-leg standing radiograph demonstrating the mechanical axis of the lower extremity (MA), mechanical axis of the femur (MA), and anatomic axis of the femur and tibia (AA). The angle between the MAF and AAF is typically between 5° and 7°. The joint line forms an angle (α) that is 93° with the MAT, or 3°of varus

However, some factors such as axial limb rotation and flexion deformity can dramatically affect the femorotibial angle [25].

Swanson et al [26] performed a comparison study of the measurement for femorotibial angle that indicated that there was a statistically significant difference in models with severe valgus or varus when rotated internally or externally. One radiographic study have also found that with increasing flexion deformity the femorotibial angle becomes more valgus [27].

Kinematic Axis

Kinematic alignment in total knee arthroplasty is based on 3 functional kinematic axes about which the knee rotates [28]. Different from the previous axes mentioned, the kinematic axes are intended to mimic the dynamic motions of the knee. They consist of a transverse axis of the femur in which the tibia flexes and extends, which passes through the center of a circle that fits the femoral condyles [28]. Another transverse axis depicts the motion in which the patella flexes and extends in relation to the femur [29••]. This axis is located anterior, proximal, and in parallel to the first transverse axis [30••]. The longitudinal axis is perpendicular to the previous 2 axes and dictates the dynamic movements of internal and external rotation of the tibia in relation to the femur [4].

Historical Concept of Knee Alignment

Normal Knee Alignment

The normal knee joint line alignment is naturally in 2° to 3° of varus compared with the mechanical axis. The primary goal of many of the alignment techniques is to achieve neutral alignment of the knee, however, neutral alignment is not always observed in healthy nonarthritic patients. Hsu et al [31] found that only 2.2 % of patients resided on the 0 degree mechanical axis. While a study by Bellmans et al [32••] of 250 healthy asymptomatic adults noted that 32 % of men and 17 % of women had constitutional varus knees with their natural mechanical alignment being 3 degrees of varus or more. A recent study by Fahlman et al [33•] examined 143 participants, and found based on radiographic evaluation that 81.8 % of the participants had both knees with the same alignment: both straight (11.2 %), both valgus (21.7 %), and both varus (49.0 %). However, they found that the remaining individuals (18.2 %) had knees characterized with different alignments.

Background to TKA Alignment

Historically, there were 2 alignment strategies employed to replicate the mechanical axis of the lower extremity when performing total knee arthroplasty. These were classical and anatomic alignments, which were based on the same limb alignment goal: to obtain a neutral mechanical axis with a line passing through the center of the knee, femoral head, and ankle joint. The classical alignment scheme described where all components are positioned in a neutral mechanical axis, which has been speculated to allow for even distribution of joint stresses. One of the goals of anatomic alignment includes placement of components in order to restore the joint line parallel to the ground.

Mechanical Alignment

John Insall originally described the use of mechanical alignment in total knee arthroplasty [34]. Mechanical alignment is performed by making an initial femoral cut that is perpendicular to the mechanical axis of the femur, which is followed by a tibial resection made perpendicular to the mechanical axis of the tibia (Fig. 2). Insall believed that mechanical alignment was the superior method, because if the joint was anatomically aligned this would lead to medial tibial plateau fixation failure, due to the increased forces across the medial joint component if the knee is anatomically aligned [34]. Insall also noted that despite the even distribution of joint loading forces between compartments found during the stance phase, but during the gait phase there might be uneven loading of the component due to a "laterally" directed ground reaction force [34]. In addition, he argued against the restoration of the anatomic knee back to a predisease state, which he believed would ultimately lead to required adjustments of the soft tissues around the knee. In addition, he placed the femoral component at 3° of external rotation in order to balance the flexion and extension gaps.

Anatomic Alignment

Anatomic alignment for total knee arthroplasties was originally described by Hungerford and Krackow [35]. They purposed that the optimal component position should anatomically recreate the joint line. The anatomic joint line places the overall component alignment at 2°–3° of varus in relation to the mechanical axis of the lower extremity [35]. Tibial resection in anatomic alignment of the knee is made at an angle between that of the true vertical and mechanical axis. This requires that the femoral cut angle be made from the difference between the sum of the vertical inclination of the mechanical axis of the lower extremity and the mechanical axis of the femur [11] (Fig. 2). This angle, which is calculated by knowing the difference between the anatomic axis and the mechanical axis of the femur, is approximately 8°–9°of valgus. When this is combined with the 2°–3° degrees of varus angulation of the tibial cut, it gives a total alignment of approximately 6 degrees of valgus that approaches the normal tibiofemoral angle. Also, this alignment provided for a joint line that is parallel to the ground during normal gait [35].

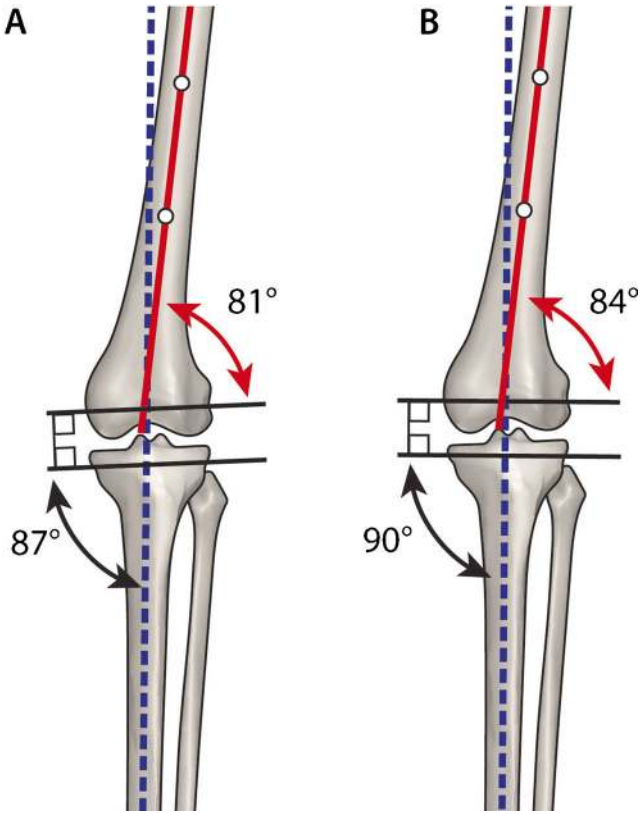

Fig. 2 Example of 2 different knee alignment schemes. Anatomic alignment (**a**) attempts to mimic the natural knee by cutting the tibia at 3° varus to the mechanical axis of the tibia and a distal femoral cut that is 9° valgus to the mechanical axis of the femur to recreate a 6° valgus joint line. Mechanical alignment (**b**) involves a tibial cut that is perpendicular to the mechanical axis of the tibia and a distal femoral cut 6° valgus to the anatomic axis (perpendicular to the mechanical axis) of the femur

Kinematic Alignment

The use of kinematic alignment for total knee arthroplasty was developed following the classic research by Hollister et al and others [36, 37] on the kinematics of the knee. This schema of alignment is considered to be a 3-dimensional alignment of components, whereas, the previous 2 techniques of mechanical and anatomic alignment were 2-dimensional [30••]. The goal of this alignment schema is to co-align the 2 transverse axes by providing the most adequate shape fitting of the symmetrical single radius femoral component design in order to achieve a "more natural" knee kinematics [28]. An in vivo study found that the contact mechanics in kinematically aligned total knee arthroplasties had more normal motion and less abnormal reverse axial rotation and adduction [38]. In kinematic alignment the thickness of all femoral bone resections including the bone from the kerf saw and the worn cartilage matches accurately with the thickness of the femoral component. In addition, in a kinematically aligned knee the femoral cut is made 1°–2° more valgus and the tibial cut is made 1°–2° varus compared with the mechanically aligned total knee arthroplasty [28].

Although both kinematic and mechanical aligned knees may have the same hip-knee-and-ankle alignment [30••, 39••], proponents believe that kinematic alignment reestablishes the obliquity and the location of the prearthritic joint line, which may potentially lead to improvements in clinical outcomes, greater ranges-of-motion, and enhanced patient satisfaction [28]. However, further studies are necessary to compare the outcomes of kinematic and mechanical or anatomically aligned total knee arthroplasties.

Clinical Results

Mechanical Alignment

It is believed that restoration of neutral mechanical axis aids in improved implant durability, and patient function following surgery [40•]. In 2009, Fang et al [41] retrospectively evaluated whether well-aligned total knee arthroplasties resulted in better survivorship compared with that of their outliers (>3° valgus or varus). The authors found that out of 6070 primary total knee arthroplasties there where 51 prosthesis failures; 21 (0.5 % in the neutral cohort), 18 (1.8 %) varus, and 12 (1.5 %) valgus group. Of all 3 alignment groups it was demonstrated that patient who had alignment between 2.4 and 7.2 degrees of valgus had the best overall survivorship. They noted that varus knees resulted in medial tibial collapse, and valgus alignment failed primarily because of ligamentous instability. This is reaffirmation of a previous study by Jeffery et al [8] who published a report examining alignment with total knee arthroplasty and aseptic loosening rates. The authors radiographically assessed the mechanical axis of a consecutive series of 115 total knee arthroplasties. They reported that when the axis passed through the middle one-third of the prosthesis, this resulted in a 3 % rate of loosening (2 out of 78 knees). Moreover, when the axis was shifted either medial or lateral, the loosening rate was noted to be much higher (24 %, 9 out of 37 knees; P=0.001).

Similarly, a prospective randomized study by Choong et al [42] evaluated whether accurate anatomic alignment resulted in better function and quality of life compared with outliers. The authors evaluated 115 patients (115 total knee arthroplasties) who underwent surgery performed with conventional or computer assisted surgery. They reported that 50 patients (88 %) in the computer assisted group compared with 33 patients (61 %) in the conventional cohort achieved alignment within 3° of neutral axis. In relation to function and quality of life, the authors reported that patients who achieved alignment within 3° of the mechanical axis had a significant increase in International Knee Society Score and Short-Form

12 physical Scores from 6 weeks postoperatively out to 12 months after surgery compared with patients who did not.

Despite the consensus among orthopedic surgeons who believe that well-aligned (within 3° of the mechanical axis) total knee arthroplasty results in improved outcomes, many recent studies have challenged this notion. A study by Khan et al [43•] retrospectively examined the relationship between the mechanical axis of the knee through its functional arc and patient's functional outcomes. They reported of the 76 patients who underwent computer-assisted total knee arthroplasties, 65 of the individuals achieved a functional arc alignment of 3° or less, whereas 11 were found to be outliers. In addition, the authors found no correlation between the 2 functional arc alignment groups and Western Ontario and McMaster University Scores (WOMAC) or Short-Form 12 surveys outcomes, however, they recognized that in patients who had greater than 3° of alignment that significantly increased difficulty with activities of daily living (P=0.05). Similarly, a study by Parratte et al [44••] examined the relationship between component alignment and survivorship in 398 total knee arthroplasties. The authors found no difference in Kaplan-Meier 15-year survivorship estimates between the prostheses place within 3° of varus or valgus compared with the prosthesis aligned outside this range. They made note that continuing to report as a dichotomous variable is not appropriate given the results of their study. However, until additional information in available to determine the best total knee arthroplasty alignment, surgeons should aim to achieve neutral mechanical axis.

Kinematic Alignment

Certain studies have questioned the use of classical alignment, and have suggested that a more appropriate method might be to recreate the patient's normal anatomy through kinematic alignment. In 2012, Dossett and colleagues [30••] published a study of 81 total knee arthroplasties evaluating alignment and clinical outcomes performed using standard mechanical alignment using conventional instruments compared with kinematic alignment with the use of patient specific guides. The authors found that there was no significant difference in relation to the hip-knee-ankle angle and the anatomic angle of the knee between the 2 cohorts in terms of alignment. However, at 6 months postoperatively, patients in the kinematically aligned TKA group had significantly higher Western Ontario and McMaster University Scores (16 points; P<0.000), Oxford scores (7 points; P=0.001), combined Knee Society Score (25 points; P=0.001), and 5° of flexion (P=0.043). Similarly, a study by Howell et al [29••] evaluated functional outcomes of 214 kinematically aligned total knee arthroplasties for 3 alignment categories. Patients were characterized by alignment as in range (between –2.5° and –7.4° valgus), varus (>– 2.5°), and valgus (<–7.4°). The authors found that the mean Oxford Knee Score of 43 and WOMAC score was 92, were similar in all alignment categories. Another study by Spencer et al [45••] examined the use of custom-fit total knee arthroplasty in relation to long-leg coronal alignment in 21 patients. The authors found that mean deviation from the mechanical axis was 1.2° of varus, which was close to previous reports.

Conclusions

The aim of the surgeon during total knee arthroplasty is to achieve good alignment of the femoral, tibial, and patellar components. Inappropriate joint alignment can result in increased implant stress, poor patient outcomes, and decreased survivorship. Historically, the goal of total knee arthroplasty has been to return the patients joint alignment to be within 3 degrees of mechanical axis, however, recent reports have challenged the theory that outliers result in increased revision. Currently, few authors have evaluated the role of kinematic alignment in improving the outcomes following total knee arthroplasty. As these newer alignment systems develop, we believe that larger studies are needed to appropriately define which alignment method will result in the optimal outcomes for patients after total knee arthroplasty.

Compliance with Ethics Guidelines

Conflict of Interest Jeffrey J. Cherian, Samik Banerjee, Julio J. Jauregui, and Kimona Issa declare that they have no conflict of interest. Bhaveen H. Kapadia reports personal fees and other from Sage Products, Inc., outside the submitted work.

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Human and Animal Rights and Informed Consent This article does not contain any studies with human or animal subjects performed by any of the authors.

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