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Research Article

Geometric Modeling of the Knee Articular Surface with Neutral Boundary Alignment

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Abstract

Knee mechanics is reliant on surface geometry and ligament attachments. Herein, we propose an elliptical cam model representing the femoral articular surface to explain the contact characteristics between the tibiofemoral and the patellofemoral articulations. This occurs in conjunction with a smooth transition of MCL and LCL tension to patella tendon tension that enables knee flexion without a loss of stability. The model is developed based on the Neutral Boundary Alignment (NBA) approach and has the following implications: 1) the asymmetry of distal femoral and tibial condyles is closely linked to the position of the epicondyles; 2) the epicondyles play important roles in femoral rotation in concert with MCL and LCL; 3) these features adjust the elliptical cam model to establish the concurrent motion between the tibiofemoral and patellofemoral motion with respect to the center of ellipse that would help dictate unique knee motion. In the foregoing analysis, we evaluate MRI knee images to illustrate various measures of knee asymmetry between individuals. As will be demonstrated, the asymmetry between the condyles varies and is not related to varus/valgus angle. This may have implications for total knee replacement planning and future implant design.

Keywords: Knee Alignment; Neutral Boundary Alignment; Kinematic Axis Alignment; Knee Surgery; Total Knee Replacement; Knee Biomechanics

Abbreviations

TKR: Total Knee Replacement; MA: Mechanical Alignment; KA: Kinematic Axis Alignment; NBA: Neutral Boundary Alignment; PCL: Posterior Condylar Line; TEA: Transepicondylar Axis; FSAA: Femur Sagittal Asymmetric Angle; FCAA: Femur Coronal Asymmetric Angle; FAAA: Femur Axial Asymmetric Angle; MTSA: Medial Tibial Slope Angle; LTSA: Lateral Tibial Slope Angle Difference

Introduction

The knee joint is a complex mechanism involving the interaction between the soft tissue structures and the bony/cartilaginous surface anatomy. Total knee replacement (TKR) is a successful treatment option for patients with end-stage knee osteoarthritis. The goal of TKR is to provide a stable and functional knee. Reconstructing natural knee mechanics is still an open question due to limitations with implant design and surgical technique. Overall, there are two major philosophies in TKR, including measured resection techniques to achieve mechanical alignment (MA) and gap balancing techniques which are more in line with kinematic axis alignment (KA) [1,2]. Many surgeons prefer a combined approach with varying degrees between the two alignment techniques. Recently, we proposed an alternative alignment technique called Neutral Boundary Alignment (NBA) [3]. The goal is to reconstruct the joint line parallel to the ground while in the single leg stance, while accounting for knee stability. This alignment, however, is not arbitrary and relates to the surface characteristics of the distal femur and proximal tibia. Indeed, knee motion is governed by the knee surface just as a bearing is based on its surface, but the knee is further guided by the passive mechanisms of the ligament attachments and patellar tendon. As this is the case, a "flexion" axis is difficult to define. We assert that understanding the surface characteristics of the knee and passive stability afforded by the ligaments are helpful in TKR planning, especially in the era of advanced imaging assisted pre-operative planning techniques.

We therefore propose to describe important surface characteristics of the knee using an elliptical cam model for the distal femur as a master input and those of patella and tibial plateau as followers. We demonstrate that the surface characteristics of the distal femur and proximal tibia have areas of asymmetry between the medial and lateral condyles that vary between individuals. This asymmetry is not related to varus/valgus angle, but it is important in their knee mechanism and is functionally related to knee rotation in concert with epicondyles. We explore the measures of asymmetry found in the knee and make suggestions for their role in the knee mechanism.

Methods

Study sample

This study assesses the surfaces characteristics of the femur and tibia with the assistance of de-identified MRI images of 26 non-arthritic knees obtained from human volunteers. MRI images of the knee, as well as scout images of the ipsilateral hip and knee were assessed. These images were viewed and analyzed using Insight Toolkit Software (ITK open-source software [4]). Images were re-oriented using ITK software and were subsequently analyzed for femoral and tibial surface characteristics. Of note, all the measurements and analyses in this study are based on the cortical bone formation of the distal femur and proximal tibia, as opposed to the cartilage surface anatomy. Also, it is noted that the measurement uncertainty is within +/- 0.5 degrees due to physical characteristics of MRI.

Defining the three knee axes

The analysis described herein is dependent on three axes of orientation, which are defined in the coronal, sagittal and axial planes. MRI images are oriented and formatted according to these axes. The coronal axis is oriented parallel to the Neutral Boundary Alignment (NBA) axis as previously described (Figure 1(a)) [3]. The axial axis is oriented parallel to the posterior condylar line (PCL) (Figure 1(b)). The sagittal axis is oriented perpendicular to the femoral mechanical axis in the sagittal view (i.e., center of the femoral head to the center of the knee in the sagittal plane) (Figure 1(c)).

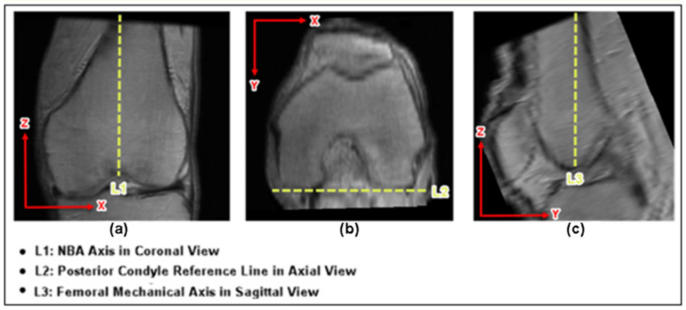

Figure 1: Illustration of the three axes used to define the model. (a) NBA axis in the coronal plane. (b) Axial plane oriented parallel to the PCL. (c) Sagittal plane oriented perpendicular to the femoral MA.

Distal femur surface modeling

The distal femur has three important articulations: 1) the medial femoral and tibial condyles; 2) the lateral femoral and tibial condyles; and 3) the patella within the trochlea. In our foregoing analysis, these articulations are geometrically modelled with circles that are tangential to the radius of curvature of these surfaces (Figure 2). We start by fitting a circle to the medial femoral condyle (Figure 2(a)) and a circle to the trochlear groove (Figure 2(b)) in the sagittal plane. Similarly, a circle is fit to the lateral femoral condyle, which nearly overlaps that of the medial femoral condyle. These circles are noted to have a nearly equivalent radius of curvature and center points (Figure 2(c)). It is also observed that the centers of these circles have a close relation to the medial and lateral epicondyles (Figure 2(d)), respectively, which may correspond to the positions of the MCL and LCL (5). These circles are used to create an ellipse that the center points of the two circles are the focal points of the ellipse with eccentricity of ~0.25. From this ellipse, we create an elliptical cam model, which is used to model the articulations of the femoral condyles and the trochlear groove (Figure 2(e)). This elliptical model is illustrated in Figure 3(a). This model may be used to describe knee flexion when used as a master input and the patella and tibia surfaces as followers (Figure 3(b)). However, femoral and tibial condylar anatomy differs between individuals with differences in femoral and tibial condyle asymmetry, as well as the position of the epicondyles. These differences affect the mechanism of the elliptical model and are detailed below.

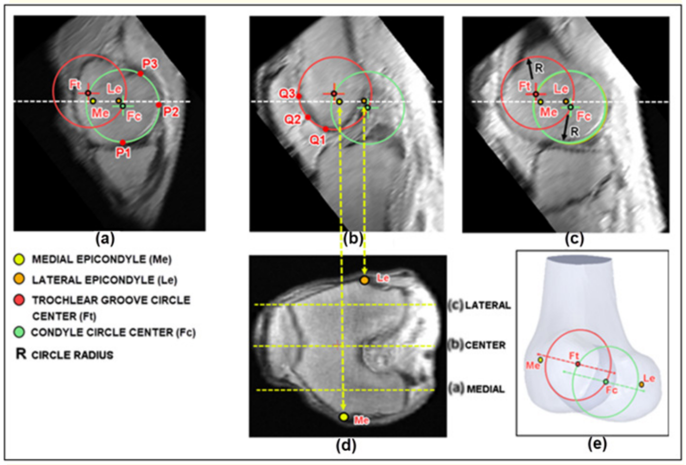

Figure 2: Geometrical representations of the trochlear groove and medial condyle. (a) Approximation of the surface characteristics of the medial femoral condyle based on a point at the distal medial femoral condyle point (P1), a point at the posterior medial femoral condyle (P2) and a third point representing the deepest point of flexion (P3). A circle is aligned to these three points which has a center point Fc. (b) Approximation of the surface characteristics of the trochlear groove based on three points Q1, Q2, and Q3. Another circle is aligned to these three points. (c) The two geometric circles define center points Fc and Ft and an equivalent radius (R). The two circles have center points that are separated by radius, R. (d) The centers of the circles align with the epicondyles in the axial plane (i.e., Fc aligns with the lateral epicondyle and Ft aligns with the medial epicondyle). (e) An ellipse generated from the circles forms the basis for the elliptical model of the distal femur.

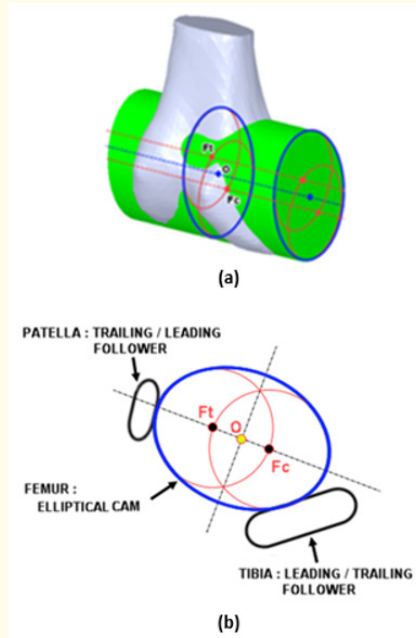

Figure 3: (a) Three-dimensional representation of the elliptical cam model of the distal femur. (b) The elliptical cam model illustrated as a master input with the patella and tibia and followers dictating knee motion.

Measures of femoral and tibial asymmetry

To identify unique characteristics of femoral and tibial anatomy that affect the elliptical cam model, we identify three anatomical surface relationships on the distal femur and two relationships on the proximal tibia. These are used to highlight differences in surface anatomy between individuals. For the distal femur, the relationships are as follows: 1) the femur sagittal asymmetric angle (FSAA, angle μ) representing the surface profile asymmetry between the medial and lateral condyles in the sagittal plane (Figure 4(a)); 2) the femur coronal asymmetric angle (FCAA, angle α) angle representing the angle formed by the distal condyles and the NBA in the coronal plane (Figure 4(b)); and 3) the femur axial asymmetric angle (FAAA, angle β) representing the angle formed by the PCL and the transepicondylar axis (TEA) in the axial plane (Figure 4(c)). The FSAA (angle μ) is found by inspecting the circle that is tangential to the medial condyle and the corresponding circle about the lateral condyle (Figure 4(a)). The circle circumscribing the medial condyle remains tangential from the posterior aspect of the femoral condyle to the distal aspect. The circle circumscribing the lateral condyle only remains tangential through the posterior aspect of the femoral condyle (the converging point PC in figure 4(a)) but is no longer tangential at the distal aspect. The portion of the circle that is not tangential to the distal aspect of the medial condyle is denoted the FSAA (angle μ, Figure 4(a)). The other two angles are more evident and are as described above. These angles are measured in the study population here to assess the range of asymmetry between individuals.

For the proximal tibia, the two anatomical surface characteristics we highlight are the following: 1) the medial tibial slope angle (MTSA, angle ψ) which is the angle of the medial tibial slope vs the NBA in the sagittal plane (a line parallel to ground in the sagittal plane, Figures 4(d)-(e)); and 2) the lateral tibial slope angle differ-

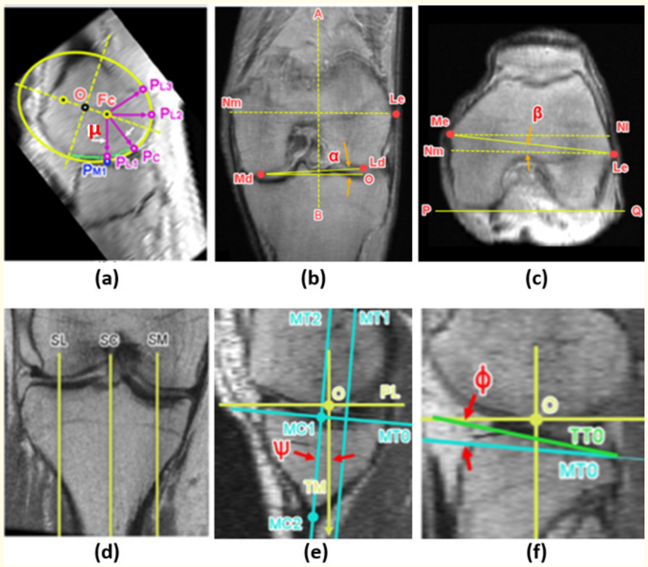

Figure 4: Measures of femoral and tibial asymmetry (a) The FSAA (angle μ) represents the portion of the lateral femoral condyle contour that is not coincident with the medial femoral condyle, which is highlighted by the dashed green line. The ellipse is coincident with points P_c, P_{L2}, and P_{L3} along the lateral femoral condyle and not coincident from points P_{m1} to P_c. This asymmetric portion of the lateral femoral condyle is measured as angle μ. (b) The FCAA (angle α) represents the angle between the NBA and the joint line defined by the distal femoral condyles in the coronal plane. It is defined by lines M_d-O and M_d-L_d. (c) The FAAA (angle β) represents the angle between the TEA and the PCL and is defined by determining the angle between lines M_e-L_e and P-Q. (d) Sagittal cuts along the tibia where the MTSA (angle ψ) and the LTSA (angle φ) are measured. (e) The MTSA represents the angle of the medial tibial slope (line MT_0) with the NBA in the sagittal plane (line PL). (f) The LTSA represents the difference between the MTSA and the lateral tibial slope, which is the angle between lines MT_0 and TT_0.

ence (LTSA, angle φ) representing the angle between the medial tibial slope and the lateral tibial slope in the sagittal plane (Figure 4(d), 4(f). The LTSA highlights the asymmetry between tibial condyles which also varies between individuals.

Statistics

Relationships were determined by Pearson correlation and linear regression analysis using MS Excel (Microsoft, Redmund, WA).

Results

Femoral asymmetricity

The sample population we explored demonstrated a range of varus/valgus angles from 2.1° varus to 1.7° of valgus (Table 1). Within this population, we found that the measures of femoral asymmetry between the medial and lateral femoral condyles were: FSAA (angle μ) of 36.2 ± 12.4° [11°, 55°] (Figure 4(a)), and the FCAA (angle α) of 2.5 ± 1.1° [0.5°, 4.2°] (Figure 4(b), Table 1). Note that an angle μ and α measure of 0° would represent perfect symmetry between the medial and lateral femoral condyles. Interestingly, we found that there was no relationship between varus/valgus angle and these measures of asymmetry (v/v angle vs angle μ p-value = 0.191; v/v angle vs angle α p-value = 0.239). Notably, we found a strong relationship between angle μ and angle α (Pearson corr = 0.94, p-value < 0.001, Figure 5(a)). Linear regression analysis demonstrates that when angle α goes to zero, angle μ goes to about 8°. Thus, even when the femoral joint line matches the NBA (i.e. joint line parallel to the ground), there would still be surface asymmetry between the medial and lateral condyles, albeit small in magnitude.

We also measure the TEA in relation to the PCL, which we notate as FAAA (angle β) (Figure 4(c)). Within our study population this angle averages 5.5 ± 1.2° [3.3°, 7.1°] (Table 1). The FAAA represents the relationship of the epicondyles with the posterior femoral condyles, and subsequently Whiteside's line. Notably, angle β is not correlated with v/v angle (p-value = 0.303). However, angle β does correlate with angle α (Pearson coef = 0.95, p-value < 0.001, Figure 5(b)) and angle μ (Pearson coef = 0.90, p-value < 0.001), which demonstrates that the orientation of the medial and lateral epicondyles relates to the asymmetry in of the medial and lateral femoral condyles. Of note, linear regression analysis demonstrates that as angle α goes to zero, angle β goes to about 2.8° (i.e. the relationship of the TEA to the PCL when the joint line is parallel to the ground), which is similar to the conception that the relationship between the PCL and TEA is about 3° that is commonly used in TKA surgery [5].

Tibial slope asymmetricity

Measures of tibial slope asymmetry were the MTSA (angle ψ, the medial tibial plateau slope angle, Figure 4(e)) and the LTSA (angle φ, a comparative angle between the medial and lateral tibial slopes, Figure 4(f)). Angle φ is the main measure of tibial plateau

	V/V	α	μ	β	ψ	φ
Ave	0.3	2.5	36.2	5.5	3.3	1.4
Std	1.0	1.1	12.4	1.2	1.1	1.4
Min	-1.7	0.5	11	3.3	1.5	0.2
max	2.1	4.2	55	7.1	5.8	5.3

Table 1: Varus/Valgus angle and measures of asymmetry for the 26 knees analyzed.
Unit: degree.

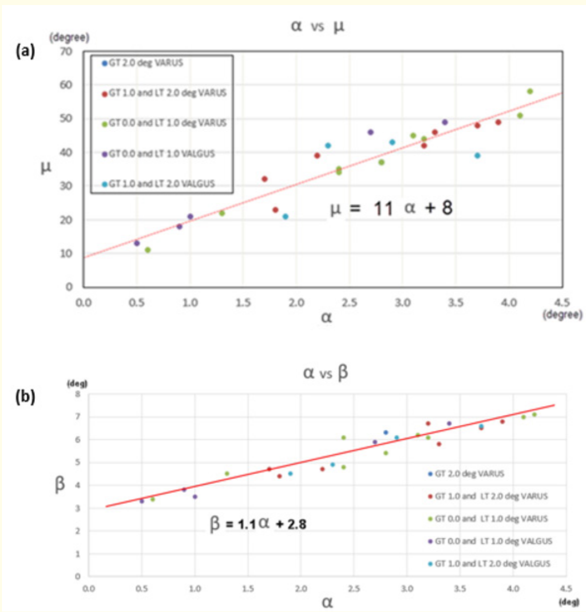

Figure 5: (a) Relationship between FSAA (angle μ) and angle FCAA (angle α). (b) Relationship between FAAA (angle β) and angle FCAA (angle α).

asymmetry. There was no correlation with v/v angle and angle ψ (p-value = 0.168) or angle φ (p-value = 0.164). The average angle ψ was 3.3 ± 1.1° [1.5, 5.8] and the average angle φ was 1.4 ± 1.4° [0.2, 5.3] (Table 1). There was no relation between the two measures (p-value = 0.784). When comparing angle α with angle φ (i.e. distal femoral asymmetry vs proximal tibia asymmetry, we found an interesting relationship (Figure 6). Linear regression analysis found that there were two linear relationships with a breakpoint at angle α at 3° (Figure 6). This relationship demonstrated that as angle α increases beyond 3°, tibial plateau asymmetry suddenly and sharply increases at rate of 3.1° per every degree increase in angle α. The relationship could also be modeled by the sigmoid activation function as shown in figure 6.

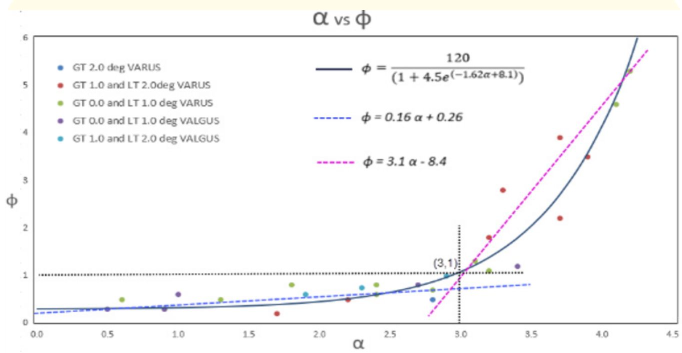

Figure 6: (a) Relationship between LTSA (angle φ) and angle FCAA (angle α).

The relationship between angle α and angle φ is further illustrated with three case examples in figure 7, which not only shows the medial and lateral tibial slope differences of the three cases, but also a comparison of the shapes of medial and lateral cartilage. Case #1 shows an example knee with angle α = 0.5° (i.e., < 3°). In this case, angle φ is 0.3° and is nearly symmetric, which can be observed with an overlap of the medial and lateral tibial condyle contours when overlayed on each other. In cases #2 and #3, angle α is > 3° and angle φ is 3.9° and 5.3°, respectively. Note that lateral condyle is higher in comparison to the medial condyle in the illustrated overlay. It is further observed from these illustrations that posterior aspects of the medial and lateral tibial condyles converge for each case.

Discussion

Theoretical consequence of the knee surface geometry model

Knee motion is governed by the connectivity between the patella, distal femur, and proximal tibia, which we propose can be summarized by the characteristics of the elliptical cam model and

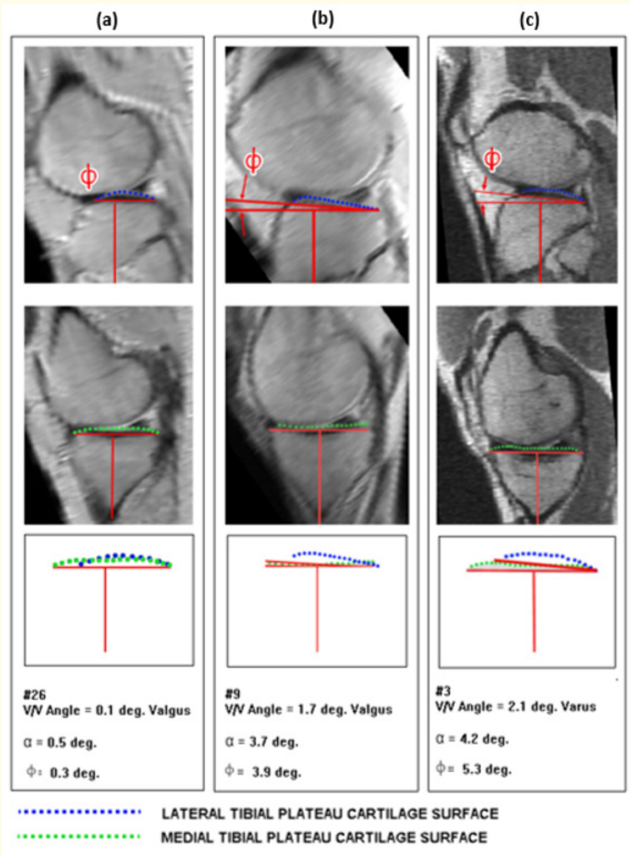

Figure 7: Three case examples illustrating relationship between angle α and angle φ. (a) Case example when angle α < 3°, where the tibial medial and lateral plateaus remain roughly symmetric. Case examples when angle α > 3° and subsequent tibial plateau asymmetry.

the asymmetric parameter angles α, β, μ and φ (Figures 3, 4). These asymmetric parameters illustrate unique contact characteristics of the femoral and tibial condyles, as well as the orientation of the epicondyles, and consequently the MCL and LCL [6]. Accordingly, at the start of knee flexion, the tibia works as a leading follower (i.e., the main force acting upon the elliptical cam), and the patella works as a trailing follower (i.e., the elliptical cam is the force acting on the patella) (Figure 3). Furthermore, the line perpendicular to the NBA axis and parallel to the PCL at the center of the ellipse represents a “flexion” axis. This model also indicates the trochlear groove has a nearly one-to-one relation with the femoral posterior condyles. Along the flexion axis, the distal femur concurrently controls both patella tracking motion on the trochlear groove and femoral condyle motion on the tibial plateau (Figures 2(c) and 3(b)). Therefore, the accurate estimate of V/V angle with respect to PCL has a direct relation to the patella tracking motion in pre-operative planning.

In its most basic form, the elliptical cam model is symmetric; hence, in this form it can only explain knee flexion. Condyle asymmetry enables knee rotation which is likely important for structural stability. At full extension, MCL and LCL tension, along with the asymmetric condyle angles α and μ for the femur and angle φ for the tibia, are factors that initiate and guide femoral rotation on the tibia. The orientation of the medial and lateral epicondyles induces knee rotation by transverse forces exerted by MCL and LCL as a secondary restraint to knee rotation to provide the full extension stability with the longitudinal force of MCL as the primary responder to valgus stress. As angle α increases, angle β also increases (Figure 5(b)), resulting in an increase of rotational force. Knee rotation is also restricted by the posterior cruciate ligament in knee full extension. The major physical role of the epicondyles could be tension control of MCL and LCL to assure the full extension stability and smooth flexion until the patella ligament takes over for further knee flexion.

When angle α > 3.0, the lateral tibial slope exhibits a sharp increase with respect to medial slope (Figure 6). Theoretically, this means that when the knee flexes, the lateral condyle causes higher translation rate of the lateral femoral condyle compared to medial condyle while sharing the same amount of flexion because lateral tibial slope is higher compared to the medial tibial slope. The translation rate difference induced by the lateral and medial tibial slopes also induces the knee rotation. Furthermore, as knee flexes past the Medial–Lateral Condyle Converging Point Pc (Figure 4(a)), knee motion becomes close to cylindrical motion, because the posterior condyles of the lateral and medial femoral condyles are nearly symmetric. From this point onwards, the patella becomes the leading follower due to increasing patellar tendon tension. This leads to further rotation induced by the patella force with the posterior translation of the lateral femoral condyle being restricted by the anterior cruciate ligament, which occurs until maximal knee flexion [7]. Also, it is noted that the trochlear groove channel exhibits the converging characteristic from the full extension to the medial-lateral converging point (P_c) [8].

Implications for TKAs

There are several important implications for TKA we suggest for the elliptical cam model and surface analysis of the knee presented here.

- If TKR preoperative planning is consistent with the elliptical cam model presented in this paper, then the patient's anatomical alignment, V/V angle, can be closely restored. Femoral component positioning in uncomplicated and primary TKA should not only be based on knee stability (within varus/valgus 3 degrees of MA) but also attempt to significantly minimize or even eliminate the ligament balancing procedure. Therefore, knee implant design and its surgical positioning should be carefully done with soft tissue interaction to achieve a consistently high degree of knee flexion since the knee system has a delicate passive mechanism that is controlled by the tensions of MCL and LCL in harmony with knee surface physical characteristics.
- Considering the range of the femoral coronal asymmetric angle (angle α) in conjunction with lateral and medial tibial slope angle difference (angle φ), it can be assumed that with α less than 3 degrees, a symmetric implant would be an appropriate choice. Whereas when α is greater than 3 degrees, an asymmetric implant with 3 degrees distal asymmetricity would be a logical choice.
- We propose that the NBA approach can be a common denominator of MA and KA. The derivation of NBA theoretically starts with establishing MA, and the restoration procedure follows on the arthritic knee. The advantage of NBA compared to MA is that if arthritic knee is analyzed to be an outlier of either varus or valgus, NBA can provide information of varus or valgus outlier resections for both femur and tibia. Otherwise, within approximately +/- 1° varus/valgus knee, NBA is nearly identical to MA. Conversely, when the coronal asymmetric angle (FCAA) is small (angle $\alpha << 3°$.), NBA resections are very similar to KA since KA is fundamentally close to a resurfacing approach. Also, both NBA and KA share the common goal of ligament balanced resection. Thus, both methods attempt to significantly minimize or even eliminate the ligament balancing procedure. An example of TKA using NBA approach is shown in figure 8.

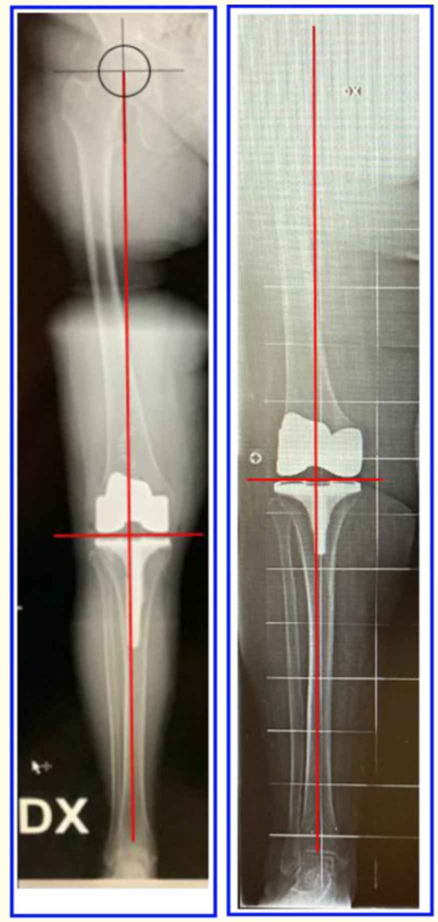

Figure 8: TKA alignment based on NBA demonstrating restoration of patient V/V alignment and joint line parallel to ground, while finding a common denominator between MA and KA.

The main limitation to our analysis is that we included only 26 non-arthritic knee MRI images of Hip, Knee, and ankle. However, our study is not meant to be an exhaustive epidemiologic study of knee measurements. Rather, we used these knee MRIs to illustrate the differences and relationships found in knee asymmetry to complement the understanding of the consequences of the elliptical cam model. Still, more research should be done in the future, and a better model can be developed to better explain knee motion of flexion, rotation, and translation in conjunction with soft tissue interaction. Also, it is important to conduct research on the nature of the asymmetric characteristics of the distal femur in conjunction with the subtle cartilage surface profiles of medial and lateral tibial plateau.

Conclusion

In conclusion, based on the NBA approach, our model demonstrates that while the lateral and medial condyles are asymmetric, portions of the condyles remain symmetric. The model helps to define the segment of lateral condyle asymmetry that varies per individual. This asymmetry is believed to affect early knee flexion and rotation, along with the tension produced by the MCL and LCL. We further demonstrate the position of the epicondyles also correlate with condyle asymmetry, which are each related to the relative positions of the MCL and LCL. We further show that surface asymmetry does not correlate with varus/valgus knee angle. Understanding characteristic surface asymmetry may be important for TKA surgical planning and future implant design.

Conflict of Interest

LD reports stock ownership with Lento Medical, Inc. IP reports stock ownership with Lento Medical, Inc.

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