Femoral and tibial malrotation in total knee arthroplasty: Causes and cures

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ABSTRACT

Prothetic malrotation is an important surgical error that can lead to patellar subluxation, chronic ligamentous instability, and a painful outcome after total knee arthroplasty. Importantly, Berger et al. [1] demonstrated that a femoral/tibial combined error of 7°-17° internal rotation was associated with patellar subluxation and patellar prosthetic failure [2,3]. Determining the rotation of the femoral and tibial components can be accomplished by direct anatomical landmarks or the use of indirect tensors [4-11]. Appropriate instruments are then used to create the flexion gap. The final goal is an articulation that is comparable to the normal state both in terms of the anatomical position of the resurfacing implants and the carefully adjusted ligamentous condition. These methods are well known but the potential for errors is less acknowledged. A careful description of the known anatomical issues will be made to allow the reader to understand the optimal choices. Additionally, the precision of the surgical techniques will be considered and what the surgeon may expect.

Recent methods have attempted to make surgical implantation more efficient and to create a more natural prosthetic implantation. This could include the use of patient-specific cutting guides and the kinematic method that attempts to restore the natural position of the joint line as opposed to the choice of the limb mechanical axis that reduces the joint line by approximately 3°. The kinematic method chooses an equal cut of the posterior femoral condyles [12,13]. Current computer navigational schemes utilize imageless registration with the combination of reference acquisition and may be combined with ligament tensors. In the future, navigation systems will rely on intra-operative digital imaging acquisition for precision.

Correction of implant rotational errors requires the surgeon to identify the malrotation problem. An axial computed tomography scan of the knee is the best method to study the position of the implants in relation to the anatomical targets. This is supplemented by a careful ligamentous evaluation where the surgeon attempts to identify abnormal gaps that may affect the flexion gap. The final decision for repair is based on a full understanding of the combination of problems [14]. To me, it would be intuitive to address the problem from the front end, and use the CT and the ligament balancing technologies that are currently available, to avoid these problems with improved surgical technique.

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I will define these technologies and project how we may improve current methods with this approach.

1. Femoral anatomical factors

Many years ago, I performed a very simple experiment to determine the relationship of the transepicondylar axis to the kinematics of the knee. A friend and colleague, Rick Komistek PhD, built me a very simple frame that allowed me to place a pin across the transepicondylar axis (Fig. 1). I then used several cadavers to move the leg through the range of motion recording the position of the center of the hip joint compared to the center of the talar dome. The results predicted that the transepicondylar axis performed well as a kinematic center of the total knee reconstruction [10]. As the knee moved into flexion, the longitudinal axis of the tibia remained virtually perpendicular to the TEA. With a cadaver study, the mean mechanical axis was 0.4° of varus in extension and 0.43° of varus at 90° of flexion. In addition, the TEA was virtually in the center of the lower extremity from the center of the hip joint to the center of the ankle joint. This study then led to the idea of the “tibial shaft axis” as a method for defining correct femoral rotation [11]. Basically, by aligning the axis of the tibia perpendicular to the TEA, appropriate femoral rotation was accomplished.

Conventional wisdom proved that methods creating a neutral limb axis or “mechanical axis” from the center of the hip joint to the center of the talar dome were more reproducible for conventional surgical instrumentation of the day. However, this maneuver required moving the joint line 3° from the anatomical state placing the tibial surface cut perpendicular to the mechanical axis. While there was a small enclave of surgeons who believed that the anatomical approach of preserving the natural joint line may be a better option, the potential for outliers made this approach somewhat risky for an exaggerated varus deformity that surely led to an early failure. As we will see that anatomical method is attractive from a kinematic point of view and may offer a better option for balancing the ligaments of the knee through the range of motion.

To use the transepicondylar axis as a surgical guide, the surgeon must choose a definite point on the medial and lateral epicondyle. This is fairly straightforward on the lateral side if it can be identified but is variable on the medial side. One may pick the most prominent point of the medial epicondyle or the deepest point of the sulcus of the medial epicondyle that represents the “surgical” epicondylar axis [7]. While many studies have evaluated how accurate this could be, the fact remains the reference points are not discreet enough [14-16]. Additionally, there is a significant anatomical variation of the basic landmark. From my viewpoint, this problem was proven when we attempted to perform referencing using computer navigation. The precision was clearly an order of magnitude inferior when compared with the results achieved from mechanical axis alignment using navigation. The explanation is fairly simple and requires considering the errors. Back to the basic transepicondylar frame, the trigonometry of the angles created from the center of the hip joint or the center of the ankle joint are far smaller than the angles created about the transepicondylar axis in flexion simply based on the distance, thus defining the potential precision [9]. To create 1° of error considering the mechanical axis, a point picked in the center of the knee would need to be off by 4 mm. However, an error of the transepicondylar axis to the joint line in flexion could be off by about 1 mm to create a degree of error.

The anterior-posterior axis of Whiteside is similar to the transepicondylar axis in terms of precision, at least from a number of clinical studies [14,15]. However, both the TEA and Whitesides line have persisted and remain common surgical landmarks, and I believe this can be attributed to the fact that they work very well, at least 50-75% of the time. This is because the primary error is manifested only with the flexion gap, which is not as important or noticed with normal ambulation. If one considers that all precision measures function on a bell-shaped curve, where outliers of one to two standard deviations are above the median, only cases where the flexion gap abnormal laxities would exceed 5 mm become problematic.

I have learned with cadaver studies that an interesting relationship can be determined when combining the TEA and the AP axis of the femur. If one compares the two axes and then superimposes the AP axis on the TEA, the point of intersection occurs at the roof of the intercondylar notch (Fig. 2). This then becomes an important reference point to use in computer navigation, and that is the center of the roof of the femoral intercondylar notch is at the center of the knee, but that point also coincides with the TEA (Fig. 3). Additionally, the AP axis can be found to be coincident with the AP axis of the tibia and Akagi’s Line, as will be shown below.

The flexion gap must also be considered from the viewpoint of the ligament balance issue. I have resolved the role of the medial and lateral collateral ligaments to be critical for the flexion gap creation and ultimate kinematic performance [16,17]. These structures functionally arise from the medial and lateral epicondyles, and this explains why the mechanical axis method works well. These ligaments are not changed in function by the alteration of the joint line. They must be
Figure 2 – Diagram demonstrating the relationship of the TEA, AP axis of Whiteside, and the roof of the intercondylar notch.

perfectly balanced for the flexion gap to work correctly, and this creates problems for the case that requires ligamentous release with increasing surgical deformity. Krakow has clearly shown that the contribution of all soft tissues about the knee diminishes as the knee goes into 90° of flexion, except for the collaterals that actually increase in performance. The collaterals must be preserved in flexion, or there will be severe gap instability. In the normal total knee case, that requires only modest release of the medial capsular ligaments or deep medial collateral ligament. The lateral collateral ligament rarely should be released as it provides the primary stability on the lateral side of the joint in flexion. With retention of the posterior cruciate ligament that contributes to flexion gap stability, the gap issue is minimal. This is the reason surgeons remain comfortable with the anatomical-defined resections, despite the potential for outliers and error.

I evolved to the ligament balancing method for creating the flexion gap resections and determining the rotation of the femoral component. The LCS system from which I had a great deal of experience, relied on a flexion gap balancing method following the original tenets of Insall and Ranawat, where the flexion gap was determined primarily by tensors [8]. All ligament balancing was performed at the outset of the procedure, and the final gap balancing determined by the tensor was then made precisely, allowing for the possibility of the correct rotation of the femoral component [18]. Even with documented malrotated femoral components, most surgeons had little fear of flexion gap instability, and the incidence of patellar subluxation has not been documented by surgeons using this method. However, I would mention the experience of the Boldt et al. [19] where they found stiff painful knees to be increased with exaggerated femoral internal rotation, which may occur with generous release of the medial lateral ligament.

My current experience is with a new computer navigation system, the eGPS system (Exactech, Inc.), that allows for a customization of choices for my specific surgical objectives (Fig. 4). This system features a computer the dimension of a laptop, and cameras with short field of view allowing the system to be placed in the operative field. Specialized cutting blocks have active LED trackers attached eliminating the need for independent bone fixed trackers. The 5-in-1 cutting block functions similar to a patient-specific cutting block allowing all cuts to be made from navigation of this block. However, this system allows for a ligament balancing protocol to be combined with the bone resection function. I use the tibia cut first protocol, and center my tibial cut on the anterior tibial axis that will be discussed below. Once this is done, the knee joint is placed precisely at 90° of flexion where a simple joint tensor tenses the joint to moderate “hand” tension (Fig. 5). A number of studies have evaluated this force but I would suggest that the appropriate tension could vary from 50 to 120 N.

Figure 3 – Method of referencing the “femoral center” of the knee utilizing the center of the roof of the intercondylar femoral notch.

Figure 4 – eGPS computer navigation system (Exactech, Inc.) has camera and computer that is placed in the operative field, and cutting blocks with active LED trackers attached.

Figure 5 – The critical flexion tensor step is made with a hand tensor that tenses the flexion space at 90°. This step has been shown to have sub-millimeter precision from cadaver tests. Navigation planning of flexion space is demonstrated showing the implant size, femoral external rotation, and the medial/lateral flexion gaps.
measurements have been made. The result is a complex calculation of the joint gaps, which in turn leads to the appropriate prosthetic sizing and bone resections that will create a rectangular space matched in extension and flexion.

Finally, I will mention an outlier that results when there is a combination of errors. If there is internal rotation of the femoral component, exaggerated lateral flexion gap laxity, and abnormal internal rotation of the tibial component, a “perfect” storm is created for a patellar instability and dislocation. While a knee may tolerate one of these errors, particularly with posterior cruciate retention, the combination will require complete revision of the implants (Fig. 7).

2. Tibial anatomical factors

Placement of the tibial prosthesis relies on finding the correct point of rotation in the axial plane and identifying the appropriate tibial plateau slope. The slope is important and depending on the measurement method varies from 6° to 8° in the sagittal plane. If the position of the tibial prosthesis is internally rotated on the proximally cut surface from the anatomical center of the joint surface, the limb alignment will be adjusted into varus. As will be discussed, this is one of the reasons that the anterior cortex centering point for tibial tray placement must be correct. Because of the high
Tibial Anatomical Axes (Berger)

Figure 8 - Transtibial axis, AP Axis, and Akagi's line.

variability of the anatomy, computer navigational imageless referencing has been difficult and not very helpful for this effort [20,21].

The choice of the centering point of the proximal tibia is controversial and several options have been advanced. I believe that the most common method is the choice of the medial one-third of the tibial tubercle [22,23]. Berger developed a method of finding the centering point by a calculation that first identified the sagittal plane middle point of the medial and lateral condyle of the tibial plateau, and then drawing a line connecting those two points which was defined as the transtibial axis. The transtibial axis is valuable as it should be coincident and parallel with the transepicondylar axis of the femur (Fig. 8). If the transtibial axis is bisected, the anterior extension that is perpendicular to that point is defined as the anterior axis of the tibia [1]. This line in extension should be coincident with the AP axis of Whiteside [6]. Another study has shown that Akagi’s line that connects the center of the posterior cruciate ligament and the medial margin of the patellar tendon is also coincident with the AP axis of the tibia [5]. From the literature, there does not appear to be a clear advantage of any of the above options. However, my typical surgical maneuver has been to take advantage of the above information to use the AP axis of Whiteside to simply create the AP axis of the tibia. The AP axis of Whiteside is drawn in the intercondylar groove of the distal femur with a Bovie [6]. The knee is then extended and this line translates over to a similar point on the proximal tibia (Fig. 9). That point is utilized throughout the procedure and should be the choice for the center of the plane of the proximal tibial cut. As noted above, I use that visual reference to register the anterior tibial axis with computer navigation. Finally, the implanted prosthesis should center on that point.

The kinematic evaluation of femoral–tibial rotation has demonstrated that tibial rotation of the joint is often reduced after joint replacement [24,25]. The normal knee shows internal rotation of the tibia as the knee goes from extension to flexion. However, with loss of the cruciate ligaments and other abnormalities of the knee with chronic arthritis, rotation can be in the opposite direction in a significant proportion of cases. I do not believe that a clinical problem comes from the abnormal tibial rotation after joint replacement, but it highlights the need for either a favorable articulation or a mobile-bearing tibial component to accommodate these irregularities [25].

The final issue of tibial placement, in my view, is the chronic difficulty of placing the tibial tray in the posterior-lateral corner for the typical medial parapatellar approach, if the knee is well balanced and snug. The same problem exists for the valgus or lateral approach and is magnified by the greater soft tension resulting from the mild valgus angle of the leg. The typical surgeon’s error is to inadvertently internally rotate the tibial tray from the desired position because of this problem. To counter outliers, I favor a mobile-bearing tibial prosthesis and often find that the tibial tray position should have been placed more external in position. However, the problem is adjusted or accommodated by the ability of the tibial insert to rotate externally, and I find this commonly [20] (Fig. 10).

3. Future digital technology in total knee replacement

An important consideration for solving the problem of outliers in total knee replacement is the potential of newer technologies to improve surgical technique. For femoral and tibial rotation errors, computer navigation and digital registration offer the potential for improving the precision, both of the implant position and ligament balancing techniques. Heyse and Tibesku [26] demonstrated the potential of pre-operative digital registration with the creation of patients

Figure 9 - (A) Bovie line is drawn over the Whiteside AP axis of the femur with the knee flexed. (B) Knee is extended and the line continues to the AP axis of the tibia.
Figure 10 – Mobile-bearing tibial insert demonstrates external rotation compared to the rotation stop, which should normally center on the insert. This results from inability to push tray into the posterolateral corner of the tight knee.

Figure 11 – D/CT Carm with integrated computer navigation system (Prototype, University of Grenoble Robotics Laboratory, Grenoble, France).

specific cutting blocks. He was able to show that the outliers of greater than 3° from the neutral TEA axis using MRI for femoral component rotation were reduced from 22.9% with conventional instrumentation and direct resection anatomical references to 2.2% with patient-specific guides. The ability to assess axial images from preoperative MRI and computed tomography scans clearly exceeds the ability to pick visual landmarks in the intra-operative setting [27–29]. We also know from prior experience that CT scan guided referencing as utilized with acetabular component computer navigation, though quite tedious for the surgeon, offered reproducible and precise referencing [30]. We have learned that ligament balancing with optical computer navigation is highly precise on the order of 3–500 μm, offering the surgeon the ability to check the ligament gaps throughout the range of motion [17]. Systems such as the eGPS have produced an efficient, yet elaborate scheme for combining the process of bone resection with ligament balancing at an early intra-operative planning stage of the procedure. Finally, the potential of combining digital imaging in the operating room with computer navigation is well known, though the current systems, such as the Medtronic Oarm, have proven cumbersome and remain limited to spinal surgery [31]. Placement of pedicle screws in cases of complex spinal deformity is difficult for the surgeon, and the use of digital imaging has been regarded as the state of the art for treating these cases.

I can envision technology improvements where high-quality three-dimensional imaging can be combined with computer navigation in the operating room to solve virtually all of the problems noted above. Digital imaging solves the precision issue of registration as “pixel” accuracy (about 17 μm) of the image reference has been available for many years, beginning with the Robodoc system of the early 1980s. Adequate computed tomography can be done in the operating room during the operative procedure with existing technologies. The CT scans can be dumped into DICOM files that can be transferred to a computer navigation system, or the scans can be directed into an integrated navigation system. An example of such a system is the 3D/CT Carm with an integrated computer navigation system (Prototype, University of Grenoble Robotics Laboratory, Grenoble, France) (Fig. 11). Ultimately, the surgeon will have control of all variables of the surgical procedure, including the appropriate placement of implants for optimal axial plane rotation and the final ligament balancing of the flexion space. For surgeons who prefer the use of flexion space sensors to guide the femoral anterior–posterior cuts, this may be planned and assessed during the operative procedure and before the cuts are completed. The surgeon will be able to assess the potential of an implant to match basic normal anatomy of the patient. We know from current literature the mid-flexion laxity possibly may result for variations in optimal prosthetic shape and joint line alteration, as well as limitations with appropriate ligament balancing. These concerns may be addressed with future technologies.

REFERENCES

[1] Berger RA, Crossett LS, Jacobs JJ, Rubash HE. Malrotation causing patellofemoral complications after total knee


