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Coronal Plane Stability Before and After Total Knee Arthroplasty

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The success of total knee arthroplasty depends in part on proper soft tissue management to achieve a stable joint. It is unknown to what degree total knee arthroplasty changes joint stability. We used a surgical navigation system to intraoperatively measure joint stability in 24 patients undergoing primary total knee arthroplasty to address two questions: (1) Is the total arc of varus-valgus motion after total knee arthroplasty different from the arc of varus-valgus motion in an osteoarthritic knee? (2) Does total knee arthroplasty produce equal amounts of varus/valgus motion (ie, is the knee "balanced")? We observed no difference between the total arc of varus-valgus motion before and after total knee arthroplasty; the total amount of motion was unchanged. On average, osteoarthritic knees were "unbalanced" but were "balanced" after prosthesis implantation. We found a negative correlation between the relative amount of varus/valgus motion in extension before and after prosthesis implantation in extension and a positive correlation between how well the knees were balanced after prosthesis implantation in extension and in flexion. Our data suggest immediately after implantation knees retain a greater than normal amount of varus-valgus motion, but this motion is more evenly distributed.

Level of Evidence: Level IV, therapeutic study. See the Guidelines for Authors for complete description of levels of evidence.

Surgical navigation systems for TKA have demonstrated the ability to achieve more accurate postoperative mechanical axis alignment of the limb[3,5,18] and reduce outliers[20,23,41,51] compared with traditional instrumentation. In addition to improving surgical accuracy, navigation systems are valuable research tools and have been used to investigate knee kinematics,[10] soft tissue balancing,[30,53] and surgical technique[48,49] in cadavers. The principal advantage of using a navigation system as a research tool is the ability to make measurements in the operating room, where researchers are able to investigate an individual surgeon's technique during the procedure, characterize the functional properties (eg, kinematics, stability) of a diseased joint, and measure how the surgical procedure immediately changes those properties. DiGioia et al[9] provided an early example of using navigation as a research tool when examining the effects of patient positioning and pelvic motion on the alignment of the acetabular component during THA. Other researchers have used navigation systems to intraoperatively measure passive knee kinematics.[26,47]

Perhaps no aspect of TKA could benefit more from accurate intraoperative measurements than soft tissue balancing to ensure proper stability. Knee stability can be defined by two distinct regions, laxity and stiffness,[31] and is influenced by several factors. Knee laxity, or "looseness," can be characterized by relatively large amounts of joint motion when relatively small loads are applied to the limb. Conversely, knee stiffness can be characterized by relatively small amounts of joint motion under relatively large applied loads. In a native joint, knee stability is maintained by the menisci, cruciate, and collateral ligaments, and the joint capsule.[31] Following total knee arthroplasty, stability is influenced by surgical management of soft tissues (ie, soft tissue balancing),[13,21,24,27,33,34,56] prosthesis selection,[57] prosthesis size, and femoral rotational alignment.[1,11,37,50,55]

Adequately managing (or balancing) the soft tissues is a key factor in achieving a successful operation. Postop-

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erative malalignment or imbalance of the collateral ligaments can lead to a lax joint and result in early loosening and instability, and leaving the knee too tight may cause stiffness and limited motion.[12,21,25] The severity and location of wear patterns on the polyethylene insert is also associated with knee stability from ligament balancing.[54] Instability, tightness, and wear are common causes for revision surgery.[25,35,44]

Despite the importance of stability to the success of the operation, debate exists regarding how much soft tissue balancing is appropriate. Ligament-balancing techniques may not be necessary in a mildly deformed knee if proper limb and component alignment is achieved.[43] In general, surgeons believe the knee should not be too tight and a little varus-valgus laxity should be achieved postoperatively with the ideal knee being looser in flexion than in extension and looser laterally (ie, under varus stress) than medially,[4] but little evidence supports these beliefs. Similarly, patients have reported they are more comfortable with a lax knee than with an over-tight knee.[29] Normal knees are not balanced and have more varus laxity than valgus laxity.[36,52] While many clinicians have become skilled in developing a qualitative "feel" for knee laxity or stiffness, an objective and quantitative definition of what constitutes a postoperatively stable knee does not exist.

Given this lack of an objective definition of a stable knee, perhaps it is not surprising that establishing a balanced soft tissue envelope remains a challenge that is not always achieved.[17] Part of the difficulty in achieving a stable (or balanced) knee, and in establishing an objective definition for joint stability, may be related to the fact the precise change in joint stability resulting from TKA is unknown. Sharma et al[45] reported the varus-valgus motion in joints with osteoarthritis is greater than the varus-valgus motion in healthy, age-matched control subjects, and varus-valgus motion is increased with increased severity of osteoarthritis. It remains unknown how the amount of varus-valgus motion in the osteoarthritic knee is changed or whether preoperative deformity and imbalance persists. Knee stability has important functional implications; thus, understanding how TKA changes the stability of the knee and how that change is related to surgical technique is an important step toward improving surgical reconstructions. Navigation offers the possibility of making the intraoperative measurements of coronal plane joint stability before and after TKA, allowing us to answer two fundamental questions: (1) Is the total arc of varus-valgus motion after TKA different from the arc of varus-valgus motion in an osteoarthritic knee? (2) Does TKA produce equal amounts of varus-valgus motion (ie, is the knee "balanced")?

MATERIALS AND METHODS

We prospectively recruited 24 male patients undergoing a primary TKA for treatment of advanced osteoarthritis to participate in our study. We considered differences of greater than 6° in the overall arc of varus-valgus motion and differences in varus or valgus motion from unloaded alignment of greater than 3° to be clinically relevant; this was based on the Knee Society Rating System[22] for joint laxity in which points are deducted with 6° or more of mediolateral laxity. Using these criteria, we considered a knee "balanced" when there was less than a 3° bias of either varus or valgus motion. Using those values as a base and assuming a 3° standard deviation associated with varus-valgus motion,[47] our study of 24 patients had a statistical power greater than 0.99 to detect differences in the total arc of varus-valgus motion and directional varus or valgus motion.

All patients had tricompartmental osteoarthritis. No patient had prior trauma requiring surgery to the knee or ipsilateral hip disease. Preoperatively, all patients had intact anterior and posterior cruciate ligaments clinically. In surgery, all knees had ACL fibers exiting the intercondylar notch of the femur and attaching to the tibia. Whether these fibers were attached to the femur posteriorly was not carefully evaluated. Clinically, no patient had a positive Lachmann test or anterior drawer test. All had advanced meniscal degeneration or disease resulting from previous meniscectomy or advanced osteoarthritis. Our general approach to anesthesia was a regional anesthetic—femoral and sciatic nerve blocks, plus a general anesthetic. No patient had severe deformity. Twenty patients were in greater than 2° of mechanical axis varus alignment in extension, two were in greater than 2° of mechanical axis valgus, and three were in less than 2° varus or valgus alignment. Institutional Review Board approval and informed consent were obtained for this study. The cohort of 24 patients was selected from a consecutive series of 30 subjects who met the inclusion criteria, signed the informed consent, and had surgery when the navigation equipment was available.

We measured intraoperative joint stability with a surgical navigation system.[8] This system has a linear accuracy of less than 2 mm[46] and a worst-case angular accuracy in the transverse plane of approximately 1.25°.[49] After inflating the tourniquet and exposing the knee through a medial parapatellar approach, we attached passive optical reference frames (Traxtal Inc, Toronto, Ontario, Canada) onto the anteromedial side of the distal femur and the proximal tibia. We established anatomic coordinate systems on both the femur and tibia using a previously described procedure.[47]

Measurements of knee motion occurred before any osteophytes were removed. With the knee as fully extended as possible, the resting position of the tibia with respect to the femur was recorded with the navigation system as the surgeon supported the distal tibia in one hand. We then applied varus and valgus moments to the knee by holding the distal femur in one hand and applying medially or laterally directed force to the distal tibia with the other hand. The amount of force applied was not measured but was clinically standardized to achieve what we believed to be a hard end point to movement with no slack remaining in any of the supporting ligaments. The navigation system recorded the rotation of the tibia with respect to the femur while under load. A similar procedure was performed with the knee positioned in 90° of flexion. To perform this measurement, the surgeon first flexed the knee to 90°. He then stabilized the femoral condyles with one hand and manipulated the tibia into varus and valgus with the other hand. We attempted to limit hip movement during this maneuver, but because the navigation system tracks both the femur and the tibia separately, movement at the hip did not influence the varus-valgus measurement.

We then performed the bony cuts for the TKA using the conventional mechanical instrumentation and, with the trial components in place, manually evaluated the limb for stability and balance. Flexion and extension gap spaces were evaluated with the trial components in place. All knees underwent removal of osteophytes to help achieve stability and balance. No soft tissue releases were needed in this cohort of patients. The trial components were then removed and we used the navigation system to record the position and orientation of the bone cut planes on the femur and the tibia. The navigation system was not used to guide the surgeon's actions and was only used as a measurement tool.

After cementing the final prosthetic components (Zimmer Nexgen Legacy Posterior Cruciate Substituting Knee; Zimmer Inc, Warsaw, IN), we recorded the varus-valgus motion of the knee in full extension and 90° of flexion using the previously described procedure. We then removed the reference frames from the bones and completed the surgery.

We used the paired t-test to compare the magnitudes of the arc of initial varus-valgus motion with the magnitudes of the arc of varus-valgus motion after TKA to investigate changes in the total amount of varus-valgus motion. Similarly, we used the paired t-test to analyze varus and valgus motion and to investigate differences in varus or valgus motion before and after implantation of the prosthesis. We followed the t-tests with two additional analyses. By labeling knees with a less than a 3° difference in varus to valgus motion as "balanced" and labeling knees with a greater than a 3° difference as "unbalanced," we categorized patients as having a balanced or unbalanced knee and a balanced or unbalanced knee after prosthesis implantation in both extension and 90° of flexion. After categorizing patients in this way, we used the chi-squared test to investigate whether there was a relationship between having a balanced knee and having a balanced knee following prosthesis implantation. Lastly, we examined differences in varus and valgus motion and used the Pearson correlation coefficient to determine whether there was a relationship between how well knees were balanced to how well the knees were balanced after prosthesis implantation in both flexion and extension (for instance, a knee with equal magnitudes of varus and valgus motion was perfectly balanced, but a knee with a 3° more varus motion than valgus motion would be relatively less balanced due to the varus bias). All statistical tests were performed using SPSS V14.0 (SPSS Inc, Chicago, IL) and the level of significance was set at $\alpha = 0.05$.

RESULTS

The mean total arc of varus-valgus motion following TKA was similar to the mean total arc of varus-valgus motion in the osteoarthritic knee in extension and flexion (Table 1). However, we observed a range of data: one subject exhibited 6° more motion in extension after TKA implantation, and another patient exhibited 5° less motion after implantation.

On average, TKA produced equal amounts of varus-valgus motion and resulted in a "balanced" knee. Knees in full extension (average of 4.4° ± 5.5° of knee flexion) had greater ($p < 0.001$) valgus (3.9° ± 1.7°) than varus (2.0° ± 1.2°) motion. After prosthesis implantation, we recorded similar valgus and varus motion in extension (0.7° ± 3.8° of knee flexion) (Fig 1). Likewise, in 90° of flexion, knees had greater ($p < 0.001$) valgus (2.5° ± 1.5°) than varus (0.6° ± 1.5°) motion. We recorded similar valgus and varus motion following prosthesis implantation (Fig 2). On average, we observed an increase ($p = 0.019$) in the amount of varus motion in extension and a decrease ($p = 0.011$) in the amount of valgus motion in flexion after prosthesis implantation. We found no changes in the magnitude of valgus motion in extension or varus motion in flexion (Fig 3). Having a balanced/unbalanced knee in extension was not related to having a balanced/unbalanced knee after implantation in extension (Table 2), but we did observe that having a balanced/unbalanced knee in flexion was related ($\chi^2 = 18.360$; $p < 0.001$) to having a balanced/unbalanced knee after implantation in flexion (Table 3). We found a negative ($p = 0.02$) correlation between how well balanced knees were in extension and how well knees were balanced after prosthesis implantation in extension and a positive correlation ($p = 0.011$) between how well the knees were balanced after prosthesis implantation in extension and in flexion (Table 4). Aside from these two pairings, we observed no additional relationships with how well balanced the knee was before or after prosthesis implantation.

DISCUSSION

We characterized joint stability before and after TKA and answered two questions: (1) Is the total arc of varus-valgus motion after TKA different from the arc of varus-valgus motion in an osteoarthritic knee? (2) Does TKA produce equal amounts of varus/valgus motion (ie, is the knee "balanced")?

We note several limitations. This study represents the results of only one experienced arthroplasty surgeon using

TABLE 1. Average Arc of Varus-Valgus Motion Before and after TKA

Arc of Motion	OA Knee	TKA Knee
Extension	5.9° ± 2.2°	6.5° ± 2.3°
Flexion	3.1° ± 1.8°	2.7° ± 2.3°

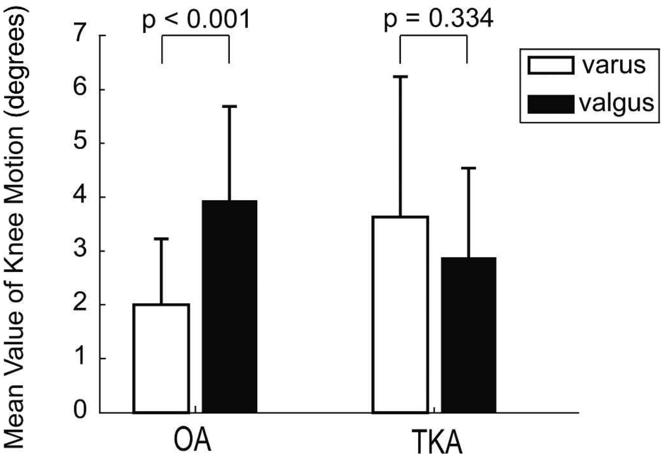

Fig 1. Mean values are shown for varus and valgus motion of osteoarthritic knees before (OA) and after (TKA) implantation with the knee in full extension. The error bars represent one standard deviation. In extension, osteoarthritic knees are not balanced but are balanced after implant installation.

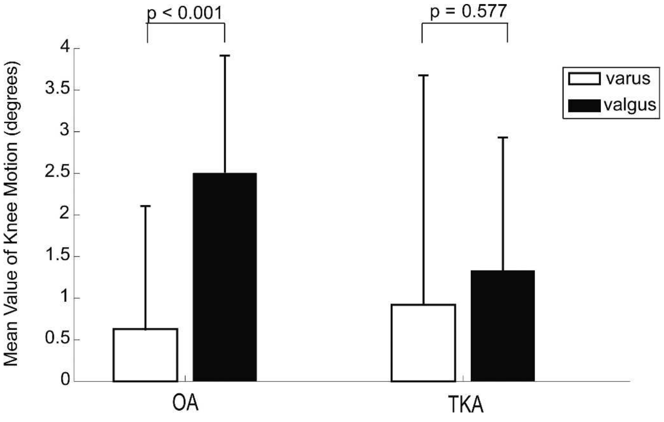

Fig 2. Mean values are shown for varus and valgus motion of osteoarthritic knees before (OA) and after (TKA) implantation with the knee in 90° of flexion. The error bars represent one standard deviation. In flexion, osteoarthritic knees are not balanced but are balanced after implant installation.

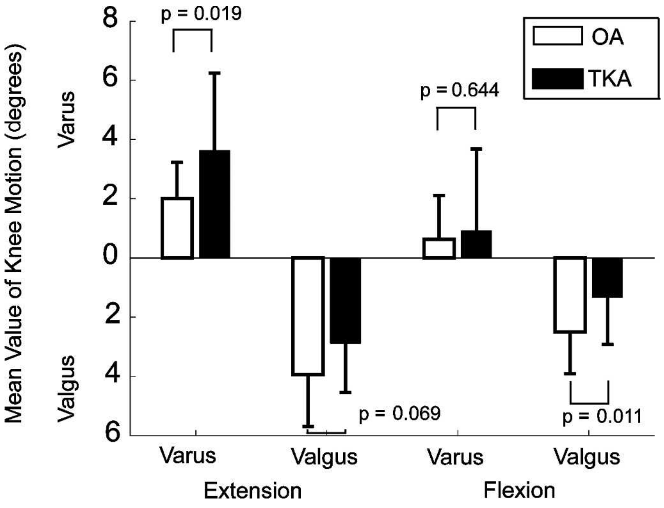

Fig 3. Mean values are shown for varus and valgus motion of osteoarthritic knees before (OA) and after (TKA) implantation in extension and flexion. The error bars represent one standard deviation. Knees displayed more varus laxity after implantation in extension. No other considerable changes in knee motion were observed.

a particular posterior cruciate-substituting TKA system in a cohort of patients who the surgeon believed did not require soft tissue releases. Different surgeons with different patients using different implants and techniques may yield different results, because different implants provide different patterns of stability.[19] Repeating the study with a posterior cruciate-retaining prosthesis could also yield different results. The posterior cruciate ligament (PCL) is a secondary stabilizer to varus and valgus motion of the knee, and previous research has shown an increase in varus-valgus motion following release of the PCL.[2,40] A different cohort of patients who require more aggressive ligament releases may demonstrate different results as would patients implanted with different posterior cruciate-retaining designs or rotating tibial platforms.

We recorded knee stability under passive manipulation. Postoperative knee stability may be different from what can be recorded intraoperatively. The methods did not account for stress relaxation, remodeling, or ligament healing that occur postoperatively into account. Bellemans et al[4] recently reported varus-valgus laxity measurements taken as soon as 30 minutes after prosthesis implantation were considerably greater than laxity measurements recorded immediately after implantation. Additionally, the knee is stabilized by not only the ligaments and the geometry of the prosthesis, but also by the muscles and tendons crossing the joint. It is not currently possible to simulate the influence of muscle contraction on knee stability intraoperatively. The comparison between intraoperative varus-valgus stability and postoperative stability, with both short- and long-term followup, warrants future investigation.

The measurement technique itself has a further limitation: the forces applied to the limb to assess stability were

TABLE 2. Frequency of Balanced and Unbalanced Knees in Extension

OA Balanced/Unbalanced	TKA Balanced	TKA Unbalanced
OA balanced	10	6
OA unbalanced	5	3

$\chi^2 = 4.33$; p = 0.228; OA = osteoarthritis

TABLE 3. Frequency of Balanced and Unbalanced Knees in Flexion

OA Balanced/Unbalanced	TKA Balanced	TKA Unbalanced
OA balanced	14	3
OA unbalanced	6	1

$\chi^2 = 16.333$; $p < 0.001$; OA = osteoarthritis

manually applied and not measured. Additionally, applying varus or valgus stress to the knee in 90° of flexion may prove challenging due to motion at the hip. Although stability was assessed by the same experienced arthroplasty surgeon with the same technique for all patients, some degree of variability in the applied forces is expected. Detailed characterizations of joint stability require an accurate means of recording both the forces applied to the limb and the resulting displacements. Because navigation systems do not generally include instrumentation to record forces, this remains an open challenge for system developers and might be accomplished through the use of a force transducer,[15] through differential variable reluctance transducers, or instrumented spacer blocks.

We found no difference between the total arc of varus-valgus motion in knees with ACLs and small flexion contractures and knees after TKA; the total amount of motion was unchanged. Additionally, we found, on average, knees were "unbalanced" (experienced unequal magnitudes of varus/valgus motion) before surgery but were "balanced" after TKA implantation, although we did observe exceptions to this general trend. Our results suggest knees immediately after implantation retain a greater than normal amount of varus-valgus motion,[45] but this motion is more evenly distributed.

Two relationships concerning joint stability warrant discussion. The negative correlation between the relative balance of a knee in extension before prosthesis implantation and the relative balance of the knee following implantation suggests that if an OA knee is relatively balanced, or biased, in one direction in extension, it will likely be biased in the other direction after prosthesis implantation. For instance, an OA knee that has more preoperative varus motion is likely to have more valgus motion after prosthesis implantation. Due to this relationship, it might be possible to preoperatively predict if a knee will be balanced after TKA and tailor a soft tissue release protocol to a certain level of preoperative stability. Although release patterns for different levels of bony deformity have been presented previously,[7,28,43] we are unaware of any release pattern specifically related to the level of ligamentous balance in the osteoarthritic knee. Additionally, without soft tissue release, how well balanced a knee is in extension after implantation appears positively related to how well balanced the knee is in flexion. This suggests that if it is possible to accurately balance the joint in extension or in flexion, then the knee will likely be balanced at other flexion angles. This emphasizes one cannot simply balance the knee in extension, for example, without simultaneously impacting the level of balance in flexion. Future research should explore these relationships in greater detail.

We observed differences in stability in flexion and extension. The arc of motion was smaller in flexion than in extension for both the osteoarthritic knee and the knee following prosthesis implantation. Additionally, following prosthesis implantation, approximately nine of 24 (37%) patients were unbalanced in extension and four of 24 (16%) patients were unbalanced in flexion. There are a few possible explanations for this occurrence. Different structures and different parts of the collateral ligaments come into play at different degrees of knee flexion to stabilize the joint, so it is possible performing a TKA without ligament balancing affects the collaterals differently. In addition, as discussed previously, the varus-valgus moment that can be applied in extension is probably greater than the varus-valgus moment that can be applied at 90° of flexion due to motion at the hip. Since we did not quantify the force that was being applied, this measurement error, although consistent for all patients, may have affected our results. Future research should explore the differences in varus-valgus motion in extension and flexion and why more subjects following TKA presented with an unbalanced knee in extension than in flexion.

TABLE 4. Correlations Between OA and TKA Soft Tissue Balance

OA and TKA Balance	OA Relative Balance		TKA Relative Balance	
	Extension	*Flexion*	*Extension*	*Flexion*
OA relative balance in extension	R = 1	R = −0.115 p = 0.585	R = −0.471 p = 0.02*	R = −0.368 p = 0.077
OA relative balance in flexion	R = −0.115 p = 0.585	R = 1	R = 0.119 p = 0.579	R = 0.145 p = 0.500
TKA relative balance in extension	R = −0.471 p = 0.02*	R = 0.119 p = 0.579	R = 1	R = 0.509 p = 0.011*
TKA relative balance in flexion	R = −0.368 p = 0.077	R = 0.145 p = 0.500	R = 0.509 p = 0.011*	R = 1

*$p < 0.05$; OA = osteoarthritis

Both balanced and unbalanced knees occurred with consistent surgical technique. Postoperatively, the knees were in 0.9° ± 3.0° of mechanical axis varus in extension (range, 5° varus to 6.5° valgus) and the femoral components were externally rotated and average of 2.9° ± 3.8° with respect to an intraoperatively digitized epicondylar axis (range, 5.2° internal rotation to 8.7° external rotation). We did not find a relationship between limb alignment or rotational alignment of the femoral component to either the total arc of varus-valgus motion or directional varus-valgus motion of the knee after implant installation. Our findings concerning femoral rotational alignment agree with those of Romero et al,[39] who also found femoral rotational alignment did not affect varus-valgus laxity in full extension or in 90° of flexion. Although the surgical goals of establishing proper mechanical axis alignment and proper rotational alignment of the femoral component were achieved in this study, these factors alone did not always lead to a balanced joint. These data suggest proper alignment alone may not be a sufficient condition to consistently establish a balanced knee.

Navigation systems could be used in conjunction with computer simulations. Previous biomechanics research has used computational models to examine the kinematics of TKA.[6,14,16,32,38,42] A computational model of knee kinematics, for example, could facilitate surgical decision-making by taking as input joint stability and implant position and orientation and then suggesting adjustments to the surgical procedure that could optimize postoperative kinematics.

Currently, navigation systems have demonstrated the potential to improve surgical accuracy and function as unique tools to facilitate clinical research. We found TKA creates a balanced joint on average, although with some variations of varus-valgus instability. Advances in navigation technology may allow researchers to relate preoperative and intraoperative measurements to postoperative function and lead to improved surgical reconstructions.

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