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Comparison of Gap Balancing vs Measured Resection Technique in Patients Undergoing Simultaneous Bilateral Total Knee Arthroplasty: One Technique per Knee

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ABSTRACT

Background: Total knee arthroplasty requires careful surgical technique to attain the goal of a well-aligned and symmetrically balanced knee. Soft tissue balance and correct femoral component rotation are paramount in achieving these goals. The two competing techniques to select femoral component rotation and soft tissue balance are the gap balance technique and the measured resection technique.

Methods: We performed a randomized, prospective study to compare the two techniques in patients undergoing simultaneous bilateral total knee arthroplasty, whereby one technique was performed in each knee. Fifty (50) subjects were enrolled into the study. The inclusion criteria were osteoarthritic varus knee deformities with similar deformities in both knees. Subjects were followed up for a minimum of two years.

Results: The knees balanced via the gap balance technique had significantly more posterior medial bone removed from the femur than those knees balanced via the measured resection technique ($P < .001$). Knees in the gap balance group tended to require more medial knee releases in extension and tended to have smaller sized femoral components as a result of cutting more bone from the femur in flexion. The modular tibial polyethylene bearing tended to be thicker in the gap balance group. Despite these differences, average knee flexion and functional revised Oxford Knee Scores at 2-year follow-up were not statistically different.

Conclusion: At 2-year follow-up, there were no differences between the function and scores using the two techniques. Long-term follow-up will be necessary to evaluate any differences in long-term durability.

Primary total knee arthroplasty (TKA) is a well-established procedure utilized worldwide. It provides pain relief, improves functional mobility, and helps patients maintain an independent lifestyle. Ultimate knee function requires precise implant positioning and alignment. Furthermore, soft tissue balancing, both in the coronal and sagittal planes, is critical for successful TKA function [1]. Despite using 3rd generation implant designs and adhering to surgical techniques that recreate flexion kinematics of the knee, about 20% patients are not satisfied with their TKA procedure. The two main issues are residual knee pain and deficits in knee function [2]. Although accurately performed bone cuts restore mechanical alignment and provide proper fit of the prosthesis, ligament and capsular stability remain key components for the success and longevity of TKA [3].

Soft tissue balancing in TKA is influenced by a number of factors. These include laxity of soft tissues, individual bone geometry, and the accuracy of bone resection (the thickness of the resected bone should equal the thickness of the metal implants inserted) [4]. Although

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infection is the leading cause of early failures within the first two years, instability and aseptic loosening are currently the greatest causes of concern for TKA survival [5–7]. The understanding of TKA balancing is evolving, and TKA survivorship is subsequently improving with fewer revisions due to instability. However, component malpositioning and flexion/extension gap imbalance still remain unresolved issues [8–10]. Furthermore, debate on coronal alignment persists as to whether a kinematically or mechanically aligned TKA provides the best knee function and implant longevity [11,12].

The position and placement of the femoral component in the axial (ie, femoral component rotation) and sagittal planes has an impact on kinematics of the tibiofemoral and patellofemoral joints. There are currently two distinct methods of balancing a TKA: the measured resection (MR) technique and the gap balancing (GB) technique [13]. The aforementioned techniques create strong controversy, almost to the point of espousing religion. With the MR technique, the priority is to make all bone cuts first, followed by soft tissue/ligament releases to balance the knee. All bone cuts are made first using jigs that measure the amount of bone resection and replace the bone with prosthetic implants of similar size and thickness. In our technique, the distal femur is cut with an intramedullary jig. Before any additional femoral bone cuts are made, an axial rotation reference line is chosen. The MR technique relies on defining a reference line to determine the anterior and posterior cuts of the femur. There are three reference lines to choose from the posterior condylar axis (PCA), the transepicondylar axis (TEA), and the anterior-posterior axis (APA) in which the rotation line is marked perpendicular to this line [14,15]. After all femoral cuts, the proximal tibia is cut with a jig perpendicular to the mechanical axis of the tibia. Trial implants are placed, and soft tissue/ligament releases are then performed to create balanced extension and flexion gaps. The problem with the selected reference line is its accuracy and reproducibility. All reference lines have advocates and detractors. If the reference line is not accurately chosen, the ligament releases required to balance the knee may be difficult, resulting in potentially excessive or incomplete knee balance. This can affect the overall function and survival of the prosthetic construct [16].

The competing technique is the “gap balancing” (GB) method to establish femoral component rotation. The priority with this method is to release contracted soft tissues first, and then set femoral component rotation without relying on any anatomic landmarks [17]. There are two ways to perform this technique: extension first or flexion first. Balancing in extension first is considered more reliable, as releases are more precise [13]. In the extension first technique, the distal femur is cut, followed by proximal tibial resection to cut the tibia perpendicular to the mechanical axis. Starting in extension, a spacer block is placed into the extension gap. Ligaments/soft tissues are released to create a rectangular (ie, balanced) gap [13]. In flexion (90°), a tension device is placed. Next, a line is made on the posterior femur that creates a rectangular flexion gap of the same thickness as the extension gap. The posterior femoral bone cut is then made regardless of any of the femoral rotational reference lines. This technique creates a rectangular flexion gap without the need of soft tissue/ligament releases. The femoral size is chosen to fit the remaining bone, anterior to posterior. With trialing, since the gaps are already balanced, the only decision is to select a polyethylene (PE) bearing that allows full extension without recurvatum. The GB technique is not without its share of criticisms, including the tendency to increase joint line elevation and increase femoral component external rotation (compared to fixed bone landmarks), which may result in midflexion and flexion gap laxity [18–20].

Numerous studies comparing the MR and GB techniques performed by conventional methods or using computer-assisted surgery (CAS) have reported on multiple parameters, including coronal stability as measured by condylar lift-off [21], intra-compartmental force distribution [3], femoral component rotation [22], and functional outcomes [23]. The results are somewhat discordant. This study attempted to fill a gap in the existing literature by comparing these two techniques in similar knee deformities with comparable soft tissue quality. Considering that soft tissue laxity is different in different subjects but similar in the same patient with symmetric deformity, the ideal study would be to perform each technique in one patient requiring simultaneous bilateral TKA (SBTKA). There is no literature, however, directly comparing these two techniques in the same patient. In this report, we conducted a randomized study comparing the MR and GB techniques in patients undergoing SBTKA, whereby one technique was performed in each knee. Our null hypothesis for this study was that knees balanced by the GB technique would have better functional scores because of more precise balancing when compared with the MR technique in patients undergoing SBTKA using the same implant system.

Methods

A randomized prospective study was designed to compare the techniques of MR vs GB in patients undergoing SBTKA. Each patient enrolled in the study was to undergo TKA via the MR technique in one knee and via the GB technique in the contralateral knee. The side for each technique was selected randomly. This study received IRB approval at the performing medical center before its initiation.

Beginning in September 2014 and concluding in September 2016, subjects were enrolled into this study. Inclusion criteria included subjects with bilateral osteoarthritis of the knee who failed nonoperative treatment. Subjects also had to have a varus deformity that matched within 5 degrees of the contralateral knee. Valgus knee deformities were excluded from this study. Exclusion criteria included a flexion contracture greater than 15 degrees, any extra-articular knee deformities, and subjects with inflammatory arthritis. All subjects were informed of the study protocol, and written consent was obtained from all subjects before enrollment. Consent was conducted well in advance of the surgical procedure.

Preoperative demographic data were recorded for all subjects, including height, weight, age, and gender. Preoperative radiographs were obtained for all subjects and included a standing full-length anterior-posterior (AP) view that spanned from the hip joint to the ankle joint. Radiographic measurements included the anatomic varus angle and the medial proximal tibial angle (mPTA). These were measured via digital radiographs using a software tool (ImageJ 1.52a; National Institute of Health, Bethesda). Functional assessment was measured using the revised Oxford Knee Score [24] (ROKS) beginning at the preoperative evaluation and continuing at each follow-up examination. At one-year follow-up, all patients had a repeat radiographic analysis including a standing full-length AP radiograph.

Fifty-five (55) subjects were enrolled into the study. Two (2) of these subjects were subsequently excluded after the surgical procedure, as one subject required additional constraint for stability in one knee and the other subject required a medial epicondylar slide osteotomy in one knee to correct the varus deformity. Three (3) subjects underwent the surgical procedure but never returned for follow-up examinations. Repeated attempts to contact these subjects were made, but after one year of unsuccessful attempts, each subject was declared as lost to follow-up.

Surgical Protocol

Each knee was randomized to undergo primary TKA using either an MR technique or a GB technique. Randomization was conducted by a research fellow and was performed utilizing a random numbers table. The surgeon was informed of the randomization on the day of surgery. Anesthesia was standardized per protocol of the institution, including epidural and spinal anesthesia with a single shot adductor canal block. Preoperative antibiotic was a 1st generation cephalosporin (cefuroxime) administered 30 minutes before tourniquet inflation and continued for 24 hours after surgery. A pneumatic tourniquet was inflated just before skin incision and deflated after the cement had set. A single knee system was used for all cases. This was the Vanguard (Zimmer-Biomet, Warsaw) posterior-stabilized knee system. All femoral and tibial implants were cemented concomitantly using Palacos (Heraeus, Hanau, Germany) bone cement. All patellae were resurfaced with a cemented PE dome-shaped implant.

Surgical Technique

All surgeries were performed by the first author utilizing a posterior-stabilized knee technique and mechanical alignment technique (as opposed to kinematic alignment technique). All surgeries were performed using a midline skin incision with a medial parapatellar arthrotomy. The patella was retracted laterally and not everted during the instrumentation. Initial deep medial collateral ligament (MCL) release and excision of all tibial and femoral osteophytes were conducted in all knees as part of the exposure. All bone resections were performed using the same saw blade for uniformity (#2108118000 Stryker, Kalamazoo, MI). Distal femur resection was executed using an intramedullary jig set at a valgus cut angle of 5° for all knees. This cut angle was selected based on our prior analysis of 4000 primary TKAs performed at our center, where in 81% of patients, the valgus cut angle measured 5°. The proximal tibia was resected perpendicular to the tibial mechanical axis at a posterior slope of 3° using an extramedullary jig. During the procedure, the thickness of the cut femoral condyles and of the cut proximal tibial condylar surfaces were measured with a sterile caliper and recorded. All femoral condylar measurements were taken from the point of maximum thickness of the convexity. The medial tibial condyle (a concave surface) was measured at its thinnest point of the concavity. The lateral tibial condyle (a convex surface) was measured at the thickest point of the convexity.

The knees of patients in the MR cohort had femoral axial rotation set parallel to the TEA. Femoral implant anterior/posterior sizing was measured using a posterior condyle referencing device. A 4-in-1 cutting guide was pinned onto the cut distal femur. This guide was used to make the anterior femoral, posterior condylar, and chamfer cuts. The central posterior stabilized femoral box cut was prepared using a mill and jig technique. The tibial cut surface was prepared for the tibial keel with a tibial punch jig. Tibial component rotation was set over the medial one-third of the tibial tubercle. Trial implants, including a metal tibial base plate and a modular plastic tibial bearing to adjust tibial implant thickness, were placed. Soft tissue/ligament releases were performed as needed to balance the knee. Knee “balance” was defined as full knee extension, flexion to 120°, equal medial and lateral compartment tension as tested in extension and 90° of flexion, and no condylar lift-off as tested with the knee at 90° of flexion.

The knees of patients in the GB cohort first had the distal femoral and proximal tibial bone resections performed in a similar manner to that described previously. With the knee in extension, a spacer block was placed into the gap to balance the extension gap. Sequential medial releases were performed to create a rectangular (ie, balanced) gap that could accept a minimal thickness (combining the PE tibial bearing and the metal base plate) of 10 mm. When necessary, an additional tibial bone resection was made to obtain full knee extension. The knee extension gap was defined as “balanced” when the knee was in full extension, and with valgus stress, there was no medial gap opening. In addition, with varus stress, there had to be no more than 2 mm of lateral gap opening (Fig. 1).

The knee was then positioned at 90° of flexion, and the flexion gap was balanced using a mechanical tension device (Pro-Flex G; Biomet, Warsaw) (Fig. 2A-C). First, a spacer of the same thickness as the extension gap was attached to the tension jig. This jig has an internal tension–generating device and a transverse metal arm to mark rotation that lies parallel to the tibial spacer block. The tension jig was also attached to an intramedullary guide rod that was placed into the femoral canal. The entire jig was inserted into the medullary canal with the tension jig placed flush with the cut distal femur. Next, a set tension was applied with a torque screwdriver. The screwdriver was turned clockwise until the torque-limiting device released with an audible and palpable click. The tension device depressed the tibia inferiorly away from the intramedullary rod. The tension created was between the intramedullary canal rod, which is transferred through the jig to the medial and lateral sides of the tibia. If the gap is asymmetrical, the tight/contracted compartment will have a smaller gap and the contralateral loose side will have a larger gap. Because the tension jig marker was set parallel to the base of the tibial spacer, the metal T-arm served as the reference line to create a rectangular flexion gap by cutting bone rather than releasing ligaments (Fig. 3A-D). The transverse reference line was set by placing two drill pins into the distal femur to lock rotation. The holes created were the site where the 4-in-1 spacer block pins were to be inserted. The femur was sized anterior to posterior using an anterior reference guide placed onto the anterior femoral cortex. Great care was taken during the tensioning procedure to ensure the patella did not cause a tethering effect to the lateral side of the knee, thus falsely increasing tension to the

Fig. 1. Intraoperative photograph of the left knee showing extension gap balance with the GB technique. This picture shows the modular rectangular spacer block after balancing the extension gap. Notice that with the knee in full extension, no gaps exist between the spacer block and the cut bony surfaces. The spacer block is modular, which allows for precise measurement of the extension gap space. This same size block is to be used in flexion with the GB tension device, which is demonstrated in Fig. 2. GB, gap balancing.

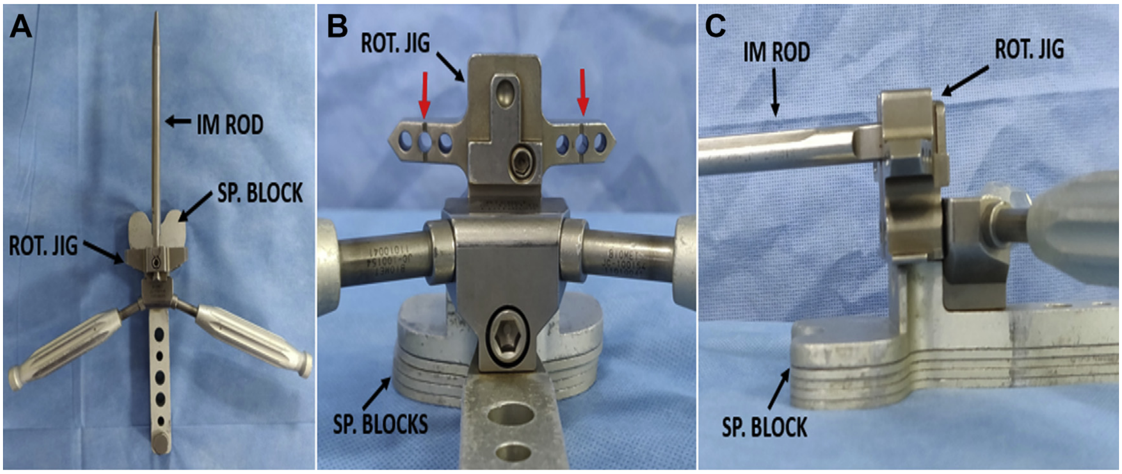

Fig. 2. (A-C) Pictures of the Pro-Flex G flexion gap tension device used to balance the knee flexion gap. (A) Top view of the device. This illustrates the jig setup for a left knee. The intramedullary guide device is connected to the tension jig. The two handles are used to steer the device into the flexed knee gap. (B) Anterior-posterior view of the entire jig device as if the device was placed into the flexion gap. The tibial spacer block is connected to the tension device and tightened with the inferior large hexagonal screw. The transverse metal outriggers with the three holes are set parallel to the tibial spacer block. (C) Sagittal view of the entire jig device. When the tension device is activated, tension stress is created between the medullary guide rod and the tibial spacer block. This acts to depress the tibia away from the femur, with equal tension applied to both the medial and lateral sides of the tibia. If the soft tissues/ligaments of one side are weak and stretched, the gap on that side will open up further than the intact side. This will create a trapezoid appearing flexion gap. The bone on the posterior femur is then cut to make the gap equal in size. This is the entire premise of GB technique.

lateral knee compartment. After all bone cuts had been made, trial implants were placed. A tibial trial bearing was tested to provide full knee extension without recurvatum. We ensured that no further soft tissue or ligamentous releases were performed after trialing.

Postoperatively, all patients had knee radiographs performed in the recovery room. Patients started gait training the day following surgery, when medically cleared. All drains were removed on the day following surgery. Gait training and knee range of motion were progressed as the patient tolerated. Clinical follow-up and assessment scores were performed at 4 weeks, 3 months, 6 months, 1 year, and annually thereafter. Any complication in treatment or return to the operating room was recorded. Postoperative range of motion, stability, and ROKS were recorded. Radiographic examination was conducted at the 3-month, annual, and biannual assessments. Statistical analysis of recorded data was analyzed using the Excel software (Microsoft, Redmond). A two-tailed paired T test with equal variance was performed to test for significance ($P < .05$).

Results

Fifty patients (40 females, 10 males) with a mean age of 66 ± 7.4 years (range 51-89 years) were followed up for a minimum of 2 years. Physiologically, 34 patients were American Society of Anaesthesiologist [25] (ASA) grade 2, whereas 16 were ASA grade 3. The tourniquet time was 46.5 ± 7.1 minutes (range 31-70 minutes) in the GB group and 46.3 ± 9.4 minutes (range 27-75 minutes) in the MR group, with no statistically significant difference between the two groups ($P = .929$). In the GB group, 9 knees required a release of the posterior oblique ligament (POL) of the MCL to achieve extension balance. In the MR group, 3 knees required a release of the POL of the MCL to achieve extension balance. There was no

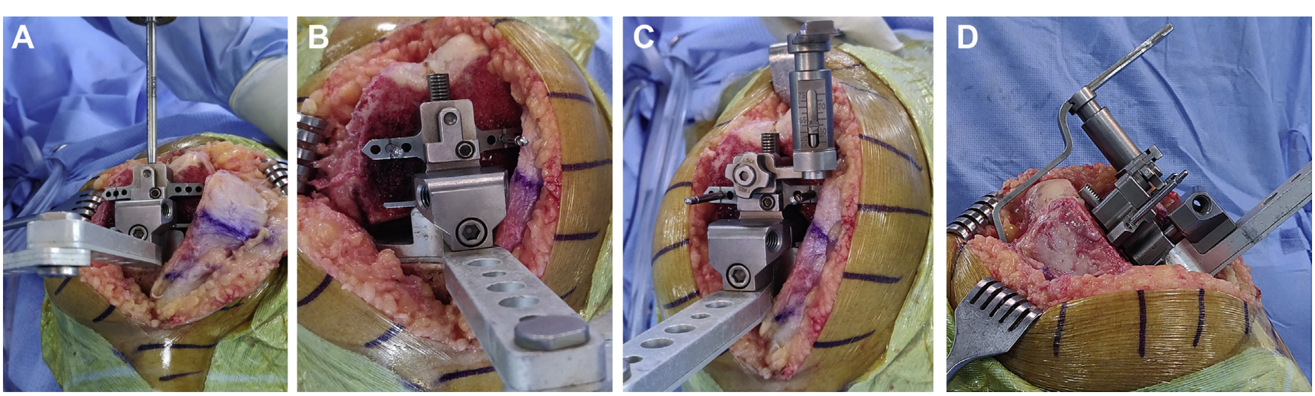

Fig. 3. (A-D) Intraoperative photographs demonstrating implementation of the Pro-Flex G device in GB technique in a left knee. (A) This picture shows the entire jig apparatus in position with the knee at 90° of flexion. The screwdriver is placed superiorly into the tension device and turned clockwise to tension the flexion gap. The screwdriver is turned until the torque limiter within the tension device releases, which tensions the flexion gap. Notice how the patella is positioned so as not to tether the lateral flexion gap. (B) This picture shows that the tension device is fully tensioned, as the superior metal with the notches is seen superiorly. The tibia is depressed inferiorly, thus tensioning the flexion gap. In this case, the lateral soft tissue/ligament complex is weaker, creating a trapezoid flexion gap. Drill pins are placed into the transverse arms of the tension jig. In this case, the posterior condylar bone cut will be thicker on the medial side than the lateral side. (C) The next step in the gap balance sequence is sizing for the femoral implant. The drill pins are in position for the 4-in-1 cutting block. The anterior referencing guide is placed to touch the anterior femoral cortex (seen in Fig. 3D). In this case, the femur is sized to a 62.5-mm implant. (D) Lateral view of the same step, showing the entire tension jig pinned at 90° of flexion and the anterior-posterior sizing guide touching the anterior femoral cortex just superior to the trochlea.

statistically significant difference between the two groups ($P = .06$). Implant survivorship was 100% for both groups with no revision surgery performed for any indication at the end of the final follow-up.

Radiographic Analysis

Radiographic analysis of the study groups is presented in Table 1. The preoperative clinical varus alignment, as measured by femoral-tibial angle (FTA), was similar in both the GB and MR groups. The measured anatomic FTA was 191.7 ± 3.1 degrees in the GB group and 192.1 ± 3.3 degrees in the MR group ($P = .855$). The preoperative clinical proximal tibial varus was also similar in both groups. The measured mPTA was 83.6 ± 2.6 degrees in the GB group and 84.4 ± 2.4 degrees in the MR group ($P = .117$). The postoperative clinical valgus alignment was similar in the two groups as well. The measured anatomic FTA was 174.6 ± 2.3 degrees in the GB group and 174.9 ± 2.6 degrees in the MR group ($P = .295$). There was no statistically significant difference between the two groups in terms of clinical proximal tibial angle, as well. The measured mPTA was 89.4 ± 2.7 degrees in the GB group and 89.2 ± 2.3 degrees in the MR group ($P = .913$).

Bone Resection Measurements

The thickness of resected bone cuts from the femur and tibia is presented in Table 2. The amount of distal femoral bone resected was similar in both groups. The thickness of the distal medial femoral condyle measured 8.9 ± 1.2 mm in the GB group and 8.1 ± 1.2 mm in the MR group ($P = .170$). The thickness of the distal lateral femoral condyle measured 10.0 ± 1.1 mm in the GB group and 9.6 ± 1.0 mm in the MR group ($P = .438$). The thickness of the cut posterior medial femoral condyle was significantly different between the two groups. The cut posterior medial femoral condyle measured 10.1 ± 1.9 mm in the GB group and 8.9 ± 0.8 mm in the MR group ($P < .001$). In contrast, the thickness of the cut posterior lateral femoral condyle was similar in the two groups, measuring 6.8 ± 2.5 mm in the GB group and 6.6 ± 0.8 mm in the MR group ($P = .649$). The thickness of the cut proximal tibial bone was also similar between the two groups. The cut medial tibial condyle measured 1.5 ± 1.5 mm in the GB group and 1.6 ± 1.4 mm in the MR group ($P = .757$). The cut lateral tibial condyle measured 8.7 ± 1.4 mm in the GB group and 9.2 ± 1.6 mm in the MR group ($P = .138$).

Implant Variation

The implant sizes selected for each knee in the same patient theoretically should have been the same, but not infrequently differed. The selected implant sizes are summarized in Table 3. The selected femoral implant size was the same between the GB and MR sides in 28 cases. Interestingly, the femoral implant size was smaller on the GB side in 17 subjects and smaller on the MR side in only 5 subjects ($P = .01$). The selected PE bearing thickness overall tended to be thicker on the GB side. The selected PE thickness was similar between the two sides in 28 subjects. The selected PE thickness was thicker on the GB side in 15 subjects and thicker on the MR side in only 7 subjects ($P = .09$). Of the 15 cases with a thicker PE bearing on the GB side, 14 were one size (2 mm) thicker and 1 was two sizes (4 mm) thicker. Of the 7 cases with a thicker PE bearing on the MR side, 6 were one size (2 mm) thicker and 1 was two sizes (4 mm) thicker. Tibial implant size was generally consistent between the GB and MR sides. The selected tibial implant size was the same on both sides in 41 subjects but was smaller on the GB side in 6 cases and smaller on the MR side in 3 cases ($P = .32$).

Table 2
Thickness of Resected Bone Cuts.

Site	Side	Balancing Method		*P* Value
		Gap Balancing	Measure Resection	
Distal femur	Medial	8.9 ± 1.2 mm	8.1 ± 1.2 mm	.170
	Lateral	10.0 ± 1.1 mm	9.6 ± 1.0 mm	.438
Proximal tibia	Medial	1.5 ± 1.5 mm	1.6 ± 1.4 mm	.757
	Lateral	8.7 ± 1.4 mm	9.2 ± 1.6 mm	.138
Posterior femur	Medial	10.1 ± 1.9 mm	8.9 ± 0.8 mm	**<.001**
	Lateral	6.8 ± 2.5 mm	6.6 ± 0.8 mm	.649

Bolded value indicates the statistical significance.

Patient Outcomes

Functional outcomes for the series are presented in Table 4. Preoperative knee flexion was comparable between the GB and MR groups. Average knee flexion measured 103.7 ± 16 degrees in the GB group and 103.6 ± 16 degrees in the MR group ($P = .94$). Postoperative knee flexion at the 2-year follow-up mark was comparable in the two groups. Average knee flexion measured 122 ± 16 degrees in the GB group and 124 ± 14 degrees in the MR group ($P = .083$). Preoperative ROKS were similar between the groups. Preoperative ROKS averaged 19.2 ± 6.8 in the GB group and 19.3 ± 6.5 in the MR group ($P = .94$). Postoperative ROKS at 2-year follow-up was also similar in both groups, averaging 36.3 ± 4.5 in the GB group and 37.8 ± 4.5 in the MR group ($P = .092$). The net improvement in ROKS was similar as well. Net improvement in ROKS measured 17.1 ± 7.2 in the GB group and 18.5 ± 7.4 in the MR group ($P = .328$). Finally, at the two-year follow-up visit, subjects were asked to provide his/her subjective opinion as to a preferred knee. Twenty-eight (28) subjects stated no preference. Thirteen (13) subjects preferred the MR knee, whereas 9 subjects preferred the GB knee.

Complications

There were no reoperations in this study series over the two-year follow-up span. There were no wound complications requiring additional oral or intravenous antibiotics. At the 2-year follow-up mark, there were no cases of chronic periprosthetic

Table 1
Radiographic Analysis of Measured Clinical Limb Alignment and Proximal Tibial Alignment.

Measurement Parameter	Gap Balancing	Measured Resection	*P* Value
Preoperative anatomic FTA	191.7 ± 3.1 degrees	192.1 ± 3.3 degrees	.855
Preoperative mPTA	83.6 ± 2.6 degrees	84.4 ± 2.4 degrees	.117
Postoperative anatomic FTA	174.6 ± 2.3 degrees	174.9 ± 2.6 degrees	.295
Postoperative mPTA	89.4 ± 2.7 degrees	89.2 ± 2.3 degrees	.913

FTA, femoral-tibial angle; mPTA, medial proximal tibial angle.

Table 3
Variation in Implant Sizes in the Same Patient.

Femoral Component	Number	Tibial Component	Number	Polyethylene Insert	Number
GB > MR	5	GB > MR	3	GB > MR	15
GB = MR	28	GB = MR	42	GB = MR	28
GB < MR	17	GB < MR	5	GB < MR	7

GB, gap balancing; MR, measured resection.

joint infection. Two (2) subjects required manipulation under anesthesia for stiffness in one knee. One subject was on the GB side, and one subject was on the MR side.

Discussion

Most surgeons agree that a TKA that is well aligned and balanced will provide a good long-term functional outcome for a patient requiring prosthetic TKA. Soft tissue balancing and femoral component rotational alignment play a critical role in achieving this goal. Thus, the techniques of MR vs GB come to the forefront. The two techniques are dissimilar as to the priority of bone cuts and ligament/soft tissue releases.

In extension, the two techniques are similar. It is with the flexion gap that the two techniques differ significantly in philosophy. In the MR technique, femoral component axial rotation is set along either the PCA, or TEA, or APA and then the ligaments/soft tissues of the knee are released to balance the extension and flexion gaps of the knee. The aforementioned landmarks, however, have considerable variability and are not always reliable [26]. Poilvache et al believed that the anterior extent of femoral condyles is not reliable in arthritic knees and setting axial rotation along the AP axis in trochlear dysplasia would increase external rotation of the femur [27]. Furthermore, it has been shown in a CT study that the AP axis is more externally rotated in medial osteoarthritic knees than in normal knees. Thus, using this landmark in knees with medial tibiofemoral arthritis is likely to increase femoral component external rotation. This excess external rotation may result in coronal instability in flexion [28]. The problem with placing the femoral component parallel to the TEA is the difficulty in identifying the epicondylar sulci accurately. A CT scan correlation of surgical landmark identification revealed that when referencing with TEA, only 75% of knees would be implanted within 3° of the true epicondylar axis, with errors ranging from 6° of external rotation to 11° of internal rotation [29]. A cadaveric study performed by experience arthroplasty surgeons to identify epicondylar landmarks showed a median variability of 6.4 mm laterally and 9.7 mm medially, indicating high interindividual discrepancy in defining TEA [30]. Similarly, the PCA has its own fallacies, especially in the presence of posterolateral condylar hypoplasia or condylar erosion in valgus knees, wherein relying on this landmark would result in net internal rotation of the femoral component [31]. Furthermore, in varus arthritic knees with chronic ACL insufficiency, the posteromedial femur is eroded and would lead to excessive external rotation when referencing using the PCA. The incidence of obtaining a rectangular flexion gap using PCA was found to be just 51% by Schnurr et al [32]. In addition, there is a wide variation in the relationship between the PCA and TEA [31]. Therefore, relying on a single anatomic landmark (or even 2 of the 3 landmarks) to set femoral rotation is fraught with potential errors that can adversely impact patellofemoral kinematics and/or coronal stability. This could adversely impact functional outcomes. Thus, the GB technique was developed to balance the flexion gap utilizing bone cuts to create symmetry with that of the extension gap. Our premise was that the GB technique is more consistent and more reliable overall in balancing a TKA and that overall function would be superior in knees balanced via the GB technique.

This study provided enlightening information when comparing a MR technique to a GB technique in patients with similar knee deformities and similar soft tissue integrity. The first important finding of this study is that the GB technique does not result in better functional outcomes at two-year follow-up when compared with the MR technique in SBTKA for varus gonarthrosis of the knee. Average knee flexion and ROKS were very similar between the two techniques. Furthermore, most subjects stated no subjective preference to a particular knee.

Our findings in general are consistent with previous comparisons. Studies comparing the MR technique with the GB technique do discern technical differences in results; however, it is difficult to detect a consistent superiority of either technique utilizing functional outcome scores and/or revision rates [33–35]. The meta-analyses by both Moon and Huang found that both the techniques were comparable with respect to gap symmetry, except for a difference in medial and lateral extension gaps [36,37]. Matsumoto et al found that the balance was better achieved in cruciate-retaining TKA than in posterior substituting TKA with the GB technique and both were superior to the MR technique. However, there was no difference in clinical outcome [38]. Another comparison study by Singh et al showed that although improvement in functional scores (Knee Society Score and ROKS) was better in the GB group, it was not statistically significant [39]. Similar outcomes have also been reported by Churchill at 3 years of follow-up [23]. Conversely, Pang et al reported significantly better outcome scores at 6 months and 2-year follow-up for knees which underwent CAS-TKA by the GB technique as opposed to conventional MR TKA [40]. Our study is unique in that the GB technique was compared to the MR technique in the same patient with similar knee deformities. We feel that our study more conclusively demonstrates the findings in the existing literature, that there is no difference in functional outcomes between the two techniques.

Table 4
Functional Outcome Scores.

Outcome	Gap Balancing	Measured Resection	*P* Value
Flexion preoperative	103.7 ± 16 degrees	103.6 ± 16 degrees	.940
Flexion postoperative (2-y follow-up)	122 ± 16 degrees	124 ± 14 degrees	.083
ROKS preoperative	19.2 ± 6.8	19.3 ± 6.5	.940
ROKS postoperative (2-y follow-up)	36.3 ± 4.5	37.8 ± 4.5	.092
Improvement in ROKS	17.1 ± 7.2	18.5 ± 7.4	.328

ROKS, revised Oxford Knee Score [24].

Another important finding in our study is that the GB technique requires a larger bone resection from the posterior medial femur to achieve a rectangular (ie, balanced) flexion gap. The posterior medial femoral condylar bone resection was significantly greater in the GB group ($P < .001$). This indicates that flexion gap balance in the GB technique is achieved at the expense of additional bone resection. This has two subtle implications. First, by cutting additional bone from the posterior medial femur (when compared to the MR technique), this maneuver may, in some cases, cause increased external rotation of the femoral component. As a result, patellar tracking could be adversely affected. The finding that the GB technique can cause excess external rotation is not novel [36,37]. Scuderi et al and others have noted increased external rotation in the gap balance technique [3,22,41]. While supporting these findings, our study is unique as it documents a statistically significant difference in the amount of resected posterior medial femoral bone in subjects with similar knee deformities and soft tissue quality undergoing the competing techniques simultaneously. We infer from this finding that there would be increased external rotation of the femoral component on the GB knee compared with the MR knee. In retrospect, the study could have been made stronger through the study of postoperative femoral rotation via CT scan. Based on our findings, we feel the GB technique can provide a more subjectively exact tension intraoperatively between the flexion and extension gaps but prioritizes extension/flexion balance over femoral component rotation. Because functional outcomes are similar between the two techniques, the potential excess rotation of the femoral component is perhaps too small to have an adverse clinical impact in early follow-up [37]. We emphasize with the GB technique, the proximal tibial cut directly influences femoral component rotation. A source of error that can cause abnormal femoral rotation with the GB technique is a tilted tibial cut that is not perpendicular to the tibial mechanical axis [42]. For example, if the tibia is cut in varus, the medial flexion gap will be bigger with the GB technique, requiring a smaller medial femoral bone cut in flexion. The net result will be a relative internal rotation of the femoral component. In contrast, if the tibia is cut in valgus, the lateral flexion gap will be larger and, thus, a bigger posterior medial femoral bone cut will be required to create a symmetrical flexion gap. This can result in an excess external rotation of the femoral component. In our study, we were careful with our surgical technique when cutting the proximal tibia. Our preoperative and postoperative mPTAs were similar in both groups.

The second subtle implication is that the anterior referencing system employed in this study tended to undersize the femoral component. There are two reasons for this. First, the anterior reference sizing jig in the Pro-Flex G instrumentation is set to the intramedullary guide rod, which, in this study, was not canal filling. When the tension device is activated, tension pushes the tibia away from the rod, but if the distal femoral bone is soft, the guide rod can be pushed upward toward the anterior femoral cortex. This falsely decreases the measured size of the femur. This phenomenon, combined with the increased posterior medial femoral bone resection, can undersize the femur. The result is a more lax flexion gap that can potentially result in midflexion instability. Subtle laxity in the flexion gap causes no significant functional problems early in the prosthetic lifecycle. However, this laxity can progress over time as soft tissues are stretched, resulting in a painful swollen TKA from clinical midflexion/flexion instability, which manifests in the intermediate lifecycle of the TKA [43]. We will continue to follow up this study group to observe if additional surgery is required within the first decade of the prosthetic lifecycle.

The need for a release of the POL of the MCL was more common in the GB group (n = 9, 18%) compared with the MR group (n = 3, 6%). We attribute this finding to what we describe as secondary rebalancing of the knee in extension. Specifically, in cases where a significant posterior medial femoral bone resection was required and a smaller femoral component selected, a thicker PE bearing was more frequently used. In trialing, this may cause, in extension, a tighter medial extension gap that requires an additional release of the POL of the MCL (the POL of the MCL is tight in extension). Thus, a secondary release of the POL of the MCL was performed in several cases.

Finally, as a corollary, the use of a thicker PE modular bearing can also cause, in some cases, joint line elevation from the native knee joint line. The finding that the GB technique causes elevation of the joint line has been confirmed in two meta-analyses as statistically significant [36,37]. This is attributed to the fact that flexion and extension gap symmetry is prioritized over rotational alignment when employing the GB technique. Sabbioni et al reported joint line elevation to be 4.09 mm in the GB technique and 3.50 mm in the MR technique using a posterior stabilized knee system. This change was significantly greater for GB knees ($P = .036$) [44]. Tigani et al also compared the GB and MR techniques performed with CAS-TKA and found that although both led to joint line elevation, there was statistically greater elevation in GB knees ($P = .008$) [19]. Similar findings were reported by Babazadeh et al and Lee et al, as they found this to be due to significantly thicker distal femoral resections and thicker PE inserts. Again, there was no difference in the functional outcome between the GB and MR groups at 5 years [18,45,46]. Keeping this in mind, no subject in our series underwent additional femoral resection after the primary distal femur cut to avoid raising the joint line. With a varus knee deformity, the distal femoral cut is usually referenced off the intact lateral femoral condyle. Thus, there was no difference in the thickness of the bone cut at this site between our two groups. This indicates that the femoral component was not proximalized in our knee series and the thicker tibial bearings used in the GB group were more related to the tendency to use smaller sized femoral components. Therefore, on occasion, a secondary posterior capsular release was performed to achieve full knee extension during the final implant trialing phase.

This study, although unique and specific, has multiple limitations. First, our strict inclusion criteria mean that our findings cannot be extrapolated to comment upon the efficacy of the MR vs GB technique for balancing all arthritic knees. For example, small-sized patients with significant osteoporosis may be better treated with an MR technique to preserve bone stock. Another consideration would be younger patients (<60-year-olds) where revision knee surgery is more likely and bone conservation is therefore a priority. Our selection of a 5° valgus cut angle for all subjects merits further discussion as well. We selected this cut angle as it was the predominant value measured in our overall population (81%). We have employed this valgus cut angle for all of our patients, as we find this cut angle to be salutary and allow for predictable intraoperative balance and postoperative knee function. However, to be critical, for those 19% of subjects with a valgus cut angle greater than 5°, the gap balance technique could be impacted. For example, if the valgus cut angle measured 7° and the distal cut angle was made at 5°, the medial compartment in extension would require less soft tissue release, as the extra 2° of bone resection relaxes the medial compartment tissues. However, in flexion, because the medial compartment tissues have not been released, the gap balance tension may be tighter overall, requiring further bone resection of the medial compartment. This effect would increase the mean value of resected bone of the posterior medial femur compared with cutting all femora at their true valgus cut angle. Unfortunately, we did not measure this effect. In our opinion, however, this net effect is minimal as it is only present in a minority of our subjects.

A further criticism is not objectively assessing patellar tracking. In our entire series, there were no lateral retinacular releases performed. We attribute this to careful surgical technique and component sizing. However, we did not perform a CT scan protocol to assess femoral component rotation in the technique described by Berger et al [47]. Furthermore, in our radiographic analysis, we did not perform a standardized sunrise view to measure patellar tilt and maltracking. Although excess femoral component rotation or patellar maltracking may be different between the two techniques, our clinical ROKS did not reflect any salient dysfunction between the two groups. In addition, the intraoperative assessment of knee balance, flexion and extension stability, and overall soft tissue tension was based solely on the subjective feel of an experienced joint replacement surgeon (S.T.) using a conventional surgical technique. In the future, computer-assisted feedback with force transduction measurements would better validate our subjective "feeling of knee balance." In many countries, however, CAS surgical techniques are expensive, making the use of this technology prohibitive. Finally, our follow-up duration of two years is not enough to validate superiority of either technique. We will continue to follow this series of subjects long-term to assess revision rates or any other untoward finding that may occur. To date, we remain optimistic that our initial salutary results will extend into the long term.

Conclusion

The knees that were balanced by the GB technique had similar functional outcomes and scores to those balanced by the MR technique, thus negating our null hypothesis. However, balancing these knees by the GB technique leads to larger bone resections of the posterior medial femoral condyle in flexion and more secondary soft tissue releases in extension. Furthermore, GB knees tended to have smaller femurs and thicker PE inserts implanted more frequently. Although not specifically measured in this study, it is likely that the femoral components in the GB group are rotated more externally as posteromedial bone resections are larger. In future follow-up, we plan to have these subjects undergo a CT scan to assess femoral rotational alignment. Long-term follow-up will be necessary to evaluate any differences in long-term durability between the two techniques.

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