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CLINICAL ARTICLE

Comparison of the Imaging and Clinical Outcomes among the Measured Resection, Gap Balancing, and Hybrid Techniques in Primary Total Knee Arthroplasty

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Objective: Although many studies have compared the measured resection (MR) technique to the gap balancing (GB) technique, few studies have investigated the hybrid technique. In this study, we compared imaging and clinical outcomes of the MR, GB, and hybrid techniques in primary total knee arthroplasty (TKA).

Methods: From January 2016 to January 2019, we conducted a retrospective study on 90 patients who underwent unilateral primary TKA; 30 received the MR technique, 30 received the GB technique, and 30 received the hybrid technique. Radiological outcomes, including joint line level, mechanical alignment of the lower limb, positions of the femoral and tibial components, and rotation of the femoral component, and clinical outcomes, including the visual analog scale score for pain, the Knee Society Score, and the range of motion, were assessed among the three groups. One-way analysis of variance and Dunnett's test were performed for normally distributed data. Kruskal–Wallis H test and Dunn–Bonferroni test were conducted for non-normally distributed data.

Results: No significant difference in the mechanical alignment ($p = 0.151$) and the positions of the tibial and femoral components ($p = 0.230$ for α angle, $p = 0.517$ for β angle, $p = 0.686$ for femoral flexion angle, and $p = 0.918$ for tibial slope angle) was found among the three groups. No significant difference in the elevation of the joint line between the MR and the hybrid groups was found (2.1 ± 0.3 mm *vs* 2.1 ± 0.1 mm, $p = 0.627$), but the GB group (2.8 ± 0.2 mm) differed significantly from the other two groups ($p < 0.001$). Although rotation of the femoral component in the GB group was larger than that of the MR and hybrid groups, the difference was not significant ($1.8° \pm 0.2°$ *vs* $1.7° \pm 0.3°$ *vs.* $1.7° \pm 0.2°$, $p = 0.101$). The clinical outcomes were not significantly different ($p > 0.05$), although the results in the hybrid group were slightly higher.

Conclusion: The hybrid technique helped to restore the mechanical alignment of the lower limb and realize optimal positions of the femoral and tibial components without significant differences relative to the MR and GB techniques. The hybrid technique was more helpful for maintaining the original height of the joint line, which was similar to the MR technique. Additionally, although the improvement in the clinical outcomes in the hybrid group was slightly higher, it was not significantly different among the three groups.

Key words: component alignment; gap balancing; hybrid technique; measured resection; primary total knee arthroplasty

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Introduction

Knee osteoarthritis (OA) commonly occurs in the elderly, causing pain, stiffness, and limited movement, thus affecting daily activities[1]. Primary total knee arthroplasty (TKA) is an effective surgical treatment for advanced end-stage OA, which can relieve the pain of patients and improve the function of the knees, thus improving the long-term quality of life[2,3].

The TKA is performed to obtain a knee with good alignment, soft tissue balance, and stability[4]. Inappropriate implant alignment is the primary reason for revision[5]. Implant malalignment may lead to many problems, including pain, stiffness, short implant life, and poor patellofemoral trajectory[6,7]. The balance of soft tissue is affected by many factors, including the looseness of the surrounding soft tissue, the variation of bone geometry, and the extent to which the bone is cut[8]. Although most patients achieve satisfactory clinical outcomes after TKA, 15%–20% of patients are dissatisfied with the prognosis, mainly due to persistent pain and poor function[9]. Aligning the implant correctly and maintaining a balance of soft tissues are important for improving patient outcomes, but the best way to achieve these goals is still controversial[10]. The measured resection (MR) and gap balancing (GB) techniques are the commonly used surgical techniques to properly align the implant and achieve soft tissue balance.

The MR technique was proposed by Hungerford in the early 1980s[11,12] and usually relies on reference lines, including the posterior condylar line (PCL), the transepicondylar axis (TEA), the trochlear anterior–posterior axis (TAPA), and the sulcus line[13], to determine the anterior and posterior cuts of the femur. Maintaining the accuracy and repeatability of the selected reference line is a key problem. An inaccurate line might cause difficulty in loosening the ligaments for balancing the knee and might even lead to excessive or incomplete balancing[6]. The MR technique strongly suggests that the posterior cruciate ligament should be preserved, and the lateral collateral ligament should be balanced after the trial is in place[7]. The GB technique was proposed by Freeman *et al.* in 1986[14]. Initially, the tibia is cut perpendicular to the mechanical axis. Then, the posterior condyle and distal condyle are resected without relying on any anatomical landmarks for producing the symmetrical rectangular flexion gap and extension gap[6,7]. Although the improved GB technique first balances the extension gap, it might still lead to the elevation of the joint line in some severely deformed knees[15]. Several studies have compared many aspects of the MR and GB techniques, including imaging evaluation, functional outcomes, femoral component rotation, implant survival rate, and stress distribution, but there is no definite conclusion about which technique is more superior[6,7,16–20].

Recently, a hybrid technique, which combines the advantages of the MR and GB techniques, was proposed. First, the anatomical landmarks of the distal femur are determined by the MR technique, and then, the soft tissue tension is checked and balanced by the GB technique[10,21]. Studies comparing the postoperative outcomes between the hybrid technique and the other two techniques are limited.

Therefore, in this study, patients who underwent unilateral primary TKA using different techniques were followed up at least 2 years after surgery. The purpose of this retrospective study was: (i) to evaluate and compare the postoperative imaging outcomes and mid-term clinical outcomes among the patients treated with the hybrid, MR, and GB techniques, respectively; and (ii) to provide references for the choice of techniques for surgeons. The potential advantages of the hybrid technique may include improving the accuracy of osteotomy and components implantation, maintaining the original height of the joint line, and obtaining better clinical outcomes.

Methods

Patient Selection

This was a single-center, retrospective study. The study was approved by the ethics committee of the Third Hospital of Hebei Medical University (No. Z2020-001-2), and written informed consent was obtained from all participants. The study was conducted following the ethical standards of the Declaration of Helsinki (as revised in Brazil in 2013). Patients who received unilateral primary TKA from January 2016 to January 2019 participated in the study and were assigned to three groups based on the adopted technique: the MR group, the GB group, and the hybrid group. The inclusion criteria were primary, degenerative, and non-inflammatory knee OA with moderate to severe pain and failure of conservative treatment. All included patients were followed up for at least 2 years after surgery. The exclusion criteria were: (i) previous knee surgery; (ii) knee infection; (iii) stiffness or ankylosis of the hip; (iv) bone loss or nerve function defect; (v) the requirement of highly restrictive prostheses; (vi) severe knee deformity: knee flexion <90°, flexion contracture >20°, varus or valgus deformity >10°. The preoperative demographic data of all patients, including height, weight, age, and gender, were collected. All patients were asked to visit the clinic for follow-up, and follow-up over the telephone was performed if the patients could not visit the clinic for some reason.

Indications of Surgical Techniques

There is no clear distinction in the indications among the MR, GB, and hybrid techniques. The MR technique was mainly used with identifiable and clear anatomic landmarks as references to set femoral implant rotation, including the PCL, the TEA, the TAPA, and the sulcus line. It is also suitable for patients with large posterior osteophytes or fixed coronal deformities, such as contracted ligaments. The GB technique was used when it is difficult for surgeons to reproducibly and accurately identify the anatomic landmarks, especially in patients with advanced patellofemoral arthritis or a valgus knee with hypoplastic distal and posterior lateral condyles, including trochlear dysplasia or other distal femoral deformities. However, collateral ligaments should be nonpathologic and osteophytes can be removed prior to femoral preparation when performing the GB technique[10]. The hybrid technique combines elements of both MR and GB techniques and was mainly used in patients with relatively clear landmarks, mild deformity, and small osteophytes.

Surgical Technique

All surgeries were performed by an experienced surgeon. Anesthesia was standardized according to the scheme of the institution, including laryngeal mask inhalation anesthesia and femoral nerve block anesthesia. The antibiotic administered before surgery was the first-generation cephalosporin, cefuroxime. It was administered 30 min before the tourniquet was inflated and used continuously for 24 h after surgery. The tourniquet was inflated before skin incision and was relaxed before skin incision suture. The same design implant, i.e., cemented knee prosthesis (cruciate-retaining, LINK, Hamburg, Germany, Gemini MK II), was used in the knees of all patients to reduce errors in the study. The patellar surface was not replaced in all patients. During the postoperative period, all patients in the three groups attended standardized rehabilitation and pain management programs. The rehabilitation programs included practicing walking with a walking aid and performing several motion exercises on the first day after surgery.

All surgeries were performed with a standard midline skin incision and medial parapatellar arthrotomy. The patella was retracted outwards and turned over if the exposure was insufficient. All accessible osteophytes from the tibia and femur were removed. Using an extramedullary guide, the proximal tibia resection was performed at a posterior slope of 3° perpendicular to the mechanical axis of the tibia. Then, distal femoral resection was performed. The internal femoral alignment rod was introduced into the intramedullary canal, and the distal femur was resected at a valgus angle of 5°.

For the MR cohort, the femoral rotation was set parallel to the TEA. After resection of the distal femur, the size of the femoral component was measured using the posterior condyle referencing device. A suitable 4-in-1 cutting block was used for making anterior and posterior bone cuts. Drilling was performed based on the approximate value of the TEA, which was rotated 3° relative to the PCL. The tibial component rotation was arranged on the inner third of the tibial tuberosity. The tibial and femoral implant trials were placed at the appropriate site, and the soft tissues and ligaments were loosened to balance the knee. This allowed the tension of the medial and lateral compartments to be equal at knee extension and 90° of flexion, and no femoral condyle lift-off occurred at 90° of flexion.

For the GB cohort, the knee was straightened after the proximal tibia and distal femur were resected. Any accessible osteophyte behind was removed. First, the extension gap was balanced, a spacer block was put in the gap, and the medial and lateral soft tissues were released until a rectangular extension gap was obtained, which could at least accommodate the thinnest insert. To avoid the elevation of the joint line, an extra tibial cut was performed when necessary to allow the knee to fully extend. Then, the flexion gap was balanced at 90° of flexion. A torque matching the measured value recorded in the extension was applied. Then, holes were drilled to match the thickness of the extension gap and parallel to the resected tibia, to obtain a rectangular symmetrical gap. Next, a 4-in-1 femoral cutting block was used for the femoral condyle. After all the bone cuts were made, the trial was put in place, and if necessary, proper soft tissue release was performed.

For the hybrid technique cohort, the proximal tibia was resected first, and then, the distal femur was resected perpendicular to the femoral mechanical axis using an intramedullary guide to obtain the correct position of the joint line. The large posterior osteophytes and residual meniscus were removed to obtain a balanced extension gap. The rotation of the femoral component was set based on the TEA. The tension of the soft tissues was cross-verified by a tensioner to confirm the presence of a rectangular flexion gap. The planned posterior condylar resection was parallel to the tibial resection, and adjustments were made if necessary. The choice of the MR or GB technique was considered based on the condition of the patients. If there was a large osteophyte behind the knee, the MR technique was preferred. If it was difficult to identify anatomical landmarks, such as the TAPA and the TEA, in patients with trochlear dysplasia, the GB technique was used to determine femoral rotation.

Radiological Parameters

Radiological outcomes, including joint line level, mechanical alignment of the lower limb, and positions of the tibial and femoral components, were obtained from radiographs. Radiological examinations were performed before and 3 months after surgery for the full-length standing anteroposterior view and a lateral view with the knee at 45° of flexion.

The hip-knee-ankle (HKA) angle and positions of the tibial and femoral components in the coronal plane were measured on the anteroposterior radiographs. The HKA angle was defined as the angle between the line from the center of the hip joint to the center of the knee joint and the line from the center of the knee joint to the center of the ankle joint (Figure 1)[7]. The placement of the femoral component was the angle (α) between the line across the base of the femoral component and the femoral shaft axis (Figure 2A). The placement of the tibial component was the angle (β) between the base of the tibial plate and the tibial shaft axis (Figure 2B)[22].

The joint line level and positions of the tibial and femoral components in the sagittal plane were measured on a standard lateral view with the knee at 45° of flexion. The joint line was the vertical distance between the tibial tuberosity and tibial plateau before surgery (Figure 3A) and the vertical distance between the tibial tuberosity and the parallel

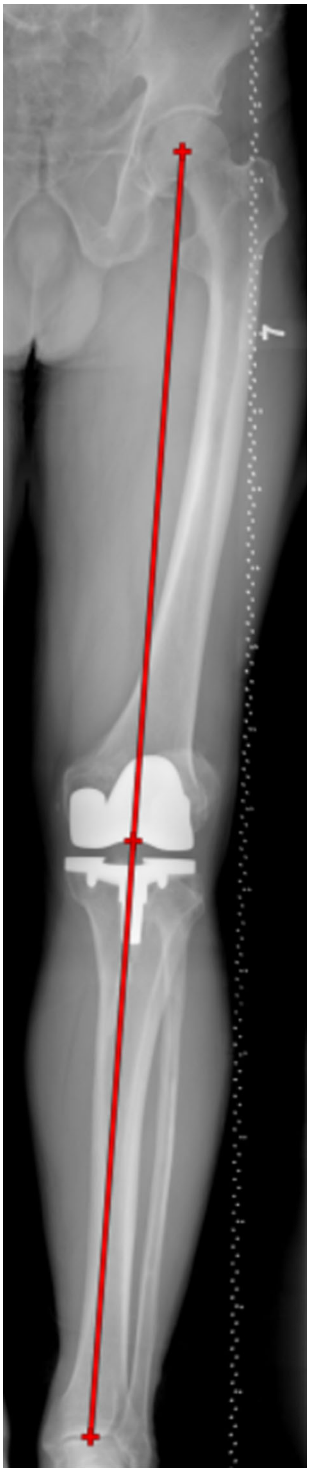

FIGURE 1 Measurements of HKA angle. HKA angle, hip-knee-ankle angle

line of the tibial component weight-bearing surface after surgery (Figure 3B)[7]. The flexion of the femoral component (FF) was the angle between the bottom of the femoral

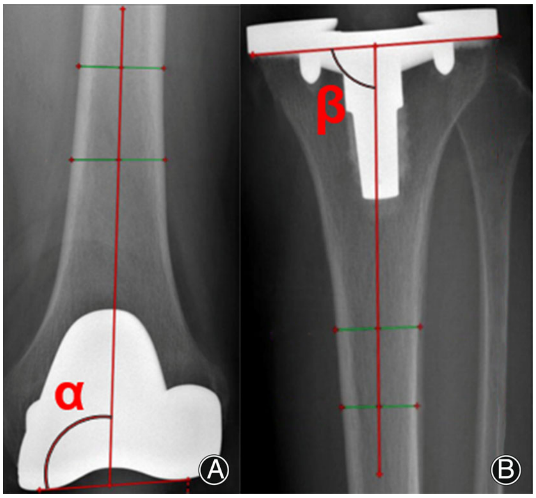

FIGURE 2 Measurements of femoral and tibial component placement in the coronal plane. (A) Placement of the femoral component: α. (B) Placement of the tibial component: β

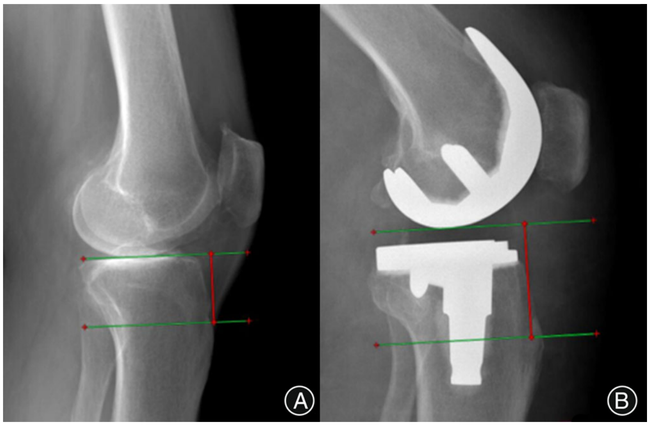

FIGURE 3 Measurements of joint line. (A) The preoperative joint line. (B). The postoperative joint line

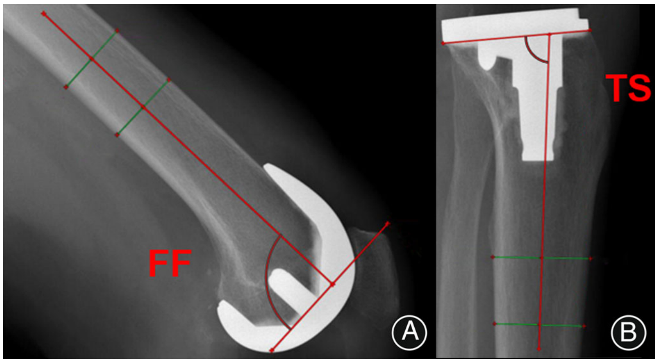

FIGURE 4 Measurements of femoral and tibial component placement in the sagittal plane. (A) Placement of the femoral component: FF. (B) Placement of the tibial component: TS. FF, femoral flexion; TS, tibial slope

component and the femoral shaft axis (Figure 4A). The tibial slope (TS) was the angle between the bottom of the tibial plate and the tibial shaft axis (Figure 4B)[23].

Rotational alignment of the femoral component was measured based on the axial computed tomography (CT) scans. The patients were required to fully extend their knees in the supine position. The collection ranged from the distal femoral metaphysis to the tibial tuberosity, and the slices were 1 mm thick. Rotation of the femoral component was defined as the femoral component rotation angle (FCRA), which was the angle between the surgical TEA (sTEA) and the PCL (Figure 5). The sTEA was defined as the line connecting the highest point on the lateral epicondyle to the lowest point of the sulcus on the medial side[24]. A positive value was defined if the PCL rotated externally relative to the sTEA, and a negative value was defined if the PCL rotated internally relative to the sTEA.

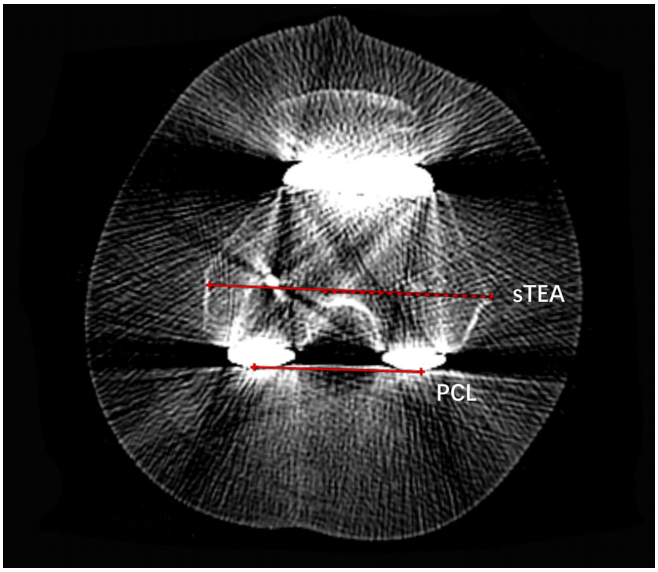

FIGURE 5 Measurements of rotational alignment of femoral component. sTEA, surgical transepicondylar axis; PCL, posterior condylar line

The RadiAnt-DICOM software (Medixant Ltd., Poznań, Poland), which has a mouse cursor that can automatically determine the distance and angle, was used for measuring. To reduce the measurement error, two independent experienced orthopaedic surgeons checked all the images and measured the relevant parameters. Another researcher discussed and solved problems together if there were differences.

Clinical Outcome Measures

Clinical outcomes, including the visual analog score for pain (VAS), the Knee Society Score (KSS), and the range of motion (ROM), were used to evaluate patient-reported outcomes to indicate the functional status of the patients[25,26]. These outcomes were evaluated before surgery and 1, 6, 12, and 24 months after surgery. All patients were evaluated by an experienced researcher who was blinded to the surgical techniques. The ROM was measured using a goniometer. All instances of postoperative complications or reoperations during the follow-up were recorded.

Statistical Analysis

The data were expressed as the mean ± standard deviation (SD) and analyzed using the SPSS statistical software (version 21.0; SPSS Inc., Chicago, IL, USA). One-way analysis of variance (one-way ANOVA) was performed for analyzing normally distributed data and Dunnett's test was conducted for pairwise comparisons between groups. Kruskal–Wallis H test was conducted for analyzing non-normally distributed data, and the Dunn–Bonferroni test was conducted for pairwise comparisons between groups. All differences were considered to be statistically significant at $p < 0.05$. To determine the reliability of inter-observer and intra-observer measurements, the intra-class correlation (ICC) values were calculated. Two measurement series of 30 radiographs and CT scans (10 per group) were randomly selected and either repeated by one researcher at intervals of 2 weeks or independently measured by two researchers.

TABLE 1 Patients' demographics in the three groups

demographics	MR group	GB group	Hybrid group	F	*p* value
Total patients	30	30	30	-	-
Age (years)	65.8 ± 2.0	65.4 ± 1.9	65.0 ± 2.1	1.100	0.338
Sex				0.089	0.956
Male	15 (50%)	16 (53%)	16 (53%)		
Female	15 (50%)	14 (47%)	14 (47%)		
BMI (kg/m^2)	22.5 ± 1.3	22.4 ± 1.4	22.5 ± 1.3	0.085	0.919
Side				0.356	0.837
Left	16 (53%)	14 (47%)	14 (47%)		
Right	14 (47%)	16 (53%)	16 (53%)		

The data was shown as n (%) or mean ± standard deviation.
Abbreviations: BMI, body mass index; GB, gap balancing; MR, measured resection.

Results

Patient Demographics

In total, 90 patients were included in the study, and each group consisted of 30 patients. All patients were followed up for at least 2 years. No complication occurred or reoperation was required in any patient. The demographic data of all patients, including gender, age, body mass index (BMI), and side, were collected before the surgery (Table 1). The demographics of the MR, GB, and hybrid groups were not significantly different. The inter-observer and intra-observer ICCs are shown in Table 2.

General Results

All surgeries were completed successfully. There was no significant difference among MR, GB, and hybrid groups in the operative time (114.2 ± 12.7 *vs* 115.8 ± 15.1 *vs* 115.7 ± 15.8 min, $p = 0.888$), intraoperative blood loss (852.7 ± 30.5 *vs* 853.3 ± 33.8 *vs* 852. ± 35.2 ml, $p = 0.993$), and the length of hospital stay (8.3 ± 2.3 *vs* 8.5 ± 2.2 *vs* 8.3 ± 2.6 days, $p = 0.877$). No wound complications occurred, such as wound infection, non-healing incision, and soft tissue injury. No major complications occurred as well, including periprosthetic fracture, aseptic loosening, knee infection, deep venous thrombosis of lower limbs, and patellofemoral joint-related complications.

Mechanical Axis

The mean values of the postoperative HKA angle in the MR, GB, and hybrid groups were 178.7° ± 1.4°, 179.2° ± 1.5°, and 179.4° ± 1.1°, respectively, with no significant difference ($p = 0.151$) (Table 3). In seven patients, the postoperative mechanical axis angle deviated by more than 3° from the ideal value of 180°. Three of these outliers occurred in the MR group, two in the GB group, and two in the hybrid group.

Position of the Components

The mean α angles of the MR, GB, and hybrid groups were 92.9° ± 0.7°, 92.7° ± 0.9°, and 93.1° ± 0.7°, respectively, and the mean β angles were 89.9° ± 0.9°, 89.9° ± 1.6°, and 90.2° ± 0.9°, respectively (Table 3). The values of the α angle ($p = 0.230$) and the β angle ($p = 0.517$) were not significantly different among the three groups. The mean FF angles

TABLE 2 Reliability assessment for measurements

Variable	MR group		GB group		Hybrid group	
	inter-observer (ICC)	intra-observer (ICC)	inter-observer (ICC)	intra-observer (ICC)	inter-observer (ICC)	intra-observer (ICC)
HKA angle	0.903	0.908	0.917	0.921	0.893	0.901
α angle	0.911	0.898	0.930	0.915	0.926	0.917
β angle	0.921	0.902	0.889	0.914	0.904	0.922
FF angle	0.903	0.887	0.902	0.912	0.911	0.896
TS angle	0.895	0.891	0.866	0.924	0.923	0.908
elevation of joint line	0.921	0.919	0.917	0.922	0.907	0.890
FCRA	0.914	0.923	0.889	0.893	0.910	0.896

Abbreviations: FCRA, femoral component rotation angle; FF, femoral flexion; GB, gap balancing; HKA, hip-knee-ankle angle; MR, measured resection; TS, tibial slope.

TABLE 3 Imaging outcomes in the three groups

	MR group	GB group	Hybrid group	F	*p* value
HKA angle (°)					
Pre-operation	170.3 ± 2.0	169.5 ± 2.3	170.8 ± 1.6	1.173	0.254
Post-operation	178.7 ± 1.4	179.2 ± 1.5	179.4 ± 1.1	1.935	0.151
α angle (°)	92.9 ± 0.7	92.7 ± 0.9	93.1 ± 0.7	1.493	0.230
β angle (°)	89.9 ± 0.9	89.9 ± 1.6	90.2 ± 0.9	0.665	0.517
FF angle (°)	88.5 ± 1.5	88.8 ± 1.2	88.7 ± 1.2	0.378	0.686
TS angle (°)	83.2 ± 1.0	83.1 ± 1.1	83.2 ± 1.1	0.085	0.918
elevation of the joint line level (mm)	2.1 ± 0.3	2.8 ± 0.2	2.1 ± 0.1	118.773	<0.001*
FCRA (°)	1.7 ± 0.3	1.8 ± 0.2	1.7 ± 0.2	2.359	0.101

The data was shown as mean ± standard deviation.
Abbreviations: FCRA, femoral component rotation angle; FF, femoral flexion; GB, gap balancing; HKA angle, hip-knee-ankle angle; MR, measured resection; TS, tibial slope.; * Significant difference: $p < 0.05$.

of the MR, GB, and hybrid groups were 88.6° ± 1.5°, 88.8° ± 1.2°, and 88.7° ± 1.2°, respectively, and the mean TS angles were 83.2° ± 1.0°, 83.1° ± 1.1° and 83.2° ± 1.1°, respectively (Table 3). The values of the FF angle ($p = 0.686$) and the TS angle ($p = 0.918$) were not significantly different. These three techniques achieved good alignment of the femoral and tibial components in the coronal and sagittal planes, but the hybrid group was closer to neutral alignment.

Joint Line

Patients in three groups had a moderate elevation of the joint line after TKA. The average elevation of the joint line in the MR, GB, and hybrid groups was 2.1 ± 0.3 mm, 2.8 ± 0.2 mm, and 2.1 ± 0.1 mm, respectively (Table 3). The elevation of the joint line was not significantly different between the MR and hybrid groups ($p = 0.627$) but was significantly different between the GB group and the other two groups ($p < 0.001$). This indicated that the MR and hybrid techniques had more advantages in maintaining the original height of the joint line.

Rotation of the Femoral Component

The mean FCRA of the MR, GB, and hybrid groups were 1.7° ± 0.3°, 1.8° ± 0.2°, and 1.7° ± 0.2°, respectively (Table 3). Although the FCRA of the GB group was larger than that of the MR and hybrid groups, the difference was not statistically significant ($p = 0.101$). This indicated that the MR, GB, and hybrid techniques performed comparable corrections of the femoral rotational alignment.

Clinical Outcomes

The preoperative and 1-, 6-, 12-, and 24-month postoperative KSS, which included the clinical scores and the functional scores, and the VAS and the ROM are shown in Table 4. Although there was no significant difference among the three groups in the improvement of clinical outcomes, the improvement in the hybrid group was slightly higher.

Discussion

The main finding of this study was that the hybrid technique achieved comparable alignment of the lower limb, the positions of the femoral and tibial components, and the rotation of the femoral component compared to the MR and GB techniques. Additionally, the hybrid technique was more helpful to maintain the original height of the joint line, which was similar to the MR technique. The hybrid technique achieved better clinical outcomes compared to the other techniques, although the differences were not statistically significant.

Mechanical Alignment of the Lower Limb

Restoration of the neutral mechanical alignment of the overall lower limb is one of the goals of TKA. According to most studies, the alignment of the lower limb should be within

TABLE 4 Clinical outcomes in the three groups

	MR group	GB group	Hybrid group	F	*p* value
KSS					
Preop	36.9 ± 4.8	36.5 ± 3.9	36.7 ± 4.2	1.049	0.356
Postop 1 month	51.3 ± 4.4	52.3 ± 4.8	52.9 ± 3.6	1.230	0.245
Postop 6 months	81.6 ± 8.0	80.7 ± 7.7	82.2 ± 9.1	0.976	0.376
Postop 12 months	88.6 ± 4.3	88.9 ± 5.2	89.0 ± 5.3	0.609	0.541
Postop 24 months	93.7 ± 6.3	92.9 ± 5.2	94.0 ± 5.8	1.041	0.357
Functional score					
Preop	36.8 ± 5.6	36.1 ± 4.2	37.4 ± 5.0	0.870	0.423
Postop 1 month	63.2 ± 8.8	65.4 ± 3.6	65.3 ± 4.5	2.140	0.124
Postop 6 months	78.5 ± 4.5	77.6 ± 5.6	78.9 ± 5.4	1.320	0.227
Postop 12 months	80.2 ± 7.8	80.9 ± 7.5	81.2 ± 6.8	1.025	0.364
Postop 24 months	86.8 ± 3.2	86.9 ± 4.0	86.8 ± 5.6	1.182	0.311
VAS					
Preop	5.0 ± 1.9	5.1 ± 1.8	5.1 ± 1.9	1.915	0.174
Postop 1 month	4.0 ± 2.1	4.1 ± 1.9	4.0 ± 1.2	1.611	0.198
Postop 6 months	3.2 ± 0.5	3.3 ± 0.8	3.1 ± 0.9	0.976	0.389
Postop 12 months	3.0 ± 1.6	2.9 ± 1.1	2.8 ± 0.9	1.322	0.277
Postop 24 months	2.2 ± 0.5	2.2 ± 0.6	2.1 ± 0.5	1.701	0.196
ROM (°)					
Preop	94.6 ± 5.6	95.1 ± 4.9	95.0 ± 5.1	1.825	0.185
Postop 1 month	104.5 ± 4.5	104.9 ± 4.9	105.0 ± 4.8	1.078	0.342
Postop 6 months	108.5 ± 6.8	107.4 ± 7.9	108.8 ± 7.2	1.122	0.331
Postop 12 months	109.9 ± 8.9	110.2 ± 7.9	110.6 ± 9.2	2.045	0.153
Postop 24 months	115.9 ± 2.3	114.8 ± 3.6	116.2 ± 2.9	1.280	0.286

The data was shown as mean ± standard deviation.; Abbreviations: GB, gap balancing; KSS, Knee Society Score; MR, measured resection; Preop, pre-operation; Postop, post-operation; ROM, range of motion; VAS, visual analog score for pain.

0 ± 3° of the neutral mechanical axis after TKA[27,28]. In this study, the postoperative HKA of the MR, GB, and hybrid groups were 178.7° ± 1.4°, 179.2° ± 1.5°, and 179.4° ± 1.1°, respectively, which showed that the mechanical alignment could be accurately restored using any of the three techniques. Three outliers were found in the MR group, two in the GB group, and two in the hybrid group. Although the alignment in the GB and hybrid groups was closer to the neutral alignment than the alignment of the MR group, the difference was not significant ($p = 0.151$). Tigani *et al.*[7] found that the mean value of the mechanical axis was 179.2° for the MR group and 179.4° for the GB group, which supported our results. Lee *et al.*[18] also showed that the mechanical alignment of the MR and GB techniques was similar after TKA, but there were fewer outliers in the GB group. However, Pang *et al.*[20] found that the GB group had significantly better limb alignment with fewer outliers than the MR group, which might be due to the introduction of the computer-assisted GB technique that improved the accuracy of soft tissue balance and the position of the implants. The meta-analysis conducted by Huang *et al.*[17] showed that the mechanical alignment in the GB group was better than its restoration in the MR group. However, they stated that these two techniques did not affect the coronal alignment, and thus, the differences were difficult to explain.

Positions of the Femoral and Tibial Components

Neutral alignment of the lower limb should be achieved based on the optimal positions of the femoral and tibial components[26]. Poor positioning of the components can increase the failure rate after TKA and adversely affect postoperative clinical outcomes[29]. We found that the positions of the components in the coronal and sagittal planes were not significantly different among the three groups, indicating that these techniques could achieve good alignment of the femoral and tibial components, but the alignment in the hybrid group was closer to the neutral alignment. Tigani *et al.*[7] reported a good alignment for the femoral and tibial components in the coronal and sagittal planes with no significant difference between the GB and MR techniques. However, they found greater alignment variability in the sagittal plane, especially for the tibial component, which was due to the different implants used with a different posterior slope[7]. Sabbioni *et al.*[30] also reported no cases of misalignment of the femoral or tibial components in the coronal and sagittal planes; more than 96% and 98% of the cases had a value of within ±1° of deviance for the femoral and tibial components, respectively.

Joint Line Level

We found that the MR, GB, and hybrid techniques facilitated a moderate elevation of the joint line postoperatively. The average elevation of the joint line in the MR, GB, and hybrid groups was 2.1 ± 0.3 mm, 2.8 ± 0.2 mm, and 2.1 ± 0.1 mm, respectively, showing that the difference between the MR and hybrid groups was not significant. However, the difference between the GB group and the other two groups was significant. This implied that the MR and hybrid techniques had more advantages than the GB technique in preserving the original height of the joint line. Tigani *et al.*[7] found a moderate increase in the joint line postoperatively in the GB and MR groups, where the MR technique was better in maintaining the original value of the joint line, compared to the GB technique. Huang *et al.*[17] also showed a higher position of the joint line in the GB group. A normal position is beneficial for restoring postoperative kinematics and avoiding adverse effects on the outcomes[17]. The elevation of the joint line by applying the GB technique might be due to the priority of gap symmetry. Removing more bones and enlarging the components in the GB technique might lead to an increase in the symmetry of the gap and the joint line[31]. Because the hybrid technique also uses certain aspects of the MR technique for the resection of the proximal tibia and the distal femur, the level of the joint line in the hybrid technique might be similar to that of the MR technique. Our results confirmed this hypothesis.

Rotation of the Femoral Component

Correct rotation of the femoral component is important for good kinematics after TKA. In this study, we showed that all three techniques could accurately determine the rotation of the femoral components. The mean FCRA of the MR, GB, and hybrid groups was 1.7° ± 0.3°, 1.8° ± 0.2°, and 1.7° ± 0.2°, respectively. Although the FCRA of the GB group was larger than that of the other two groups, the difference was not statistically significant. The results were consistent with those of other studies and showed that the GB technique had more external rotation tendency, but the biomechanical effect on the knees could be ignored[19,32,33]. In the GB technique, a larger joint space opening on the lateral side could be made due to the application of equal tension on the medial and lateral collateral ligaments, which might explain the reason for the presence of a more externally rotated flexion gap[32]. The MR technique also has some disadvantages associated with the restoration of the external rotation of the femoral component. Determining the landmark in the MR technique might be difficult due to its degeneration and variation. Using the TEA as a reference might introduce inaccuracies because only 75% of the knees are within 3° of the TEA[33]. Additionally, the degeneration of the posterior condyle might be misleading when the PCL is used as the reference, especially in valgus knees[33]. However, most of the disadvantages of the MR and GB techniques can be avoided by applying the hybrid technique, which combines their strengths while determining the rotational alignment of the femoral components and maintaining the biomechanics of the knees.

Clinical Outcomes

Although the postoperative clinical outcomes did not differ significantly among the three groups, the improvement in the hybrid group was slightly higher, which indicated that the hybrid technique could achieve good clinical results. The clinical outcomes in the MR and GB techniques, including the Hospital for Special Surgery score, the KSS, the functional Knee Society score, the revised Oxford Knee score, and the ROM, were similar in many studies, although these techniques were found to differ in soft tissue balance[17,18,34,35]. This similarity might be due to the relatively small asymmetry in soft tissue balance obtained using different techniques for creating a symmetrical gap and preventing excessive medial release in each knee[18]. A relatively short-term follow-up period and inaccuracies in the clinical scoring system also affected the clinical outcomes. Therefore, whether the well-balanced knees with different techniques can achieve similar long-term good clinical outcomes needs to be investigated.

Strengths and Limitations

Our study had some strengths. This was the first study to evaluate and compare imaging and clinical outcomes among patients with MR, GB, and hybrid techniques for at least 2 years after TKA. The study focused on the joint line level, the mechanical alignment of the lower limb, the positions of the tibial and femoral components, the rotation of the femoral component, the functional scores, and the ROM. Additionally, the ICC values of all imaging parameters were more than 0.8. This indicated good reliability of inter-observer and intra-observer measurements, which enhanced the accuracy of our results.

This study had some limitations. First, this was a retrospective follow-up study, in which randomization could not be performed. Second, this study was limited by a relatively short-term follow-up of at least 2 years. This follow-up time was sufficient for our main research purpose, to evaluate the joint line, the mechanical alignment, and positions of the tibial and femoral components. However, a long-term follow-up should be considered for evaluating the clinical outcomes[30]. Third, only a few patients were included in this study.

Conclusions

We found that the hybrid technique facilitated the alignment of the lower limb, the positions of the femoral and tibial components, and the rotation of the femoral component, which was comparable to that achieved by the MR and GB techniques. Additionally, the hybrid technique was more helpful to maintain the original height of the joint line, which was similar to the MR technique. The hybrid technique achieved better clinical outcomes compared to the other techniques, although the differences were not statistically significant. These findings might provide references for the choice of techniques for surgeons. Prospective cohort studies should be conducted with long-term follow-up and sufficient sample size from multiple hospitals to evaluate long-term imaging and clinical outcomes and confirm our findings. Additionally, random allocation of the MR, GB, and hybrid techniques for patients included in the study is necessary to reduce bias. Future studies should also examine the relationship between the differences in the various techniques and the clinical outcomes of the patients.

Ethics Approval

This study was performed in line with the principles of the Declaration of Helsinki. Approval was granted by the Ethics Committee of Third Hospital of Hebei Medical University (Number: Z2020-001–2).

Consent to Participate

Informed consent was obtained from all individual participants included in the study.

Consent for Publication

Patients signed informed consent regarding publishing their data and photographs.

Availability of Data and Material

The datasets used or analyzed during the current study are available from the corresponding author on reasonable request.

Code Availability

No code was generated or used during the study.

Authors' Contributions

Fei Wang supervised, coordinated, and provided further advice on revisions. Kuo Hao conceived of the manuscript, and participated in its design, drafted and wrote the manuscript. Maozheng Wei conceived of the manuscript and participated in its design. Gang Ji conceived of data collection and data analysis. Yanfeng Jia conceived of literature search and analysis.

KH and MW contributed to the article equally.

The first draft of the manuscript was written by Kuo Hao and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Conflicts of interest

The authors have no conflicts of interest to declare.

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