Discrepancies in Coronal Alignment Measurements between Full-length Weight-bearing Radiographs and Computed Tomography in Robotic Arm-assisted Total Knee Arthroplasty with the Mako System

Hong Yeol Yang
Chonnam National University Hwasun Hospital
Khairul Ayob
University of Malaya
Hwi Woo Jeong
Chonnam National University Hwasun Hospital
Jong Keun Seon
seonbell@chonnam.ac.kr

Chonnam National University Hwasun Hospital

Article

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Abstract

Introduction: Assessment of lower limb coronal plane alignment is crucial in surgical planning of total knee arthroplasty (TKA) and is commonly performed with full-length weight-bearing radiographs (FLWBR). The aim of this study was to determine discrepancies in coronal limb alignment as assessed by conventional FLWBR versus non-weight-bearing computed tomography (CT) modalities in robotic arm-assisted TKA performed using the Mako system (Stryker).

Methods: We retrospectively analyzed 100 consecutive patients with osteoarthritic knees who underwent robotic arm-assisted TKA with preoperative FLWBR and CT assessments of knee alignment. The mechanical axes of the Mako system were established in accordance with the Mako TKA Surgical Guide. The following parameters were compared between the two imaging modalities: (1) mechanical hip-knee-ankle angle (mHKA), (2) medial proximal tibial angle (MPTA), (3) lateral distal femoral angle (LDFA), (4) arithmetic hip-knee-ankle angle (aHKA), (5) joint line obliquity (JLO), and (6) proportion of the coronal plane alignment of the knee (CPAK) types. Regression analyses were performed to identify potential factors associated with discrepancies in measurements of coronal alignment between these two imaging modalities.

Results: There were significant differences in terms of the mHKA between preoperative CT and FLWBR (CT vs FLWBR, 7.0° vs. 8.5°; $p < 0.001$), which may be attributed to the extent of the weight-bearing condition. The CT measurements with the Mako system demonstrated a lower (more varus) MPTA than the FLWBR measurements (CT vs FLWBR, 83.7° vs. 85.2°; $p < 0.001$). Furthermore, there were also significant differences between the CT and FLWBR measurements in terms of the aHKA (−4.7° vs. −3.7°; $p = 0.028$) and JLO (172.2° vs. 174.2°; $p < 0.001$). There were significant differences of proportion of CPAK types between the two imaging modalities; however, the most common category was type I in both imaging modalities. Multivariate analyses showed that greater preoperative mHKA and posterior tibial slope were associated with the discrepancy in the MPTA measurements between the two imaging modalities.

Conclusion: There were discrepancies in coronal alignment between preoperative FLWBR and non-weight-bearing CT using the Mako system. When compared with conventional FLWBR, the Mako system tended to overestimate the magnitude of tibial varus deformity in the knee joint.

Level of Evidence: Level IV.

Introduction

Total knee arthroplasty (TKA) is an established surgical option for the treatment of severe osteoarthritis of the knee and has a survival rate of 82% at 25 years[1,2]. Achievement of accurate prosthesis positioning and good lower-limb alignment are generally considered important determinants of outcomes after TKA[3,4]. New technologies are continuously being developed, and robotic arm-assisted TKA was introduced to increase the precision of the prosthetic component and limb alignment to improve clinical outcomes and implant survivorship[5–7].

Assessment of lower limb coronal plane alignment is crucial in surgical planning of TKA and is usually performed with full-length weight-bearing radiography (FLWBR) in a standing position[8]. However, various factors may influence measurement of alignment on FLWBR, including rotation of the hip and/or leg and lower limb deformities in the sagittal plane[9–11]. In robotic arm-assisted TKA, such as in the widespread Mako Total Knee application system (Stryker, Kalamazoo, Michigan, USA), preoperative computed tomography (CT) is performed for segmentation. This modality generates patient-specific three-dimensional images of the knee to enable the virtual placement of the components and to determine limb alignment for preoperative planning. The femoral mechanical axis (MA) is determined by a line connecting the center of the femoral head to the Mako femoral knee center, while the tibial MA is determined by a line connecting the Mako tibial knee center to the Mako ankle center[12]. However, measurement of coronal limb alignment is conducted in a supine and non-weight-bearing position for CT. This may influence the varus/valgus angulation at the knee joint and result in different results compared with those obtained with routine FLWBR since the loading forces on the knee joint are significantly decreased in the supine position[13–16].

The discrepancy in determining the MA as well as the weight-bearing condition between preoperative FLWBR and CT to assess knee joint alignment may result in a mismatch in coronal alignment between the intraoperative values and postoperative results[15,17,18]. Glowalla et al. have recently reported that there was a discrepancy between the residual varus deformity assessed intraoperatively with the Mako system and that evaluated with postoperative FLWBR[19]. They recommended careful preoperative planning in robotic arm-assisted TKA to prevent excessive overcorrection in varus knee osteoarthritis. In our clinical experience, these discrepancies between the robot-assessed intraoperative angle in the coronal plane of the knee and that assessed intuitively by surgeons can create a difficult situation. However, despite the possible clinical effect on postoperative outcomes after TKA, only a few previous reports have evaluated these discrepancies in coronal alignment in robotic arm-assisted TKA assessed using these two imaging modalities under different weight-bearing conditions.

Accordingly, the aim of the present study was to determine the discrepancies in coronal alignment between FLWBR and supine CT performed with the Mako system (Mako TKA 2.0 software) prior to robotic arm-assisted TKA. The Mako 2.0 software currently allows for direct measurement of coronal alignment, which was a limitation of the Mako 1.0 software that made indirect calculations by virtually positioning the femoral and tibial components[20]. Our hypothesis was that there would be a significant difference in the coronal limb alignment values determined by these two different imaging modalities.

Methods

Patients

This study was approved by the institutional review board of our institution. We retrospectively identified a total of 110 consecutive series of patients who were scheduled for robotic arm-assisted TKA (Mako, Stryker, Michigan, USA) to treat end-stage knee degenerative osteoarthritis between July 2023 and February 2024. Patients were excluded if they had prior ipsilateral knee surgery, posttraumatic osteoarthritis, inflammatory arthritis, flexion contracture greater than 10°, severe arthritic bone loss on preoperative radiographs, or incomplete data. Preoperative FLWBR was routinely performed for all the patients, and these patients also underwent a non-weight-bearing CT scan using the Mako Total Knee application (Mako TKA 2.0 software) for preoperative planning. Finally, a total of 100 patients (100 knees) were included in this study and were analyzed (Table 1).

Table 1

Patient Demographic and Radiographic Characteristics*

	Value
Age *(yr)*	72.9 ± 6.3
Female sex *(no. of patients)*	85 (85.0)
Body mass index *(kg/m²)*	26.3 ± 4.1
ASA grade *(no. of patients)*	
II	63 (63.0)
III	37 (37.0)
Side of operation *(no. of patients)*	
Right	47 (47.0)
Left	53 (53.0)
Preoperative radiographic parameters *(deg)*	
mHKA† *(deg)*	8.5 ± 4.0
MPTA *(deg)*	85.2 ± 2.3
LDFA *(deg)*	88.9 ± 2.1
JLCA‡ *(deg)*	4.3 ± 2.2
Posterior tibial slope *(deg)*	8.5 ± 3.2

*Values are presented as the mean ± standard deviations or No. (%).

†A positive angle represents varus alignment, and a negative angle represents valgus alignment.

‡A medial JLCA apex was recorded as positive and denoted as varus, while a lateral JLCA apex was recorded as negative and denoted as valgus.

ASA, American Society of Anesthesiologists; mHKA, mechanical hip-knee-ankle angle; MPTA, medial proximal tibial angle; LDFA, lateral distal femoral angle.

Image Acquisition Protocol

FLWBR was obtained following the method described by Paley et al.[21]. Patients were positioned barefoot in a bipedal stance on a radiolucent table in front of a long-length film cassette with the patella in front and with a neutral position of the ankle. The X-ray beam was centered on the knee of the imaged leg from a distance of 2 m. The voltage and current were typically 200 mA, and 85 kV, respectively. It was crucial to confirm that the patella was centered between the femoral condyles on the radiograph and that the ankle was placed in a neutral position.

For CT, the tube current was adjusted to 120 kV with an effective mAs ranging from 50 to 70. Helical scans encompassed the area from proximal to the acetabulum to distal to the ankle joint, with image reconstructions at intervals of 2 mm for the hip and ankle joints and 0.5 mm for the knee joint[22,23]. The DICOM images were subsequently sent to the robotic platform to determine the coronal plane alignment, and coronal alignment values derived from the CT scans were automatically measured within the robotic system software.

FLWBR Measurements

For FLWBR measurements, preoperative radiographic evaluation included determination of the mechanical hip-knee-ankle angle (mHKA), medial proximal tibial angle (MPTA), lateral distal femoral angle (LDFA), and joint line convergence angle (JLCA) (Fig. 1). The mHKA was measured as the angle formed by the MA of the femur (center of the femoral head to center of the distal femur at the knee joint) and MA of the tibia (center of the tibial plateau at the knee joint to center of the tibial plafond at the ankle joint), as previously described (positive for varus)[14,18]. The MPTA was defined as the medial angle between the MA of the tibia and a tangential line to the tibial plateau. The LDFA was defined as the lateral angle between the MA of the femur and a tangential line between the most distal points of the femoral condyles. The JLCA was defined as the angle between lines tangent to the femoral condyles and tibial plateau; the lateral opening was designated as a positive value. The posterior tibial slope was measured on standard lateral radiographs as previously described and calculated by measuring the angle between the line perpendicular to the proximal tibial anatomical axis and the line tangent to the medial tibial plateau (Fig. 2)[24].

Two independent orthopedic surgeons who did not directly participate in the surgical procedures and were blinded to the study aims measured all the radiographic parameters two times, with an interval of four weeks between the assessments, to determine the intra- and interobserver reliabilities of the radiographic assessments. All intra- and interobserver intraclass correlation coefficients of the measurements of the radiographic parameters indicated good agreement (> 0.75).

CT Measurements

The analogous definitions to those used for FLWBR were applied to identify landmarks using CT (mHKA) as well as cross-sectional CT imaging and three-dimensional (3D) reconstructions (MPTA, LDFA, arithmetic HKA [aHKA], and joint line obliquity [JLO]) within the robotic system. The hip, knee and ankle centers were imputed, and the MAs of the Mako system were established in accordance with the Mako TKA 2.0 Surgical Guide[12,25]. The Mako femur knee center was measured as the most distal point of the trochlear groove in both the coronal and sagittal planes; thus, the Mako MA of the femur was determined as the line connecting the center of the femoral head to the Mako knee center. The Mako tibia knee center was measured at the exit point of the tibial shaft axis in both the coronal and sagittal planes. It was located slightly anterior to the eminence peaks and posterior to the footprint of anterior cruciate ligament. The Mako ankle center was positioned along the line between the most prominent medial and lateral malleoli approximately 44% of the distance from the medial malleolus and 56% from the lateral malleolus (Fig. 3). Thus, the Mako MA of the tibia was determined as the line connecting the Mako knee center and Mako ankle center. Femoral and tibial constitutional landmarks were identified by placing points at the most distal part of the condyles for the femur and at the center of the medial and lateral articular surfaces for the tibia (Fig. 4).

The Mako 2.0 software currently allows for direct measurement of coronal alignment, and the MPTA and LDFA in the CT group were automatically measured within the robotic system software. A MAKO product specialist performed all the robotic measurements and calculations with a consistent nature and methodology; thus, there was no need for independent measurements by different observers.

Radiographic Assessment

With the MPTA and LDFA measured on both FLWBR and CT, we determined the constitutional knee phenotypes using the coronal plane alignment of the knee (CPAK) classification described by MacDessi et al.[26]. The constitutional alignment, termed the aHKA and JLO were measured according to the following algorithms: aHKA = MPTA – LDFA, and JLO = MPTA + LDFA. Patients were matched using the three subgroups of the aHKA that are set against the three subgroups of JLO in the matrix, resulting in nine possible CPAK phenotypes (Fig. 5).

Statistical Analysis

Scatterplot visualization was used to describe the proportions of native coronal plane alignment of the knee phenotype in study cohort. For normally distributed variables, paired and independent t-tests were performed to analyze differences. For non-normally distributed variables, the Wilcoxon signed-rank test and Mann-Whitney U test were used to analyze differences. The chi-square test or Fisher's exact test was used to compare differences in categorical variables. Factors that could potentially cause discrepancies in measurements of coronal alignment (gender, age, body mass index, American Society of Anesthesiologists grade, mHKA, JLCA, and posterior tibial slope) were analyzed with a generalized linear model. The threshold for significance was $P < 0.05$.

Results

Patient demographic characteristics and clinical data are summarized in Table I. All the included patients had preoperative varus knee alignment (HKA angle 8.5°) on FLWBR, and the deviation from the reference value (MPTA 87.0° and LDFA 88.0°) was higher for the MPTA than for the LDFA (1.8° versus. 0.9°, $p = 0.013$).

Radiological Outcomes

The mean preoperative mHKA, MPTA, LDFA, aHKA, and JLO as determined by FLWBR and CT are presented in Table II. There were significant differences in terms of the mHKA between preoperative CT and FLWBR measurements (CT vs FLWBR, 7.0° vs. 8.5°; $p < 0.001$). The preoperative CT measurements using the Mako system demonstrated a lower (more varus) MPTA (CT vs FLWBR, 83.7° vs. 85.2°; $p < 0.001$), a more negative (more constitutional varus) aHKA (− 4.7° vs. −3.7°; $p = 0.028$), and a lower (greater apex distal oblique) JLO (172.2° vs. 174.2°; $p < 0.001$) than the FLWBR measurements. There were no significant differences in terms of the LDFA between the two imaging modalities ($p = 0.072$).

The groups were analyzed by CPAK classification, and significant differences were observed in the distribution ($p = 0.001$); the most common was type I (FLWBR, 58.0% vs. CT, 83.0%) followed by type II (FLWBR, 17.0% vs. CT, 13.0%) (Table 2).

Table 2

Radiological Comparison between FLWBR and CT Measurements*

	FLWBR	**CT (Mako System)**	***P* Value†**
Radiological parameters			
mHKA‡ *(deg)*	8.5 ± 4.0	7.0 ± 3.0	< **0.001**
MPTA *(deg)*	85.2 ± 2.3	83.7 ± 2.0	< **0.001**
LDFA *(deg)*	88.9 ± 2.1	88.5 ± 2.1	0.072
aHKA *(deg)*	−3.7 ± 2.9	−4.7 ± 2.8	**0.028**
JLO *(deg)*	174.2 ± 3.2	172.2 ± 3.0	< **0.001**
CPAK classification distribution			**0.001**
Type I	58	83	
Type II	17	13	
Type III	4	3	
Type IV	17	0	
Type V	4	0	
Type VI	0	0	
Type VII	0	0	
Type VIII	0	0	
Type IX	0	0	

*Values are presented as the mean ± standard deviations or as the count.

†An independent t-test was used to analyze differences in radiological parameters, and Fisher's exact test was used to analyze the differences in the CPAK classification distributions. Bold indicates a significant difference.

‡A positive angle represents varus alignment, and a negative angle represents valgus alignment. The mHKA in the CT group was measured on preoperative CT without weight-bearing.

FLWBR, full-length weight-bearing radiographs; CT, computed tomography; mHKA, mechanical hip-knee-ankle angle; MPTA, medial proximal tibial angle; LDFA, lateral distal femoral angle; aHKA, arithmetic hip-knee-ankle angle; JLO, joint line obliquity; CPAK, Coronal Plane Alignment of the Knee.

Factors Influencing Differences in Coronal Alignment Measurements

Both the univariable and multivariate analyses demonstrated that a greater preoperative mHKA (p = 0.026) and posterior tibial slope (p = 0.046) were related to differences in the MPTA between FLWBR and

CT measurements (Table 3).

Table 3
Univariate and Multivariate Analyses of Preoperative Variables and the Discrepancies in MPTA Measurements between FLWBR and CT with a Generalized Linear Model*

Preoperative Variable	Univariate Analysis		Multivariate Analysis	
	Estimate (95% CI)	P Value*	Estimate (95% CI)	P Value*
Age	−0.024 (− 0.074 to 0.315)	0.367		
Sex (female vs male)	−0.191 (− 0.851 to 1.011)	0.688		
Body mass index	− 0.069 (− 0.141 to 0.019)	0.100		
ASA grade	0.179 (− 0.353 to 1.075)	0.607		
mHKA† *(deg)*	0.087 (0.007 to 0.175)	**0.027**	0.086 (0.011 to 0.162)	**0.026**
JLCA‡ *(deg)*	0.003 (− 0.214 to 0.126)	0.963		
Posterior tibial slope *(deg)*	0.104 (− 0.001 to 0.202)	**0.047**	0.103 (0.002 to 0.203)	**0.046**

*Bold indicates a p value < 0.05 (statistically significant difference).

†A positive angle represents varus alignment, and a negative angle represents valgus alignment.

‡A medial JLCA apex was recorded as positive and denoted as varus, while a lateral JLCA apex was recorded as negative and denoted as valgus.

ASA, American Society of Anesthesiologists; mHKA, mechanical hip-knee-ankle angle; JLCA, joint line convergence angle.

Discussion

The principal finding of this study is that discrepancies are evident in the coronal alignment determined by preoperative FLWBR versus non-weight-bearing CT using the Mako system. Significantly less varus deformity was reported with preoperative CT measurements than with FWLBR measurements, which may be attributed to the absence of loading or weight-bearing when this imaging study is performed. Furthermore, compared with conventional FWLBR, the Mako system tends to overestimate the magnitude of tibial varus deformity. Our findings suggest that FLWBR is still a vital tool for coronal alignment analysis in the planning of robotic arm-assisted TKA, especially for those patients with a larger preoperative mHKA and increased posterior tibial slope.

To our knowledge, the present study is the first to elucidate differences in coronal alignment in an Asian population between conventional FLWBR and CT measurements using the MAKO system. Tarasosoli et al. first reported the differences between these two imaging modalities by quantifying the coronal plane alignment of the lower limb in TKA within the same Australian population[25]. However, these results may vary in the global population. Song et al. have previously demonstrated that the mechanical alignment of the lower limb was not neutral in an Asian population and that the prevalence of constitutional varus was higher than that in the Caucasian population[27]. Furthermore, Asian patients tended to have more varus and a wider distribution in lower limb alignments than Caucasian individuals[27,28]. Our findings suggest that a greater understanding of the discrepancies in alignment between measurements made with these two imaging modalities would aid surgeons in establishing a more personalized approach to patients undergoing TKA.

Although systematical restoration of a neutral mechanical alignment of the lower limb is a classic goal for TKA, up to 20% of patients remain dissatisfied following TKA[4,29]. Furthermore, there is increasing evidence that deviations from the classic mechanical alignment does not affect long-term survivorship[30]. It remains questionable whether aligning to a standardized neutral mechanical alignment leads to the optimal solution for every patient undergoing TKA, regardless of the widely variable "constitutional alignment" between individuals[31–33]. Based on this and the relatively large amount of patient dissatisfaction after TKA, kinematic alignment has been introduced as an alternative approach. This technique involves individualized alignment target that aims to restore the pre-arthritic or native limb and joint line alignment of each patient, thereby restoring the native joint laxities[31,34,35]. The considerable variation in human lower limb alignment, as demonstrated by multiple authors, suggests the need to consider and potentially adopt a more personalized alignment approach during TKA[31,34]. Several clinical studies have demonstrated their modified alignment options and philosophies to be reliable techniques that better represent the preoperative knee phenotype[20,36,37].

Achieving the planned alignment is a crucial determinant of outcomes following TKA[38,39]. The gold standard method for assessing the lower limb coronal alignment is the MA determined using FLWBR[13,14,40,41]. FLWBR can be performed rapidly and is widely available and cost-effective [42]. However, one issue with this method is the potential errors due to suboptimal patient positioning. As previously reported, rotation of the hip and/or leg and lower limb deformities in the sagittal plane may influence measurements in the coronal alignment[9,10]. Newer imaging methods such as CT and magnetic resonance imaging (MRI) can overcome this issue and are promoted for determining lower limb alignment. Although these imaging modalities can avoid positioning errors, they cannot currently provide weight-bearing assessments; therefore, the true knee alignment may not be well represented in the supine position as there are no loading forces on the knee joint in this position[13–16]. Schoenmakers et al. evaluated the within-persons agreement in the mHKA measured on FLWBR and non-weight-bearing measurement modalities (computer-assisted surgery navigation or MRI) and demonstrated that on average, up to 2.5° differences existed between these two imaging measurement modalities, even within the same observer[15]. Holme et al. assessed the differences in knee alignment measurements between FLWBR and CT in native knees and after unicompartmental knee arthroplasty and recommended that CT should not be used as an alternative to FLWBR for coronal alignment analysis of the knee[16]. León-Muñoz et al. identified potential differences between preoperative FLWBR- and non-weight-bearing CT-based 3D models when assessing the knee joint alignment before TKA[43]. They concluded that CT-based models underestimate the extent of deformity at the knee joint and that although CT provided an accurate assessment of bone morphology, FLWBR should be the primary assessment method for preoperative planning for TKA to evaluate the extent of coronal mediolateral tension.

In the present study, there were discrepancies in coronal alignment between preoperative FLWBR and non-weight-bearing CT measurements made using the Mako 2.0 system. In particular, we observed a significant mean difference between measurements made with these two imaging modalities for the MA and MPTA; therefore, surgeons using the Mako system should be aware of these discrepancies between CT and conventional FLWBR. In our study, these differences could not be solely explained by the effect of the extent of the weight-bearing condition. The method by which we defined the femoral and tibial axes may also have contributed to these differences. Tarassoli et al. evaluated the discrepancies between these two imaging modalities (FLWBR and CT using the Mako 1.0 system) by quantifying the coronal plane alignment of the lower limb in TKA[25]. They concluded that these differences may change the CPAK type as well as JLO and showed an increase in the proportion of patients with CPAK type I as determined by CT measurements compared with FLWBR measurements. These findings are consistent with our results. Glowalla et al. studied differences in the knee alignment determined between postoperative FLWBR and CT measurements and found less varus positioning of the tibial component on postoperative FLWBR than on intraoperative measurements made with the Mako system[19]. They suggested that careful preoperative planning and fine-tuned adjustments of the component position in robotic arm-assisted TKA are necessary to prevent excessive overcorrection in varus knee osteoarthritis. However, these studies used the Mako 1.0 software, which lacks the ability to directly measure alignment; instead, the measurements were made indirectly by virtually positioning the component in the planning software, which was different from the points of reference what we measured[20].

The multivariate analysis in this study demonstrated that the discrepancies in measurements of coronal alignment were more pronounced in patients with a larger preoperative mHKA and posterior tibial slope. This is more important in the Asian population because these patients have been shown to have more varus and an increased posterior tibial slope in terms of lower limb alignment[27,28,44]. Panzica et al. have demonstrated that preoperative measurements involve a higher level of ligamentous imbalance, which results in greater alignment deformity in the weight-bearing condition[45]. A better understanding of population-level variability in the characteristics of the knee may enable surgeons to offer more individualized recommendations when considering alignment strategies.

Our study has certain limitations. First, it was an observational study performed at a single institute. Second, radiographic measurement errors including fixed flexion contractures and limb rotational mispositioning could not be excluded, suggesting that alternative advanced imaging techniques may offer greater precision. Third, geographic variation in the knee phenotypes between populations are nascent, and another limitation of this study is the potential differences between the races in terms of coronal alignment[46]. Thus, our findings may not be applicable to global populations. Finally, only the Mako system was assessed in this study, and the definition of the MA may differ among various robotic systems. A comparison between various robotic systems is needed to address this aspect in the future.

Conclusion

There were discrepancies in coronal alignment determined by preoperative FLWBR and non-weight-bearing CT measurements made using the Mako system. When compared with conventional FLWBR, the Mako system tended to overestimate the magnitude of varus deformity in the knee joint, especially the tibia.

Abbreviations

TKA
Total knee arthroplasty
FLWBR
Full-length weight-bearing radiographs
CT
Computed tomography
MA
Mechanical axis
mHKA
Mechanical hip-knee-ankle angle
MPTA
Medial proximal tibial angle
LDFA
Lateral distal femoral angle
aHKA
Arithmetic hip-knee-ankle angle
JLO
Joint line obliquity
CPAK
Coronal plane alignment of the knee
JLCA
Joint line convergence angle
3D
Three-dimensional

MRI
Magnetic resonance imaging

Declarations

Ethical approval

All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Declaration of Helsinki and its later amendments or comparable ethical standards. This study has been approved by the Institutional Review Board (IRB) of Chonnam National University Hwasun Hospital (CNUHH-2023-248) and informed written consent for participation in the study was obtained.

Consent for publication

Consent for publication in the study was obtained.

Competing interests

The authors declare that they have no competing interests.

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Author Contribution

HYY collected the data, performed the measurement and analysis, participated in the study design, and drafted the manuscript. KAA, HWJ collected the data, performed the measurement. JKS designed the study, supervised the whole study process, and helped to draft and review the manuscript. All authors read and approved the final manuscript.

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None.

Data Availability

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

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Figures

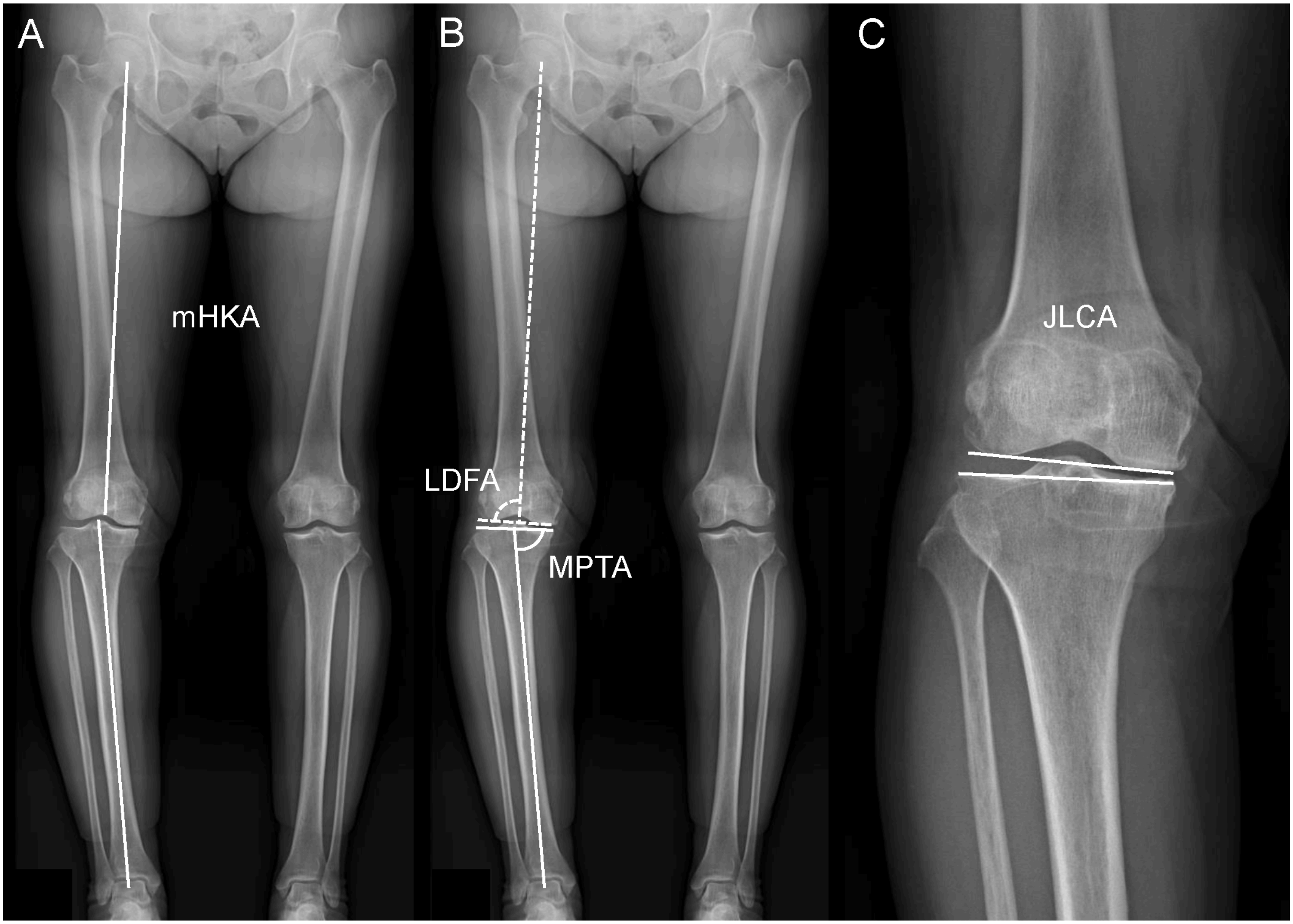

Figure 1

Measurement of the mHKA, MPTA, LDFA, and JLCA on FLWBR. (A) The mHKA was determined by intersecting the line between the femoral and tibial MAs. (B) The LDFA was defined as the lateral angle between the MA of the femur and the joint line of the distal femur. (C) The MPTA was defined as the medial angle between the MA of the tibia and the joint line of the proximal tibia. (D) The JLCA was defined as the angle between lines tangent to the femoral condyles and tibial plateau. mHKA, mechanical hip-knee-ankle angle; LDFA, lateral distal femoral angle; MPTA, medial proximal tibial angle; JLCA, joint line convergence angle; FLWBR, full-length weight-bearing radiographs.

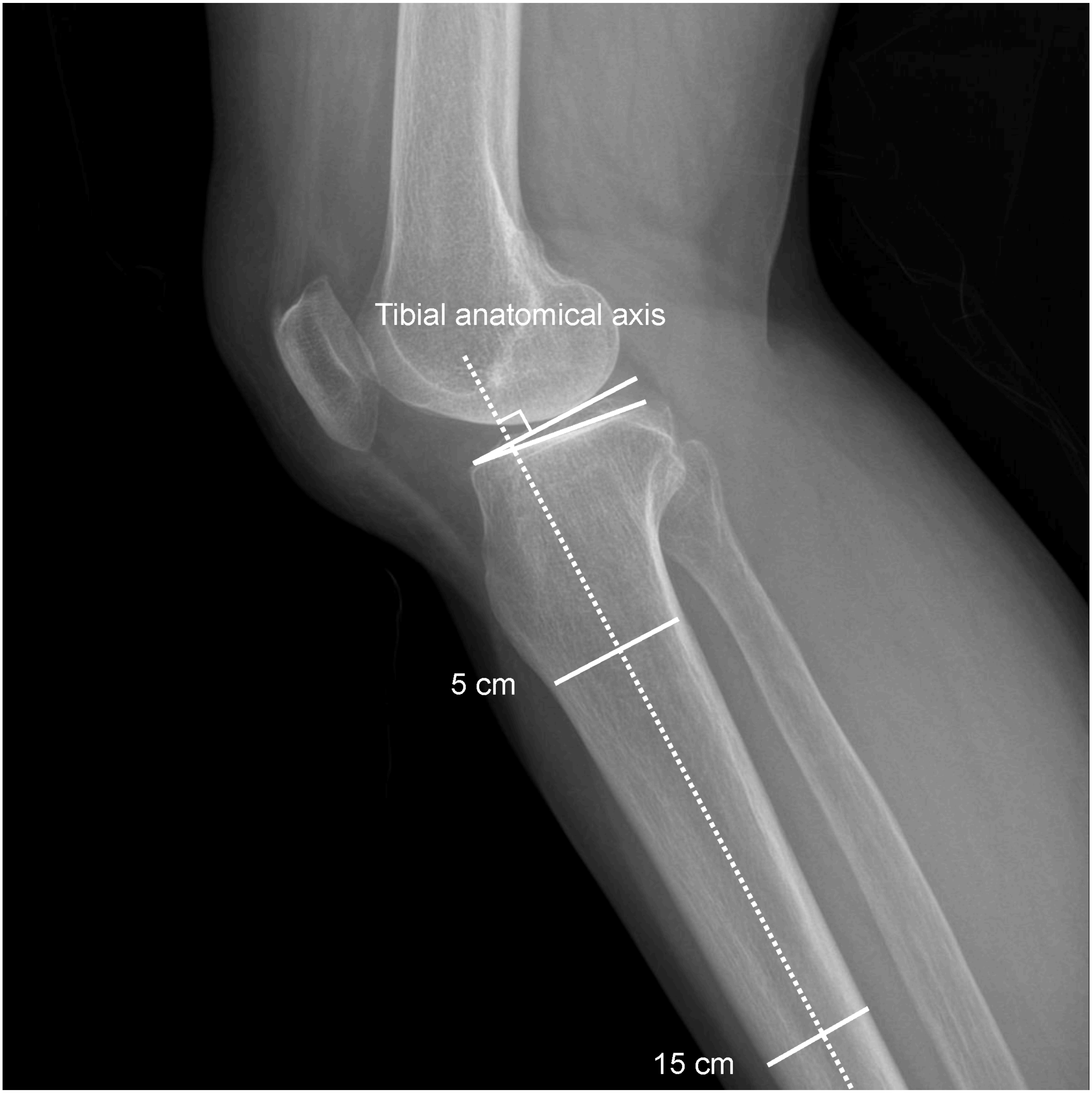

Figure 2

Lateral radiograph showing the measurement of the posterior tibial slope of a left knee. The posterior tibial slope was defined as the angle between the line perpendicular to the proximal tibial anatomical axis and the line tangent to the medial tibial plateau.

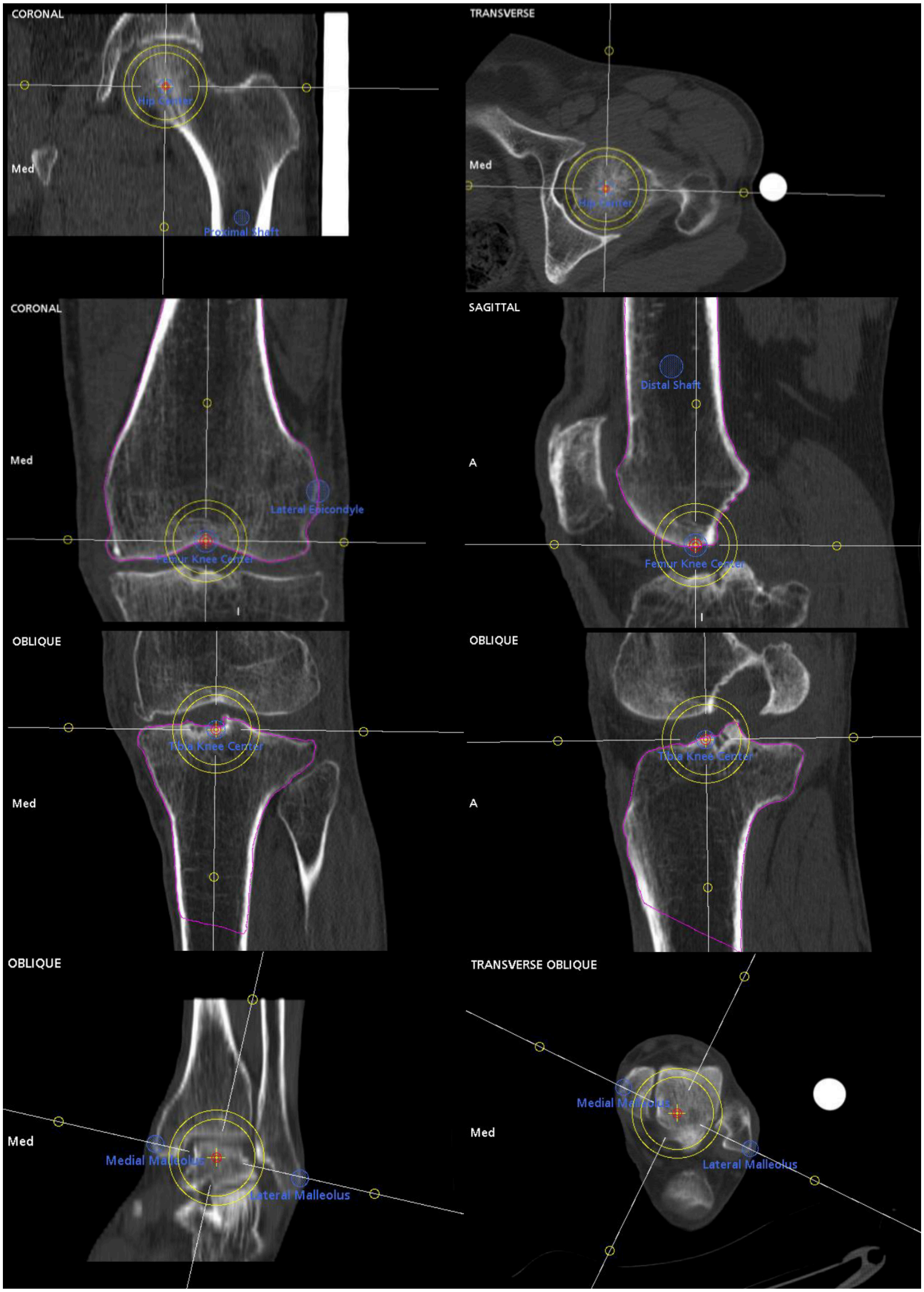

Figure 3

Mako CT planning of alignment landmarks. Cross-sectional CT images and three-dimensional reconstructions were based on preoperative CT scans performed with the Mako 2.0 software, demonstrating the process of selecting the (A) femoral head, (B) femur knee center, (C) tibia knee center, and (D) ankle center. CT, computed tomography.

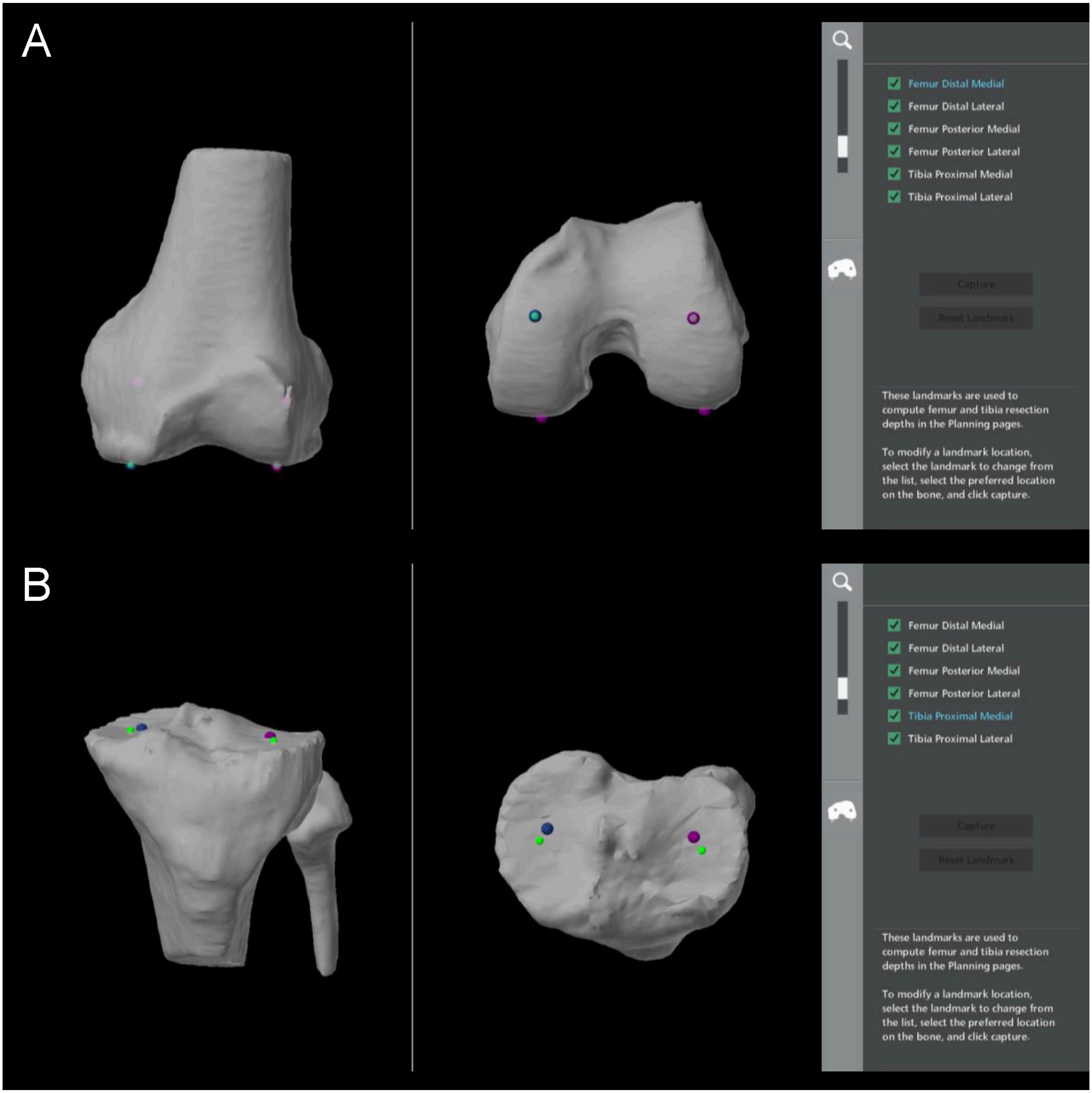

Figure 4

Distal femoral and proximal tibial constitutional landmarks (green spheres) based on preoperative CT scans performed within the Mako 2.0 software. Landmark identification was based on placing points at the most distal part of the condyles for the femur and positioning points at the center of the medial and lateral articular surfaces for the tibia. Dark blue and magenta spheres indicate the default distal femur and proximal tibia resection landmarks, respectively, which were used to indirectly measure the alignment in the Mako 1.0 software, as previously described by Clark et al. CT, computed tomography.

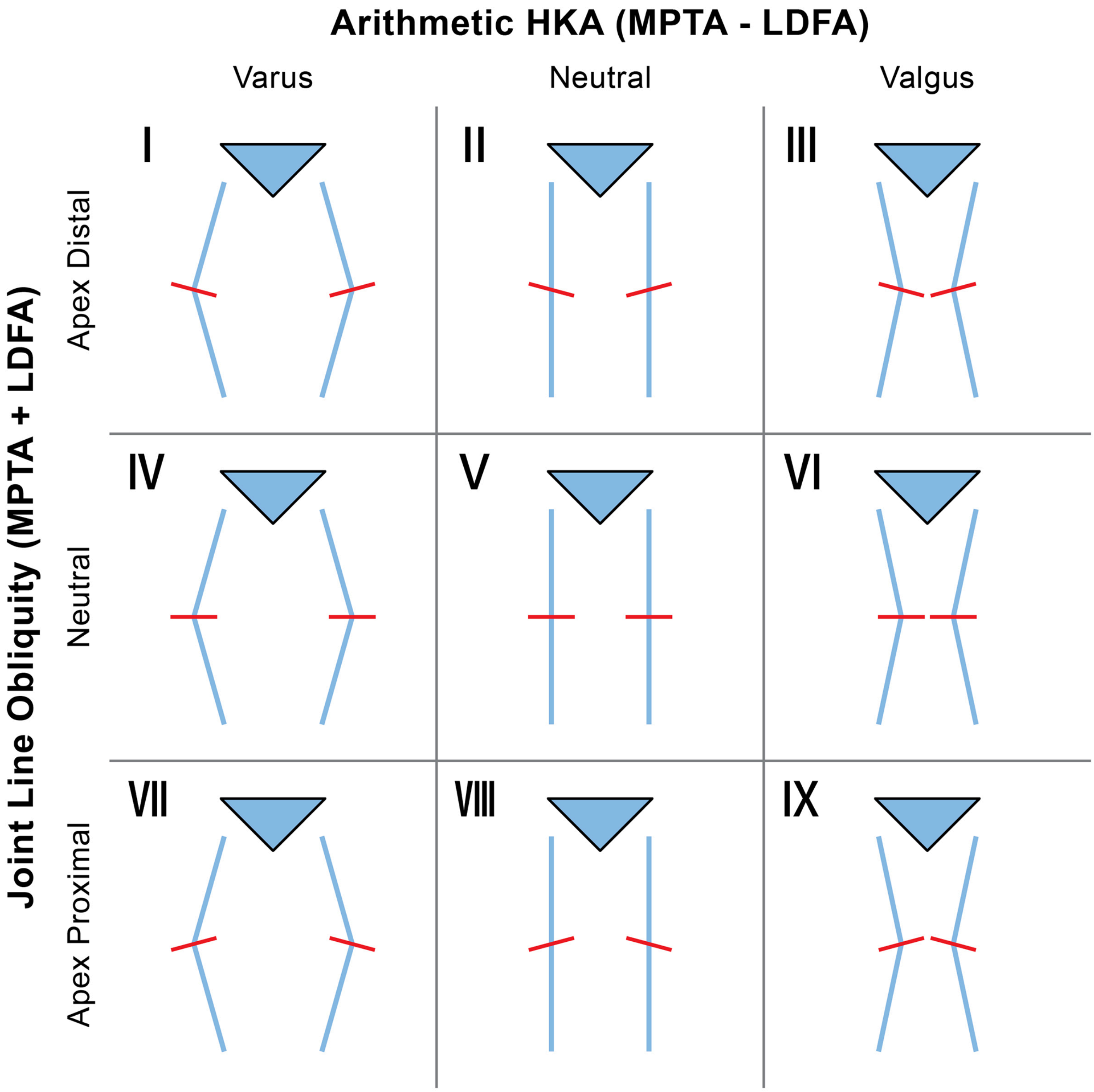

Figure 5

CPAK classification with nine theoretical types of knees, based on the aHKA and JLO measurements. CPAK, coronal plane alignment of the knee; aHKA, arithmetic hip-knee-ankle angle; JLO, joint line obliquity.