

Original Research

Preoperative Virtual Total Knee Arthroplasty Surgery Using a Computed Tomography-based 3-dimensional Model With Variation in Reference Points and Target Alignment to Predict Femoral Component Sizing

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ABSTRACT

Background: The purpose of this study was to investigate the size differences of 19 different femoral component placements from the standard position in total knee arthroplasty using 3-dimensional virtual surgery.

Methods: Three-dimensional bone models were reconstructed from the computed tomography data of 101 varus osteoarthritic knees. The distal femoral bone was cut perpendicular to the femoral mechanical axis (MA) in the coronal plane. Twenty different component placements consisting of 5 cutting directions (perpendicular to MA, 3° and 5° extension relative to MA [3°E-MA and 5°E-MA, respectively], and 3° and 5° flexion relative to MA [3°F-MA and 5°F-MA, respectively]) in the sagittal plane, 2 rotational alignments (clinical epicondylar axis [CEA] and surgical epicondylar axis [SEA]), and 2 rotational types of anterior reference guide (central [CR] and medial [MR]) were simulated.

Results: The mean anteroposterior dimension of femur ranged from 54.3 mm (5°F-MA, SEA, CR) to 62.5 mm (5°E-MA, CEA, MR). The largest and smallest differences of anteroposterior dimension from the standard position (3°F-MA, SEA, and CR) were 7.1 ± 1.3 mm (5°E-MA, CEA, and MR) and -1.2 ± 0.2 mm (5°F-MA, SEA, and CR), respectively. Multiple regression analysis revealed that flexion cutting direction, SEA, and CR were associated with smaller component size.

Conclusions: The femoral component size can be affected easily by not only cutting direction but also the reference guide type and the target alignment. Our findings could provide surgeons with clinically useful information to fine-tune for unintended loose or tight joint gaps by adjusting the component size.

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Introduction

Selecting appropriately sized components is important in total knee arthroplasty (TKA) because they can affect postoperative knee function and pain [1]. Computer-assisted surgeries such as robotic surgeries and surgeries performed using large console-type

navigation systems are accurate procedures, but many surgeons still use more conventional techniques, which requires detailed preoperative planning and various jigs for acquiring optimal alignment. In the conventional technique of TKA, it is difficult to accurately determine the proper component size because cutting surface conditions vary among intraoperative techniques despite accurate preoperative planning [2]. Nevertheless, the surgeon will attempt to perform an accurate procedure because a more accurate repair of the medial femoral condyle will improve stability, and if some lateral flexion relaxation is maintained, good range of motion can be achieved with rollback [3]. The final decisions regarding

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component size were made by measuring the joint gap via a tensioning device for the gap balance technique, whereas the measured resection technique was obtained from a joint gap that consisted of the results of all intraoperative procedures. Surgeons should know the effect of intraoperative procedures on the component size to avoid unintended loose or tight gaps [4–6].

The rotational alignment and position of the reference guide can affect component size. The transepicondylar axis (TEA) is an anatomical landmark for acquiring the optimal rotational alignment to the primary center of rotation for the knee [7]. The TEA has 2 types of axes which are surgical epicondylar axis (SEA) and clinical epicondylar axis (CEA). The SEA was defined as the line connecting the lateral epicondylar prominence and medial sulcus of the medial epicondyle. The CEA was defined as the line connecting the lateral epicondylar prominence and the most prominent point of the medial epicondyle. There is controversy over which axis is superior, and the selection of axis is based on the surgeon's preference. The femoral component is placed in a more external rotation direction with aligning to the CEA than when aligning to the SEA. It is unclear how the difference in rotation affects the component size. Generally, anterior and posterior reference guides are used to align to the target rotational alignment. The former can prevent notching at the anterior femoral condyle. However, the flexion gap may be altered by changes in posterior condyle thicknesses before and after bone cutting, making it difficult to select the appropriate component size [6]. Reference guides are also classified into 3 types according to the fulcrum rotation center: medial, central, and lateral. The rotation center affects the resection of the posterior femoral condyle even when using the posterior reference guide. Therefore, even if the repair is intended to focus on the medial posterior condyle, different laxity will occur on the medial and lateral sides [8]. With the anterior reference guide, greater resection should cause a component size difference between the medial and central rotation types. No studies thus far have investigated how the rotation type of the anterior reference guide affects the femoral component size.

Several studies showed that femoral component size can be changed by preoperative planning [9,10] and intraoperative alignment [11,12]. However, most used a 2-dimensional (2D) including 3-dimensional (3D) templating system that evaluates component size on an inappropriately derived plane that is affected by limb position and selection of reference points [13]. Virtual surgery via computer simulation is useful for precisely evaluating the effects of different component placements during TKA because it should reduce the effects of inaccurate alignment or inadequate observation by the 2D or 3D templating system [14]. The purpose of this study was to evaluate the sizes of femoral components with 20 different component placements and investigate the size differences from the standard position in TKA using a 3D virtual surgery with computer simulation. In addition, we sought to compare the size difference among cutting directions, rotational alignments, and rotational types of reference guide. The hypothesis is as follows: (1) Size can easily change from the standard position based on cutting directions, rotational alignments, and rotational types of the anterior reference guide. (2) Size significantly differs among cutting directions, rotational alignments, and reference guide rotation types.

Material and methods

Patients

One hundred and thirty-eight osteoarthritic and rheumatoid knees in 121 patients underwent primary TKA between April 2016 and March 2018. In order to standardize the sample using

individuals with similar deformities, we excluded a total of 37 knees, which consisted of 23 valgus knees, 5 rheumatoid arthritis knees, 3 operated knees (after high tibial osteotomy), 1 knee with a history of knee injury, and 5 severe bone defects in the distal femur. Finally, 101 osteoarthritic knees with varus deformity were investigated in 88 patients before primary TKA. The study group consisted of 22 men (22 knees) and 66 women (79 knees). The average age was 76.4 ± 7.2 years. The average height and weight were 152.3 ± 8.2 cm and 62.1 ± 12.8 kg, respectively. The average body mass index was 26.6 ± 4.6 kg/m². The preoperative alignments and progression of osteoarthritic knees (determined using the Kellgren-Lawrence osteoarthritis knee scale) [15] were measured on full-length, weight-bearing anteroposterior (AP) radiographs using a digital measurement software 2D template (Japan Medical Materials Corp., Osaka, Japan). The average preoperative femorotibial angle was $185.4 \pm 5.5^\circ$, and the average hip-knee-ankle angle was $193.2 \pm 8.0^\circ$. Ninety-one knees were classified as grade 4 on the Kellgren-Lawrence scale, and 10 knees as grade 3. This study was approved by the institutional review board of our institution (ID number of the approval: 2019-432). Informed consent was obtained from all patients before participation. All methods were carried out in accordance with relevant guidelines and regulations.

Three-dimensional bone model and the coordinate system

A computed tomography (CT) scan of the lower extremity that was scheduled to undergo TKA was obtained from each patient within 3 months preoperatively (Aquilion 64-slice CT Scanner; Toshiba, Tochigi, Japan). CT slices were 2 mm thick. A 3D femoral bone model was reconstructed from preoperative CT data using MIMICS (Materialise, Leuven, Belgium). The bony geometry was imported into a computer-assisted design software program (Rhinoceros; Robert McNeel and Associates, Seattle, WA) in stereolithography format. The coordinate system consisted of the femoral mechanical axis (MA) and the functional TEA, which was projected onto the plane perpendicular to femoral MA (Fig. 1a) [16]. The center of the hip was determined by fitting a sphere to the femoral head. The center of the knee joint was identified as the midpoint of the TEA, which consisted of the SEA and CEA. The femoral MA was defined as the line connecting the center of the knee and the center of the hip. The SEA was defined as the line connecting the most prominent point of the lateral epicondyle with the deepest point of the sulcus on the medial epicondyle. The CEA was defined as the line connecting the most prominent point of the lateral epicondyle with the most prominent point anterior to the medial sulcus of the medial epicondyle. The Z-axis of the knee (proximal-distal) was defined as the extension of the femoral MA. The plane normal to the Z-axis at the center of the knee was defined as the XY-plane. The Y-axis (medial-lateral) was defined as the extension of the functional TEA. The X-axis (anterior-posterior) was defined as the line normal to the coronal plane (YZ-plane) at the center of the knee (Fig. 1a).

Virtual surgery

Bone cutting and implantation were performed on the femoral bone model using the established 3D coordinates. The distal femur was cut perpendicular to the femoral MA (Z-axis) at the level of intercondylar notch in the coronal plane (Fig. 1b). In the sagittal plane, 5 different cutting directions were simulated: perpendicular to the femoral MA (P-MA), 3° and 5° extension relative to the femoral MA (3° E-MA and 5° E-MA, respectively), and 3° and 5° flexion relative to the femoral MA (3° F-MA and 5° F-MA, respectively) (Fig. 1c).

Medial rotation (MR) and central rotation (CR) types of reference guides (Zimmer-Biomet, Warsaw, IN) were used to determine

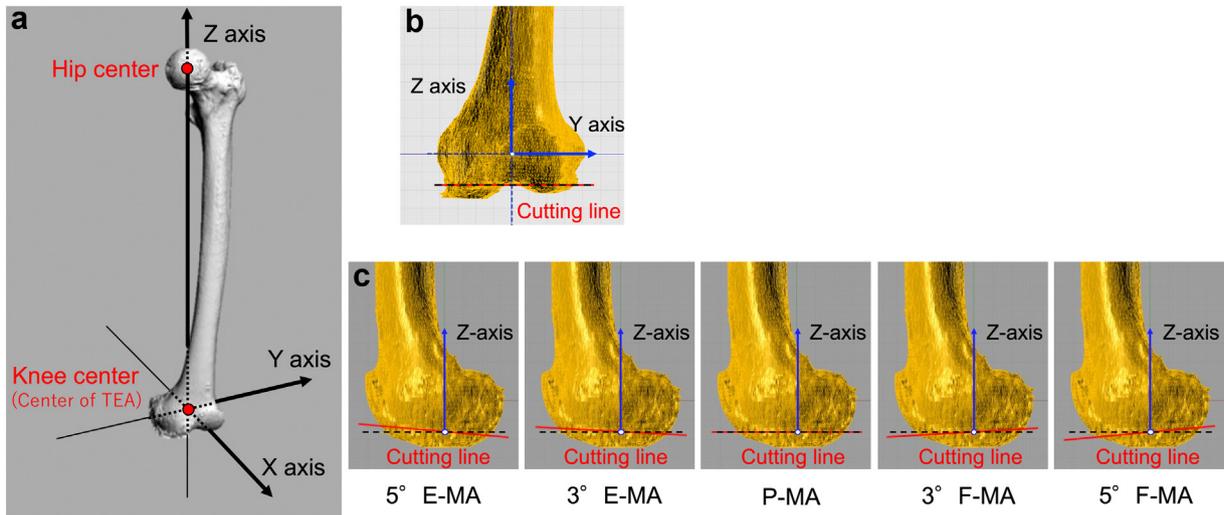


Figure 1. (a) Three-dimensional coordinates for virtual surgery. (b) Bone cutting for distal femur (coronal plane). (c) Bone cutting for distal femur (sagittal plane). Z-axis (proximal-distal): the extension of femoral mechanical axis; Y-axis (medial-lateral): the extension of functional TEA which projected TEA onto the plane perpendicular to femoral mechanical axis at the knee center; X-axis (anterior-posterior): the line normal to the coronal plane (YZ-plane) at the knee center; red line: cutting line.

the rotational alignment (Fig. 2a and b) [17]. The target rotational alignments were the CEA and SEA. The reference guide was positioned on the cutting surface, and the foot of the guide was attached to the posterior condyles. An anterior reference guide was used to measure the femoral AP dimension. The anterior boom was positioned at the lateral sulcus point at the intersection of the anterior cortex and the top of the anterior condyle (Fig. 2a and b). The femoral rotation position was defined as the position where the gold pin was inserted after clockwise rotation around the medial

fulcrum (circle with a blue line) from the posterior condyle axis in the range of 0-7° (Fig. 2a). The femoral AP dimension was defined as the distance between the attachment of the anterior boom and the rotation center of the reference guide in the XY-plane [18]. A computer-assisted design model of the Persona Knee System (Zimmer-Biomet, Warsaw, IN) was virtually implanted after completing the distal femoral bone cut using the preplanned size. Standard Persona sizes from 3 to 11 were selected to avoid exceeding the femoral AP dimension. The AP dimension of the

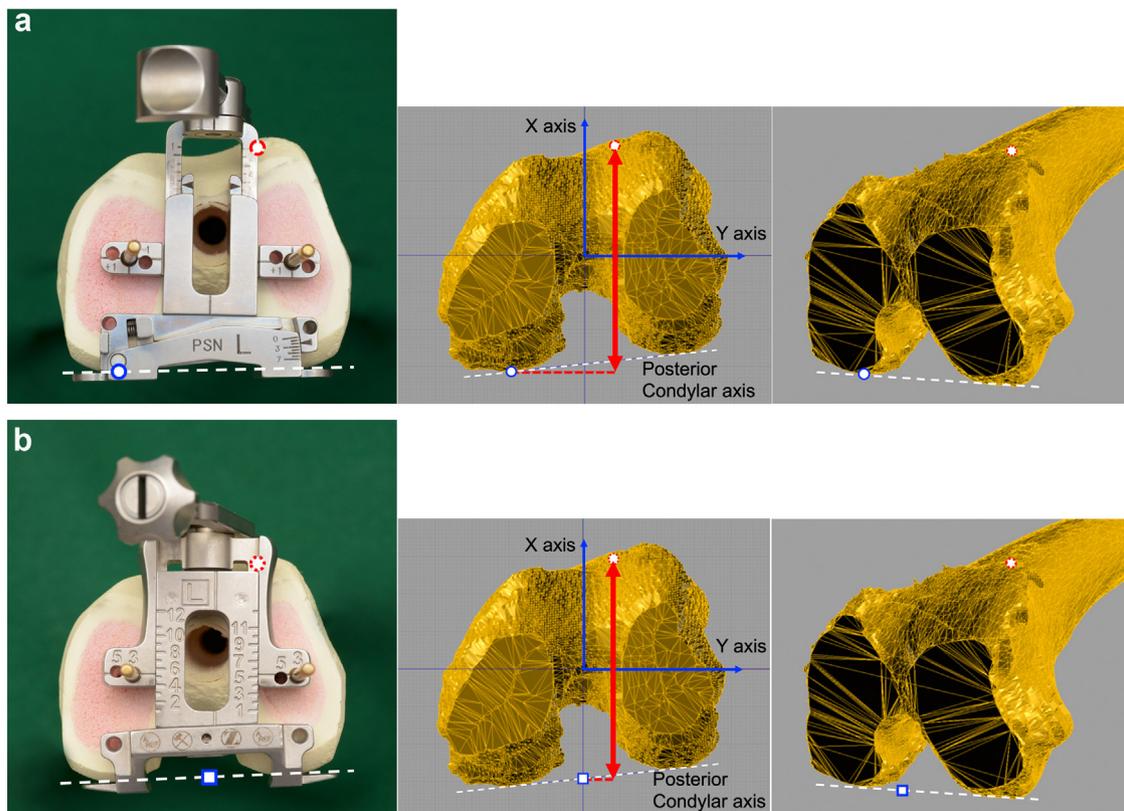


Figure 2. (a) Medial and (b) central rotation type of reference guide. Red dotted circle: attachment of anterior boom; white dotted line: posterior condylar axis; red bidirectional arrows: anteroposterior dimension in the XY-plane; blue lined circle and blue lined square: rotation center.

computer-assisted design model was 49.3 mm at size 3 and 66.2 mm at size 11, and each 1-size increase in the Persona model resulted in a mean AP dimension change of 2.1 mm.

The mean AP dimension and femoral component size were evaluated by virtual surgery using 20 different component placements, based on combinations of the following: 5 cutting directions (P-MA, 3°E-MA, 5°E-MA, 3°F-MA, and 5°F-MA) in the sagittal plane, 2 rotational alignments (CEA and SEA), and 2 reference guide rotation types (MR and CR). The sizes of 19 different component placements were compared with the standard position, which was defined as 3°F-MA, SEA, and CR [19].

Statistical analysis

Data are presented as means and standard deviations. Data analysis was performed using JMP Pro software version 12.0 (SAS Institute, Cary, NC). To investigate the reliability and reproducibility of this coordinate system for measuring AP dimension, intra-observer and interobserver reliabilities were assessed using intraclass and interclass correlation coefficients [ICC (1,1) and ICC (2,1)], respectively [20]. All measurements were obtained by 2 orthopedic surgeons (S.I., H.M.) at an interval of more than 1 week. Data were blinded and included no patient information. The ICC (1,1) and ICC (2,1) of this coordinate system were 0.97 and 0.96, respectively, suggesting excellent agreement for both. Student's t-test was used to compare differences between the CEA and SEA and between MR and CR. Different cutting directions in sagittal alignment and deviations from the standard position were compared between groups using ANOVA. A post hoc analysis was conducted using the Steel-Dwass test. Multiple regression analysis was performed to determine which factors had the greatest effect on component size, using the following factors: 5 cutting directions, 2 rotational alignments, and 2 rotational types of the reference guide (effect size: β coefficient). Statistical significance was set at a *P* value <.05.

Results

The mean femoral AP dimension and component size with 20 different component placements are shown in Table 1. The anterior boom of the reference guide was positioned at a mean distance of 17.4 ± 5.8 mm proximal to the most proximal margin of the femoral

anterior condyle. The mean difference of AP dimension ranged from 54.3 mm to 62.5 mm, which corresponded to a size difference of 3.9 in terms of the femoral component size (4.9–8.8). The mean AP dimension of the standard position was 55.5 mm, which means that the difference compared to 19 different methods ranged from -1.2 mm (5°F-MA, SEA, and CR) to 7.1 mm (5°E-MA, CEA, and MR). Significant larger sizes were selected compared to the standard position when cutting direction was 5°E-MA, 3°E-MA, and P-MA (Table 1). Despite performing with 5°F-MA and 3°F-MA in cutting direction, significantly larger sizes were selected compared to the standard position when the target rotational alignment was CEA, and the reference guide was MR (*P* < .0001).

The mean femoral AP dimension and component size with 5 different cutting directions in sagittal alignment are shown in Table 2. The AP dimension and component size increased with greater extension of the cutting direction. The component sizes with P-MA were significantly smaller than those with 5°E-MA and significantly larger than those with 5°F-MA. The component sizes with P-MA differed significantly from those with 3°E-MA and 3°F-MA except for 3 methods (3°E-MA using CEA/MR, 3°E-MA using SEA/CR, and 3°F-MA using SEA/MR). By contrast, no significant size differences were observed between 3°E-MA and 5°E-MA or between 3°F-MA and 5°F-MA.

The mean femoral AP dimension and component size with 2 different rotational alignments are shown in Table 3. The mean component sizes were not smaller in any knees using CEA than those in knees using SEA. The mean femoral AP dimension and component size with CEA as the target rotational alignment were significantly larger than those with SEA when a MR reference guide was used (*P* < .0001; Table 3). By contrast, about half of all knees (49.5%–60.4%) had the same component size with CEA compared with SEA when a CR reference guide was used (Table 3).

The mean femoral AP dimension and component size with 2 different reference guides are shown in Table 4. The mean femoral AP dimension and component size with MR were larger than those with CR (*P* < .0001), and mean component sizes in any knees using MR were not smaller than those in knees using CR when CEA was the target rotational alignment (Table 4). By contrast, fewer than half of the knees (38.6%–47.5%) had a larger component size with MR than with CR, when SEA was the target rotational alignment (Table 4).

Table 1
Mean anteroposterior dimension and component size with 20 different component placements.

Cutting directions	Rotational alignment	Reference guide	AP dimension (mm) (component size)	AP dimension difference (mm) compared with standard position (size difference)	<i>P</i> value
3°F-MA	SEA	CR	55.5 ± 3.5 (5.4 ± 1.7)		
5°E-MA	CEA	MR	62.5 ± 4.0 (8.8 ± 1.7)	7.1 ± 1.3 (3.4 ± 0.7)	<.0001
5°E-MA	CEA	CR	60.3 ± 3.7 (7.7 ± 1.7)	4.9 ± 0.8 (2.4 ± 0.6)	<.0001
5°E-MA	SEA	MR	60.3 ± 4.0 (7.7 ± 1.8)	4.9 ± 1.3 (2.4 ± 0.8)	<.0001
5°E-MA	SEA	CR	59.4 ± 3.7 (7.4 ± 1.7)	3.9 ± 0.8 (2.0 ± 0.6)	<.0001
3°E-MA	CEA	MR	61.7 ± 3.9 (8.3 ± 1.7)	6.3 ± 1.1 (3.0 ± 0.6)	<.0001
3°E-MA	CEA	CR	59.4 ± 3.6 (7.3 ± 1.6)	4.0 ± 0.6 (1.9 ± 0.5)	<.0001
3°E-MA	SEA	MR	59.4 ± 3.9 (7.3 ± 1.8)	4.0 ± 1.1 (1.9 ± 0.6)	<.0001
3°E-MA	SEA	CR	58.5 ± 3.6 (6.9 ± 1.7)	3.1 ± 0.6 (1.5 ± 0.5)	<.0001
P-MA	CEA	MR	60.3 ± 3.8 (7.7 ± 1.7)	4.8 ± 1.0 (2.3 ± 0.7)	<.0001
P-MA	CEA	CR	58.0 ± 3.5 (6.7 ± 1.7)	2.5 ± 0.4 (1.3 ± 0.5)	<.0001
P-MA	SEA	MR	58.0 ± 3.8 (6.6 ± 1.9)	2.5 ± 1.0 (1.2 ± 0.6)	<.0001
P-MA	SEA	CR	57.1 ± 3.6 (6.2 ± 1.7)	1.6 ± 0.3 (0.8 ± 0.4)	.0013
3°F-MA	CEA	MR	58.6 ± 3.8 (6.9 ± 1.7)	3.2 ± 1.0 (1.6 ± 0.6)	<.0001
3°F-MA	CEA	CR	56.4 ± 3.5 (5.9 ± 1.7)	0.9 ± 0.4 (0.5 ± 0.5)	.0562
3°F-MA	SEA	MR	56.4 ± 3.7 (5.9 ± 1.8)	0.9 ± 0.9 (0.5 ± 0.6)	.0682
5°F-MA	CEA	MR	57.5 ± 3.7 (6.5 ± 1.8)	2.1 ± 1.0 (1.2 ± 0.6)	<.0001
5°F-MA	CEA	CR	55.2 ± 3.4 (5.4 ± 1.6)	-0.2 ± 0.4 (0.0 ± 0.4)	.6594
5°F-MA	SEA	MR	55.2 ± 3.7 (5.4 ± 1.8)	-0.2 ± 0.9 (0.0 ± 0.6)	.668
5°F-MA	SEA	CR	54.3 ± 3.4 (4.9 ± 1.7)	-1.2 ± 0.2 (-0.5 ± 0.5)	.0182

The values are given as the mean with standard deviation. Standard position was defined as (3°F-MA, SEA, and CR).

Table 2
Mean anteroposterior dimension and component size with 5 different cutting directions in sagittal alignment.

Rotational alignment (rotational type)	Cutting direction					ANOVA	Steel-Dwss test
	5°E-MA	3°E-MA	P-MA	3°F-MA	5°F-MA		
CEA (MR)	62.5 ± 4.0 (8.8 ± 1.7)	61.7 ± 3.9 (8.3 ± 1.7)	60.3 ± 3.8 (7.7 ± 1.8)	58.6 ± 3.8 (6.9 ± 1.7)	57.5 ± 3.7 (6.5 ± 1.8)	<.0001	<i>P</i> = .0003 ^a <i>P</i> < .0001 ^b <i>P</i> < .0001 ^c <i>P</i> < .0001 ^e <i>P</i> < .0001 ^f <i>P</i> = .0332 ^g <i>P</i> = .0002 ^h
CEA (CR)	60.3 ± 3.7 (7.7 ± 1.7)	59.4 ± 3.6 (7.3 ± 1.6)	58.0 ± 3.5 (6.7 ± 1.7)	56.4 ± 3.5 (5.9 ± 1.7)	55.2 ± 3.4 (5.4 ± 1.6)	<.0001	<i>P</i> = .0001 ^a <i>P</i> < .0001 ^b <i>P</i> < .0001 ^c <i>P</i> = .0263 ^d <i>P</i> < .0001 ^e <i>P</i> < .0001 ^f <i>P</i> = .0188 ^g <i>P</i> < .0001 ^h
SEA (MR)	60.3 ± 4.0 (7.7 ± 1.8)	59.4 ± 3.9 (7.3 ± 1.8)	58.0 ± 3.8 (6.6 ± 1.9)	56.4 ± 3.7 (5.9 ± 1.8)	55.2 ± 3.7 (5.4 ± 1.8)	<.0001	<i>P</i> = .0002 ^a <i>P</i> < .0001 ^b <i>P</i> < .0001 ^c <i>P</i> = .0377 ^d <i>P</i> < .0001 ^e <i>P</i> < .0001 ^f <i>P</i> < .0001 ^h
SEA (CR)	59.4 ± 3.7 (7.4 ± 1.7)	58.5 ± 3.6 (6.9 ± 1.7)	57.1 ± 3.6 (6.2 ± 1.7)	55.5 ± 3.5 (5.4 ± 1.7)	54.3 ± 3.4 (4.9 ± 1.7)	<.0001	<i>P</i> < .0001 ^a <i>P</i> < .0001 ^b <i>P</i> < .0001 ^c <i>P</i> < .0001 ^e <i>P</i> < .0001 ^f <i>P</i> = .0126 ^g <i>P</i> < .0001 ^h
Total	60.7 ± 7.8 (7.9 ± 1.8)	59.8 ± 7.5 (7.5 ± 1.8)	58.4 ± 7.5 (6.8 ± 1.9)	56.8 ± 7.3 (6.0 ± 1.8)	55.6 ± 7.2 (5.6 ± 1.8)	<.0001	<i>P</i> < .0001 ^a <i>P</i> < .0001 ^b <i>P</i> < .0001 ^c <i>P</i> < .0001 ^d <i>P</i> < .0001 ^e <i>P</i> < .0001 ^f <i>P</i> < .0001 ^g <i>P</i> < .0001 ^h <i>P</i> = .0072 ⁱ <i>P</i> = .0043 ^j

ANOVA, analysis of variance.

The values of component size are given as the mean with standard deviation. The difference among 5 cutting directions was analyzed using ANOVA and Steel-Dwss test.

- ^a Significant difference between 5°E-MA and P-MA (*P* < .05).
^b Significant difference between 5°E-MA and 3°F-MA (*P* < .05).
^c Significant difference between 5°E-MA and 5°F-MA (*P* < .05).
^d Significant difference between 3°E-MA and P-MA (*P* < .05).
^e Significant difference between 3°E-MA and 3°F-MA (*P* < .05).
^f Significant difference between 3°E-MA and 5°F-MA (*P* < .05).
^g Significant difference between P-MA and 3°F-MA (*P* < .05).
^h Significant difference between P-MA and 5°F-MA (*P* < .05).
ⁱ Significant difference between 5°E-MA and 3°E-MA (*P* < .05).
^j Significant difference between 3°F-MA and 5°F-MA (*P* < .05).

Table 3
Mean anteroposterior dimension and component size with 2 different rotational alignments.

Cutting directions, rotational type	AP dimension (mm) (component size)		<i>P</i> value	Rate of component size (%)		
	CEA	SEA		CEA > SEA	CEA = SEA	CEA < SEA
5°E-MA, MR	62.5 ± 4.0 (8.8 ± 1.7)	60.3 ± 4.0 (7.7 ± 1.8)	<.0001	88.1	11.9	0
3°E-MA, MR	61.7 ± 3.9 (8.3 ± 1.7)	59.4 ± 3.9 (7.3 ± 1.8)	<.0001	83.2	16.8	0
P-MA, MR	60.3 ± 3.8 (7.7 ± 1.7)	58.0 ± 3.8 (6.6 ± 1.9)	<.0001	88.1	11.9	0
3°F-MA, MR	58.6 ± 3.8 (6.9 ± 1.7)	56.4 ± 3.7 (5.9 ± 1.8)	<.0001	87.1	12.9	0
5°F-MA, MR	57.5 ± 3.7 (6.5 ± 1.8)	55.2 ± 3.7 (5.4 ± 1.8)	<.0001	93.1	6.9	0
5°E-MA, CR	60.3 ± 3.7 (7.7 ± 1.7)	59.4 ± 3.7 (7.4 ± 1.7)	.0814	39.6	60.4	0
3°E-MA, CR	59.4 ± 3.6 (7.3 ± 1.6)	58.5 ± 3.6 (6.9 ± 1.7)	.0653	43.6	56.4	0
P-MA, CR	58.0 ± 3.5 (6.7 ± 1.7)	57.1 ± 3.6 (6.2 ± 1.7)	.0656	47.5	52.5	0
3°F-MA, CR	56.4 ± 3.5 (5.9 ± 1.7)	55.5 ± 3.5 (5.4 ± 1.7)	.0562	50.5	49.5	0
5°F-MA, CR	55.2 ± 3.4 (5.4 ± 1.6)	54.3 ± 3.4 (4.9 ± 1.7)	.0524	46.5	53.5	0
Total	59.1 ± 4.3 (6.5 ± 1.9)	57.5 ± 4.1 (5.7 ± 1.9)	<.0001	70.5	31.2	0

The values are given as the mean with standard deviation. *P* value means difference between CEA and SEA.

Table 4
Mean anteroposterior dimension and component size with 2 different anterior reference guides.

Cutting directions, rotational alignment	AP dimension (mm) (component size)		P value	Rate of component size (%)		
	MR	CR		MR > CR	MR = CR	MR < CR
5°E-MA, CEA	62.5 ± 4.0 (8.8 ± 1.7)	60.3 ± 3.7 (7.7 ± 1.7)	<.0001	87.1	12.9	0
3°E-MA, CEA	61.7 ± 3.9 (8.3 ± 1.7)	59.4 ± 3.6 (7.3 ± 1.6)	<.0001	87.1	12.9	0
P-MA, CEA	60.3 ± 3.8 (7.7 ± 1.7)	58.0 ± 3.5 (6.7 ± 1.7)	<.0001	85.1	14.9	0
3°F-MA, CEA	58.6 ± 3.8 (6.9 ± 1.7)	56.4 ± 3.5 (5.9 ± 1.7)	<.0001	82.2	17.8	0
5°F-MA, CEA	57.5 ± 3.7 (6.5 ± 1.8)	55.2 ± 3.4 (5.4 ± 1.6)	<.0001	91.1	8.9	0
5°E-MA, SEA	60.3 ± 4.0 (7.7 ± 1.8)	59.4 ± 3.7 (7.4 ± 1.7)	.094	38.6	58.4	3.0
3°E-MA, SEA	59.4 ± 3.9 (7.3 ± 1.8)	58.5 ± 3.6 (6.9 ± 1.7)	.0751	43.6	53.4	3.0
P-MA, SEA	58.0 ± 3.8 (6.6 ± 1.9)	57.1 ± 3.6 (6.2 ± 1.7)	.0748	39.6	59.4	1.0
3°F-MA, SEA	56.4 ± 3.7 (5.9 ± 1.8)	55.5 ± 3.5 (5.4 ± 1.7)	.0682	47.5	51.5	1.0
5°F-MA, SEA	55.2 ± 3.7 (5.4 ± 1.8)	54.3 ± 3.4 (4.9 ± 1.7)	.0616	41.6	56.4	2.0
Total	59.1 ± 4.4 (6.5 ± 1.9)	57.5 ± 4.0 (5.7 ± 1.8)	<.0001	64.5	34.8	0.7

The values are given as the mean with standard deviation. P value means difference between MR and CR.

Multiple regression analysis showed that flexion cutting direction (β value: -0.43), SEA (β value: -0.19), and CR (β value: -0.18) were associated with a smaller component size ($P < .0001$), and the association was strongest with cutting in flexion.

Discussion

The most important finding of this study was that intraoperative surgical techniques, including surgeons' selection of the reference guide type and the target alignment, readily affected the femoral component size. This suggests that it is difficult to achieve an accurate component size despite establishing a presumably accurate preoperative plan. The mean difference of AP dimension ranged from 54.3 mm to 62.5 mm, which corresponded to a size difference of 3.9 in terms of the femoral component size (4.9–8.8). The largest difference from the standard position was 7.1 mm in the femoral AP dimension, equivalent to 3.4 in the component size. Surgeons should be aware that inaccurate surgical techniques using conventional alignment guides and cutting blocks can not only cause difficulty in acquiring optimal alignment but also readily change femoral component size. Few studies have examined the detailed effects of surgical techniques on component size [9,13]. Therefore, we accurately compared size differences resulting from 20 different component placements performed using virtual surgery and a computer-assisted design software program.

In all knees, cutting in extension resulted in a greater femoral AP dimension than cutting in flexion. Our accurate measurements showed a similar trend with a previous study using a 3D templating software program [12]. Furthermore, multiple regression analysis showed that cutting in flexion affected the femoral component size most negatively. The size changed significantly when the difference in cutting direction was more than 3°. In previous studies using conventional methods, only 45%–65% of cases exhibited values within 3° of the target angle in the sagittal plane [21,22]. In sagittal alignment, the placement of the femoral component in flexion has the benefit of reducing notching and improving range of motion. In contrast, excessive flexion can lead to post-cam impingement. Banks et al. found that if the femoral component is placed in about 5° of flexion due to the anterior cortex and the tibial component in 5° of flexion due to the posterior tilt, the component at full knee extension will be relatively hyperextended by about 10°, which is close to the limit of anterior impingement in many designs [23]. To prevent unexpected component size changes, surgeons should be aware of several pitfalls related to cutting direction (eg, inappropriate spacing between the distal femoral cutting guide and bone saw, and improper flexure of the bone saw edge).

Regardless of rotational alignment, no knees had a smaller component size when CEA was used as opposed to SEA. SEA and

CEA are anatomical landmarks for acquiring the optimal rotational alignment to the primary center of rotation for the knee [7]. In the measured resection method, SEA and CEA are usually evaluated preoperatively as the angle compared to the posterior condylar line using preoperative images such as CT slice, epicondylar view [24], and kneeling view [25]. However, only 30% of medial sulci can be detected on a preoperative CT slice [26], leading to variation of intraoperative palpation of the medial and lateral epicondyle among the surgeons [27]. Siston et al. reported that only 17.3% of surgeons were able to place within 5° of the target TEA with cadaveric study [28]. Therefore, it is important to include SEA and CEA both to evaluate the effect of the rotational alignments on the size in consideration of wide variations. Based on intraoperative measurements, Koninckx et al. reported that the AP dimension of the distal femur increased by 2.3 mm and 3.8 mm with 3° and 5° of external rotational alignment, respectively, relative to the posterior condylar axis [11]. Our study obtained similar results using the CEA and SEA as major target rotational alignments because the CEA is usually externally aligned relative to the SEA. One reason for the larger component size when using the CEA can be explained based on the measurements shown in Figure 3. The AP dimension was calculated using the following equations: AP dimension (CEA) = $r1 \times \sin\alpha + r2 \times \sin\beta$, and AP dimension (SEA) = $r1 \times \sin(\alpha-\theta) + r2 \times \sin(\beta-\theta)$. The distance between the knee center and the attachment of the anterior boom ($r1$) and that between the knee center and the rotation center of the reference guide ($r2$) on the XY-plane are the same when using the CEA and SEA. AP dimension (SEA) is smaller than AP dimension (CEA) due to the low value of the sine of θ (the angle between the CEA and SEA).

Regarding the effects of reference guide rotation types, almost no knees had a smaller component size when using MR rather than CR due to the longer AP dimension with MR. No studies have investigated how the rotation type of the anterior reference guide affects femoral component size. The reasons why the AP dimension is longer with MR than with CR is simply because the rotation center is located more posteriorly with MR (Fig. 2a and b). When using the CEA, the component size is larger with MR than with CR in most knees, but this is the case in only about half of all knees when using the SEA; this can be explained by calculations based on the measurements in Figure 4. The difference in AP dimension when using MR vs CR was calculated using the following equations: difference in AP dimension when using MR vs CR (CEA) = $r3 \times \sin\delta$, and difference in AP dimension when using MR vs CR (SEA) = $r3 \times \sin(\delta-\theta)$ (δ : angle between the CEA and the posterior condylar axis). The distance between the rotation centers on the XY-plane when using MR vs CR ($r3$) is the same for both the CEA and SEA. The difference in AP dimension when using MR vs CR (SEA) is smaller than the difference in AP dimension when using

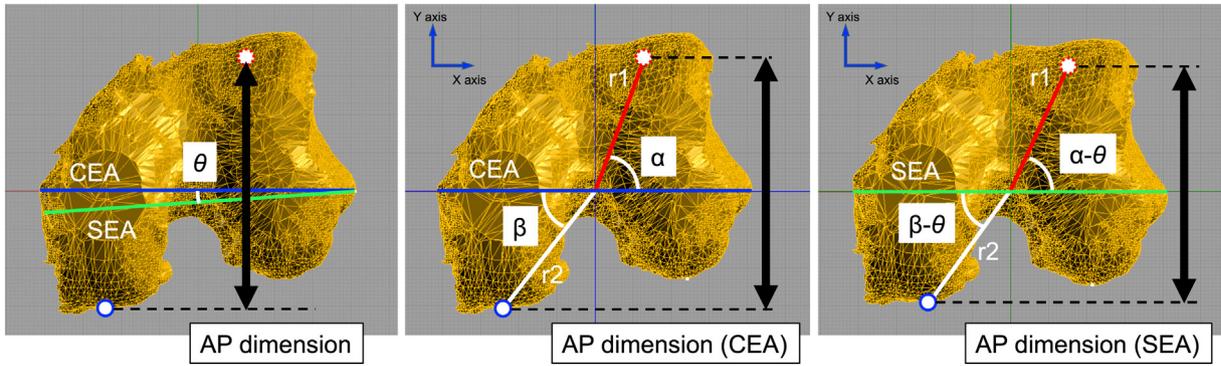


Figure 3. Anteroposterior (AP) dimension using CEA and using SEA on the XY-plane. Blue lined circle: rotation center of reference guide; red dotted circle: attachment of anterior boom. AP dimension (CEA) = $r1 \times \sin\alpha + r2 \times \sin\beta$. AP dimension (SEA) = $r1 \times \sin(\alpha-\theta) + r2 \times \sin(\beta-\theta)$, where $r1$: distance between knee center and attachment of anterior boom; $r2$: distance between knee center and rotation center of reference guide; θ : angle between CEA and SEA; α : angle between CEA and line connecting knee center and attachment of anterior boom; β : angle between CEA and line connecting knee center and rotation center of reference guide; $\alpha-\theta$: angle between SEA and line connecting knee center and attachment of anterior boom; $\beta-\theta$: angle between SEA and line connecting knee center and rotation center of reference guide.

MR vs CR (CEA) due to the low value of the sine of θ . The rotational position of the femoral component is not accurate in the measured resection techniques because of the intraoperative judgment using the bony landmark subjectively [26,28]. In addition, there is a risk of internal rotation of the femoral component when using 2D measurement including CT slice planning, even with a precise bone cutting technique [29]. Many papers have reported problems with internal rotation placement [29-31]. When the femoral component is placed in internal rotation, the quadriceps force and the effect on the collateral ligaments are increased, and maltracking of the patella, increased peak contact force in the medial compartment, and paradoxical anterior position of the medial femoral condyle are observed [30,31]. Based on the results of this study, we believe that if we can predict the size of components through accurate planning, we can suspect the possibility of internal rotation placement when the size is smaller than the planned size.

Understanding the effect of surgical techniques on the component size could provide surgeons performing the

measured resection technique with clinically useful information to fine-tune the joint gap by adjusting the component size during surgery. Even if the native femoral condyle is reproduced, there is no need to consider posterior cruciate ligament tightness or size adjustment. However, when using measured resection techniques, it is important to recognize that posterior cruciate ligament tightness can occur due to inconsistent joint line changes and posterior condyle thickness. In fine-tuning the altered gap, surgeons can downsize the component and increase the flexion gap by using CR instead of releasing the posterior cruciate ligament, as the latter may cause AP instability with cruciate-retaining implant types [32]. Surgeons can also upsize the component and decrease the flexion gap by using MR with posterior-stabilized implant types. In addition, it is possible to select either MR or CR when component oversize or undersize is predicted, both preoperatively and intraoperatively. Identification of a smaller femoral size than the preoperative predicted femoral size means the distal femoral bone was cut is in more flexion than the target sagittal alignment. The surgeon should try

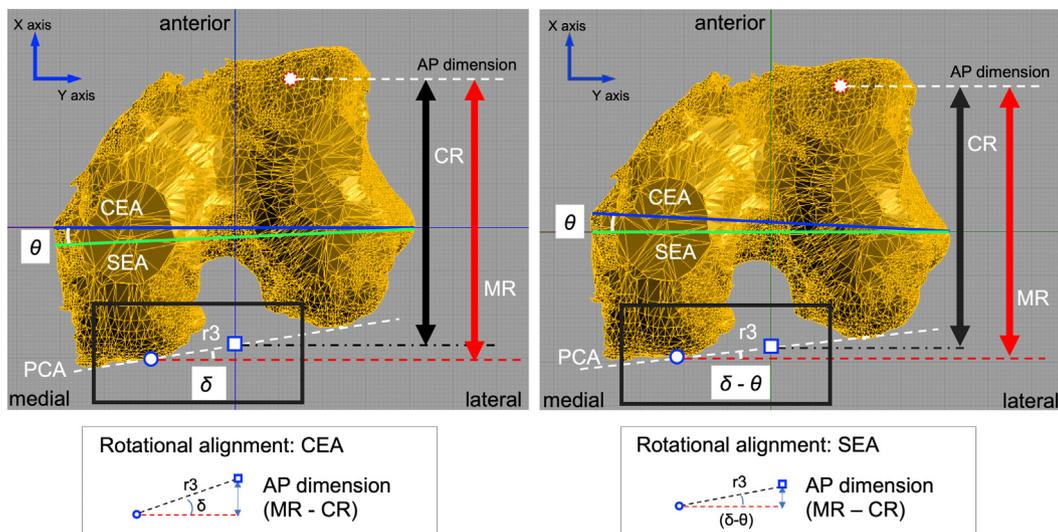


Figure 4. Difference in anteroposterior (AP) dimension using MR or CR in the XY-plane. (Left) Target rotational alignment: CEA; (right) target rotational alignment: SEA. Blue lined circle: rotation center of MR; blue lined square: rotation center of CR; red dotted circle: attachment of anterior boom. Difference of AP dimension between using MR and CR (CEA) = $r3 \times \sin\delta$. Difference of AP dimension between using MR and CR (SEA) = $r3 \times \sin(\delta-\theta)$, where $r3$: distance between rotation center of MR and rotation center of CR; θ : angle between CEA and SEA; δ : angle between CEA and PCA. PCA, posterior condylar axis.

to recut the distal femur in extension even though it is difficult to decide the cutting condition accurately with conventional techniques. There is no need to change the target rotational alignment as a compensation when accurate preoperative planning was performed. Change of the reference guide from CR to MR can increase the component size after the distal femoral cut. In addition, the factor affecting the internal rotation is selection of TEA (CEA or SEA) in the measured resection technique only. If internal rotation of component placement was suspected, it is important to check whether intraoperative determination of TEA is correct by checking the point of the medial and lateral epicondyle again and using Whiteside line. Change of the target alignment from SEA to CEA can be used if the SEA was selected from the preoperative plan. We think that our results can help surgeons to achieve the planned component size as far as possible.

There are several limitations to this study. First, no actual intraoperative measurements were performed. It may be useful to compare component sizes between MR and CR and/or between the CEA and SEA using computer-assisted surgery; however, the evaluations in this study should be reliable because accurate virtual surgical procedures were achieved using osteoarthritic knees before TKA. Further research is needed to compare actual and simulated sizes including analyzing the postoperative sagittal alignment, the type of reference guide, and the target rotational alignment. Second, no valgus osteoarthritic knees were included in this study; if they had been, our results may have been different. To minimize the potential influence of extraneous factors, we included only varus knees since these are most common at our institution. Third, only 1 position of the anterior boom of the reference guide was defined in this study. Ng et al. found that the midpoint 20 mm above the most proximal margin of the anterior femoral condyle best reflected the actual femur size [33]. The position of the anterior boom of the reference guide was at a mean distance of 17.4 ± 5.8 mm, which was close to their recommended distance of 20 mm. The effect of the location of the boom should be evaluated in further studies using computer simulation. Fourth, this study simulated surgeries using a conventional jig and mechanical alignment as the target alignment. The kinematic alignment technique is based on the concept of restoring the alignment of the prearthritic knee by adjusting the position of the femoral and tibial components [34]. In this technique, it is not necessary to consider the size change of the implant by finding the smallest amount of mismatch between the bony anatomy and available implants. Therefore, our results do not apply to surgeons who are using kinematic alignment. In addition, computer-assisted surgeries such as robotic surgeries and surgeries performed with a large console-type navigation system can provide more accuracy than conventional techniques even though some errors can occur.

Conclusions

The results of this study suggest that understanding the effects of intraoperative surgical techniques on component size can help surgeons compensate for an unexpected joint gap in conventional methods.

Conflict of interest

Dr. Hideki Mizu-uchi is in the speakers' bureau of or gave paid presentations for Zimmer Biomet. All other authors declare no potential conflicts of interest.

For full disclosure statements refer to <https://doi.org/10.1016/j.artd.2022.07.008>.

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