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Optimal anterior femoral offset for functional range of motion in total hip arthroplasty

–A computer simulation study-

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Abstract

Purpose Compared to medial femoral offset (MFO), the role of anterior femoral offset (AFO) on range of motion (ROM) in total hip arthroplasty (THA) has not been fully examined. We therefore defined AFO as the anterior distance from the center of the femoral head to the proximal femoral axis in the sagittal plane and determined the optimal AFO required for ROM needed for activities of daily living using a computer-simulated THA model.

Methods Various AFOs were obtained by changing stem anteversion (stem-AV) and stem tilt in the sagittal plane (stem-tilt) using a CT-based simulation software. The required ROM was defined as; flexion ≥ 110°, internal rotation at 90° flexion (IR) ≥ 30°, external rotation (ER) ≥ 30°, and extension ≥ 30° and we determined AFO and MFO to satisfy required ROM.

Results AFO was positively correlated with stem-AV and anterior stem-tilt. MFO was negatively correlated with stem-AV and not influenced by stem-tilt. Flexion and IR increased with both increased AFO and MFO, whereas extension and ER decreased with increased AFO. A smoothing spline curve showed the optimal AFO and MFO for required ROM to be from 15 mm to 25 mm in average and more than 32.1 mm, respectively.

Conclusions This is the first study to show that AFO directly influenced ROM in THA. Optimal AFO as well as MFO should be reconstructed to achieve sufficient ROM.

Keywords stem anteversion; sagittal stem tilt; anterior femoral offset; total hip arthroplasty

Introduction

Accurate component placement is necessary for the success of total hip arthroplasty (THA), as implant malposition directly influences postoperative instability, wear, and aseptic loosening [1-4]. On the femoral side, restoration of femoral offset is one of the most important factors to avoid impingement, improve ROM, and increase abductor strength in THA [5, 6]. The term femoral offset is often used to describe the horizontal distance from the center of the femoral head to the proximal femoral axis in the coronal plane, which we will refer to as the medial femoral offset (MFO) [5-7]. One study showed that there was a highly positive correlation between MFO and abductor strength [5]. Another cadaveric study showed that increasing MFO resulted in the significantly improved range of both flexion and internal rotation in flexion [6].

Compared to MFO, the effects of anterior femoral offset (AFO) on postoperative hip function in THA have not been fully discussed. One report revealed that when the mean femoral head-neck offset improved from 1.9 mm to 9.6 mm, mean hip flexion improved from 94.1° to 110.0° in patients who underwent osteochondroplasty for symptomatic CAM-type femoroacetabular impingement [8]. Another report found a significant linear correlation between anterior head-neck offset and hip ROM following hip resurfacing. This study demonstrated that the ROM in the high-offset group was better than that in the low-offset group [9]. However, the effect of AFO on ROM following conventional THA has not been described in literatures.

In this study, we defined AFO as the anterior distance from the center of the femoral head to the proximal femoral axis in the sagittal plane (Fig. 1). Our null hypothesis was that AFO had no influence on ROM following THA. We also examined how AFO is influenced by stem anteversion and sagittal stem tilt. Furthermore, we calculated the AFO and MFO required to fulfill the ROM needed for activities of daily living using a computer-simulated THA model.

Patients and Methods

Subjects and data collection

This study was approved by the Institutional review board at our institution. Eight healthy subjects, 4 males and 4 females, averaging 40.3 years of age (range, 29–71), 166.4 cm (152– 175), and 61.2 kg (50–80) without history of hip disease, gave informed consent to participate in this study. All CT scans were performed supine and with the patient symmetrically positioned in the scanner as confirmed on the scout views. The scans included the pelvis, proximal femur, and knee. After downloading the scan data in the Digital Imaging and Communications in Medicine (DICOM; NEMA [National Electrical Manufacturers Association], Rosslyn, VA) format onto a personal computer, computer simulation was performed using a CT-based simulation software (ZedHip Lexi Co., Ltd., Tokyo, Japan) [10, 11] (Fig. 2).

Definition of parameters

Cup anteversion was defined as the operative anteversion as described by Murray et al. [12]. Cup inclination was defined as an abduction angle using the interteardrop line as the baseline. Stem anteversion (stem-AV) was defined as the angle of the prosthetic femoral neck relative to the epicondylar line (Fig. 3a) [13]. Sagittal stem tilt (stem-tilt) was defined as the angle between the stem axis and the proximal femoral axis in the sagittal plane (Fig. 3b) [14]. Anterior stem tilt was described to be positive. AFO was defined as the anterior distance from the center of the femoral head to the proximal femoral axis in the sagittal plane when the femur was positioned in a neutral position. When the center of the femoral head indicated an anterior position in reference to the proximal femoral axis, it was described as a positive value. Likewise, the MFO was defined as the horizontal distance from the center of the femoral head to the proximal femoral axis in coronal plane (Fig. 1).

Computer simulation study

This computer simulation software (the Zed Hip® system, Lexi Co., Ltd., Tokyo, Japan) included the implant database with computed-aid design (CAD) three-dimensional (3D) models provided by the implant manufacturer. After 3D hip models were created using this software, femoral neck osteotomy was performed and the implant models were inserted. Implant models were of a cementless hemispherical press fit cup and a straight metaphyseal fit stem (AMS & PerFix HA; Kyocera Medical, Osaka, Japan) [15, 16]. For the pelvis, the Y axis was perpendicular to the plane that included the bilateral anterior superior iliac spines (ASIS) and the pubic symphysis - the anterior pelvic plane (APP). The X axis was parallel to the line that connected the two ASISs. The Z axis was perpendicular to the X and Y axes. For the femur, the Z axis was the line passing through the midpoint between both femoral epicondyles and the center of the femoral head. The X axis was the line passing through both femoral epicondyles. The Y axis was perpendicular to the X and Z axes (Fig. 2). In terms of size of the acetabular implant, the largest acetabular cup that obtained sufficient acetabular cup coverage was selected. The cup was positioned with an inclination of 45° and an anteversion of 20°. The appropriate-size femoral stem was selected so that stem was press-fitted within the medullary cavity of the femur. The stem had a neck-shaft angle of 130° and a femoral neck diameter of 9 mm in the proximal portion and 10 mm in distal portion. The stem was placed neutrally in the coronal plane. Stem-tilt was changed from -5° to 5° in 1° increments. Likewise, stem-AV was changed from 0° to 60° in 10° increments. Neck length was chosen from 0 mm to 9 mm in 3 mm increments. The level of the femoral neck osteotomy and the neck length were determined so that leg length and MFO were similar to the contralateral side. Table 1 shows the neck length that was selected in each model. We created 77 THA models (7 × 11). We measured ROM at prosthetic or bony impingement under flexion, internal rotation at 90° of flexion (IR), external rotation (ER) and extension in each THA model. We defined all of the following ROM conditions (1) flexion ≥ 110°, (2) IR ≥ 30°, (3) ER ≥ 30°, and (4) extension ≥ 30° as required ROM for activities of daily living, according to both in vitro and in vivo studies [17-19]. The AFO and MFO in each THA model were measured and the AFO and MFO to fulfill the required ROM were evaluated.

All computer simulations were performed by one observer (MH) and were repeated in a blind manner at least one month after the first measurements were taken. Intraobserver reliabilities, evaluated using intraclass correlation coefficients, were excellent (range, 0.990–0.997). Two observers (MH and MK) independently made computer simulations, and interobserver reliabilities evaluated using interclass correlation coefficients were also excellent (range, 0.919–0.997).

Statistical methods

The student's t-test was used to compare two continuous parameters. A significant difference was defined as a p-value < 0.05. A smoothing spline curve was applied to each scatter diagram. The intersection of the smoothing spline curve with a required ROM was measured as the maximum or minimum ROM to fulfill a required ROM in each ROM. Statistical analyses were performed using JMP Software (Version 9.0; SAS Institute, Cary, NC).

Results

AFO increased with increasing stem-AV and stem-tilt. When stem-tilt was 0°, the AFO increased by 3.0 mm with increase of stem-AV by 5°. When stem-AV was 20°, AFO increased by 2.0 mm with the anterior stem-tilt at 1° (Fig. 4a, b). On the other hand, MFO was influenced by stem-AV but not by stem-tilt. When stem-tilt was 0°, the MFO decreased by 1.6 mm with increase of stem-AV by 5°.

Flexion and IR increased with increasing AFO. A smoothing spline curve showed that flexion increased from 100° to 114° and IR increased from 23° to 44° when AFO was increased from 10 mm to 20 mm. The minimum values of AFO for the required ROM in flexion and IR were 15 mm and 14.7 mm, respectively (Fig. 5a, b). Impingement with flexion typically occurred between the anterior femoral neck and the anterior inferior iliac spine (AIIS). Impingement with IR typically occurred between the anterior greater trochanter and AIIS. On the other hand, extension and ER decreased with increasing AFO. When AFO increased from 10 mm to 20 mm, extension decreased from 68° to 48° and ER decreased from 56° to 38°. The maximum values of AFO for the required ROM in extension and ER were 25 mm and 27.7 mm respectively (Fig. 5c, d). Impingement with extension occurred between the neck of the stem and posterior rim of the liner or between the lesser trochanter and ischium. Impingement with ER typically occurred between the posterior greater trochanter and ischium. The value of AFO for the required ROM in order to satisfy all four defined conditions of motion was from 15 mm to 25 mm.

MFO decreased with increasing stem-AV. The minimum values of MFO in flexion, IR, extension, and ER were 21.3 mm, 21.3 mm, 32.1 mm, and 32.1 mm respectively. Therefore, MFO needed to be more than 32.1 mm in order to satisfy the four defined conditions of motion (Data was not shown).

To compensate for a small stem-AV, the stem can be tilted anteriorly to address the AFO. Conversely, the stem can be tilted posteriorly if stem-AV is too great. Stem-AV and stem-tilt for optimal AFO and

MFO are shown in Fig. 4c. When stem-AV was greater than 50°, the required ROM could not be fulfilled due to the insufficient MFO. Similarly, the required ROM was not fulfilled when stem-AV was 0°.

DISCUSSION

In this study, we examined whether AFO influenced ROM using a computer-simulated THA model. AFO, which was dictated by stem-AV and stem-tilt, directly influenced ROM. The more AFO resulted in the more range of flexion and IR, but reduced the range of extension and ER. The optimal AFO to fulfill the required ROM ranged from 15 mm to 25 mm. To our knowledge, this is the first study to demonstrate the relationship between AFO and ROM in THA.

Müller et al. introduced the concept of functional anteversion - the angle between the center of the femoral head and the proximal femoral axis. They showed that functional anteversion was influenced by both stem-AV and stem-tilt using postoperative CT data and a mathematical model [14]. Based on their concept, we defined AFO as the anterior distance from the center of the femoral head to the proximal femoral axis in the sagittal plane and examined the role of AFO on ROM. AFO was dependent on stem-AV and sagittal stem-tilt if the neck length remained constant. Greater stem-AV and anterior stem tilt resulted in greater AFO (Fig. 4a, b). Stem-AV had opposing effects on MFO and AFO - when stem-AV was greater, MFO became smaller, suggesting the need for optimal balance of AFO and MFO.

Kessler et al. showed that the anterior trochanteric region tended to impinge on the anterior rim of the acetabulum in flexion, and that the posterior trochanteric region tended to impinge on the ischium in ER [20]. This is in keeping with our results - the anterior intertrochanteric region typically impinged on the AIIS in flexion and IR. Posterior impingement occurred between the neck and liner or posterior intertrochanteric region and the ischium in extension and ER. When AFO is great, the femur is located more posterior relative to the femoral head and the distance to the anterior impingement is large. Therefore, greater AFO resulted in the increased flexion and IR. On the other hand, the distance to the posterior impingement becomes small with the decreased extension and ER, possibly leading to the anterior dislocation. As a result, the range of optimal AFO was from 15 mm to 25 mm. Regarding the surgical approach, anterior or anterolateral approach generally resulted in more anterior stem-tilt compared to the posterior approach. Müller et al. reported the mean stem-tilt was 5.2° using a direct lateral or anterolateral approach [14]. On the other hand, the mean stem-tilt of 0.3° has been reported using a posterolateral approach [15]. Therefore, it might become relatively higher anterior dislocation risk using an anterior or anterolateral approach when the stem-AV is identical.

The minimum value of MFO for the required ROM was more than 32.1 mm in this study. It is important to understand that both AFO and MFO need to be balanced and optimized but that they have opposing effects of stem-AV. When stem-AV was between 20° and 40°, AFO and MFO for the required ROM could be achieved by adjusting stem-tilt. However, when stem-AV was more than 50° or neutral, the required ROM could not be fulfilled as the adjustment of AFO by stem-tilt was limited.

There are several limitations to this study. First, this study analyzed only one stem design that was a metaphyseal fit stem, a 32 mm femoral head, a neck-shaft angle of 130°, and a femoral neck diameter of 9–10 mm. Although the design is similar to many other metaphyseal fit stems currently available, the results may differ if another implant is used. Secondly, the cup was positioned with an inclination of 45° and an anteversion of 20°. In clinical practice, surgeons change cup anteversion according to the degree of stem-AV. If the cup position is changed, the results in ROM simulation may differ [21]. Thirdly, this study used the CT data of healthy subjects to avoid the disease-specific effects on the simulation. For example, patients with dysplastic hips reportedly have greater femoral anteversion and those with the previous slipped capital femoral epiphysis have very small femoral anteversion. Further simulations are needed to follow-on from the results of this study. Fourthly, the accuracy of computer simulation should be pointed. One study tested the accuracy of CT-based simulation and revealed that the accuracy of the method was 0.7 ± 3.1° in a plastic bone setup and – 5.0 ± 5.6° in a cadaver setup [22]. They explained that the predicted ROM was generally overestimated in the cadaver series because the software calculated only the osseous restricted ROM, ignoring cartilaginous structures or soft-tissue contractures for the calculation of ROM. This is one of the limits of computer simulation studies. Finally, the optimal AFO or MFO was expressed as a measurement in mm, this may change according to the body size. One study showed that taller height resulted in a greater femoral offset in male patients [23]. Another study showed that the mean femoral offset in males was higher than that in females [24]. Although parameters such as sex and height did not significantly influence the optimal AFO in this study ($p= 0.6892$ and 0.6731 respectively), the findings in this current study may be limited.

In conclusion, AFO was positively correlated with stem-AV and anterior sagittal stem tilt, whereas MFO was inversely correlated with stem-AV. Flexion and IR increased with both increasing AFO and MFO, whereas extension and ER decreased with increasing AFO. The optimal AFO and MFO to fulfill the required ROM using a press-fit stem ranged from 15 mm to 25 mm and more than 32.1 mm respectively. This is the first study to demonstrate that AFO directly influences ROM in THA. Optimal AFO as well as MFO should be reconstructed to achieve sufficient ROM.

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Conflict of interest The authors declare that they have no conflict of interest.

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Figure legends

Fig. 1 (a–d) Measurement of AFO and MFO. In each figure, the upper part shows the sagittal view and the lower part showed axial view. (a) The stem was placed with an anteversion of 20° and a sagittal tilt of 0°. (b) The stem was placed with an anteversion of 40° and a sagittal tilt of 0°. (c) The stem was placed with an anteversion of 20° and a sagittal tilt of 5°. (d) The stem was placed with an anteversion of 20° and a sagittal tilt of -5°.

Fig. 2 3D hip model and definitions of pelvic and femoral coordinate systems.

Fig. 3 Measurement of stem-AV (a), and stem-tilt (b).

Fig. 4 (a) Correlation between AFO and stem-AV. (b) Correlation between AFO and stem-tilt. (c) Stem placement to fulfill a required ROM. The gray circle shows the optimal stem placement to fulfill a required ROM.

Fig. 5 (a–d) Correlation between AFO and each ROM condition. Each dot shows the average value of each patient. (a) Flexion. (b) Internal rotation at 90° of flexion. (c) Extension. (d) External rotation.

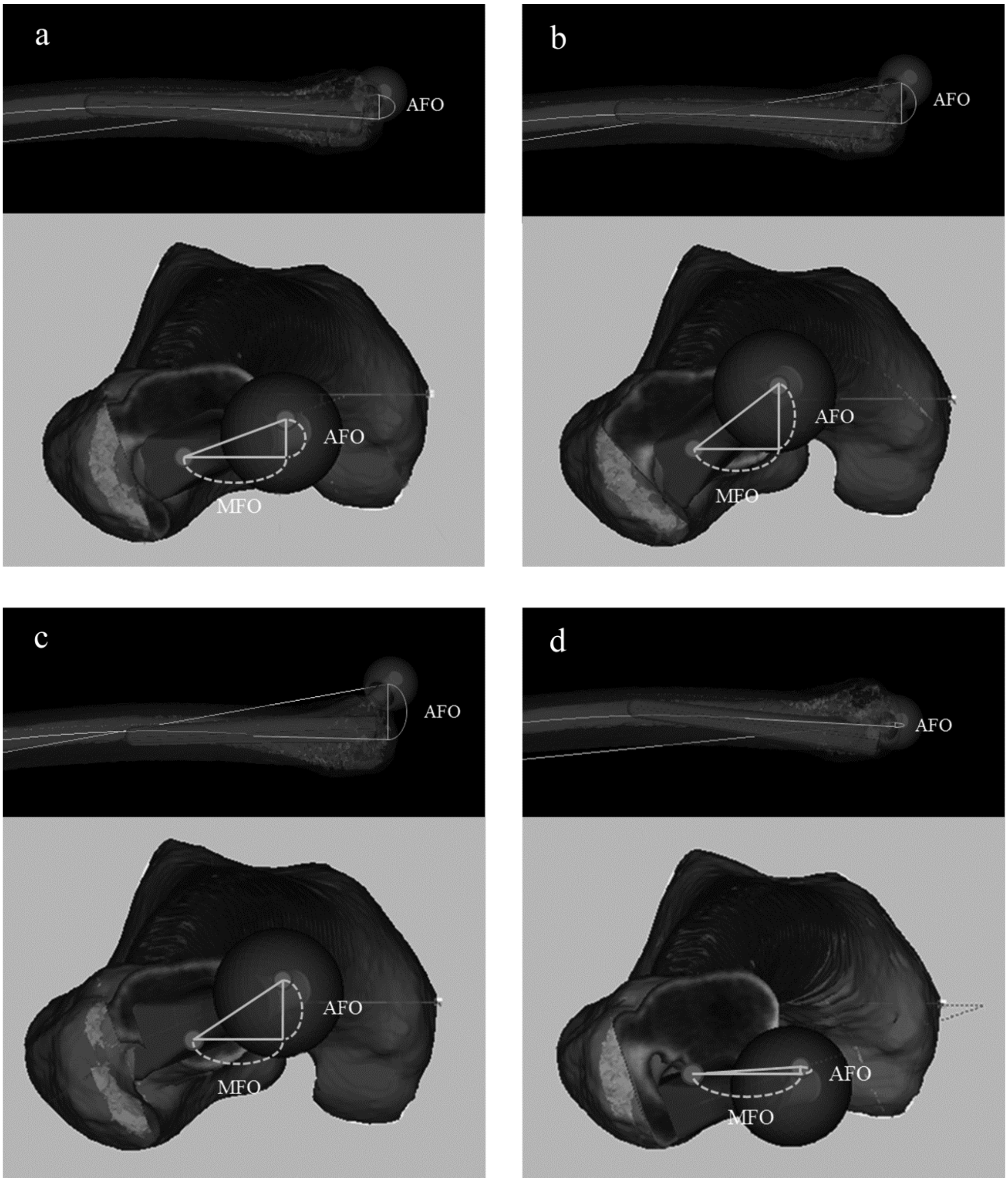

Fig. 1

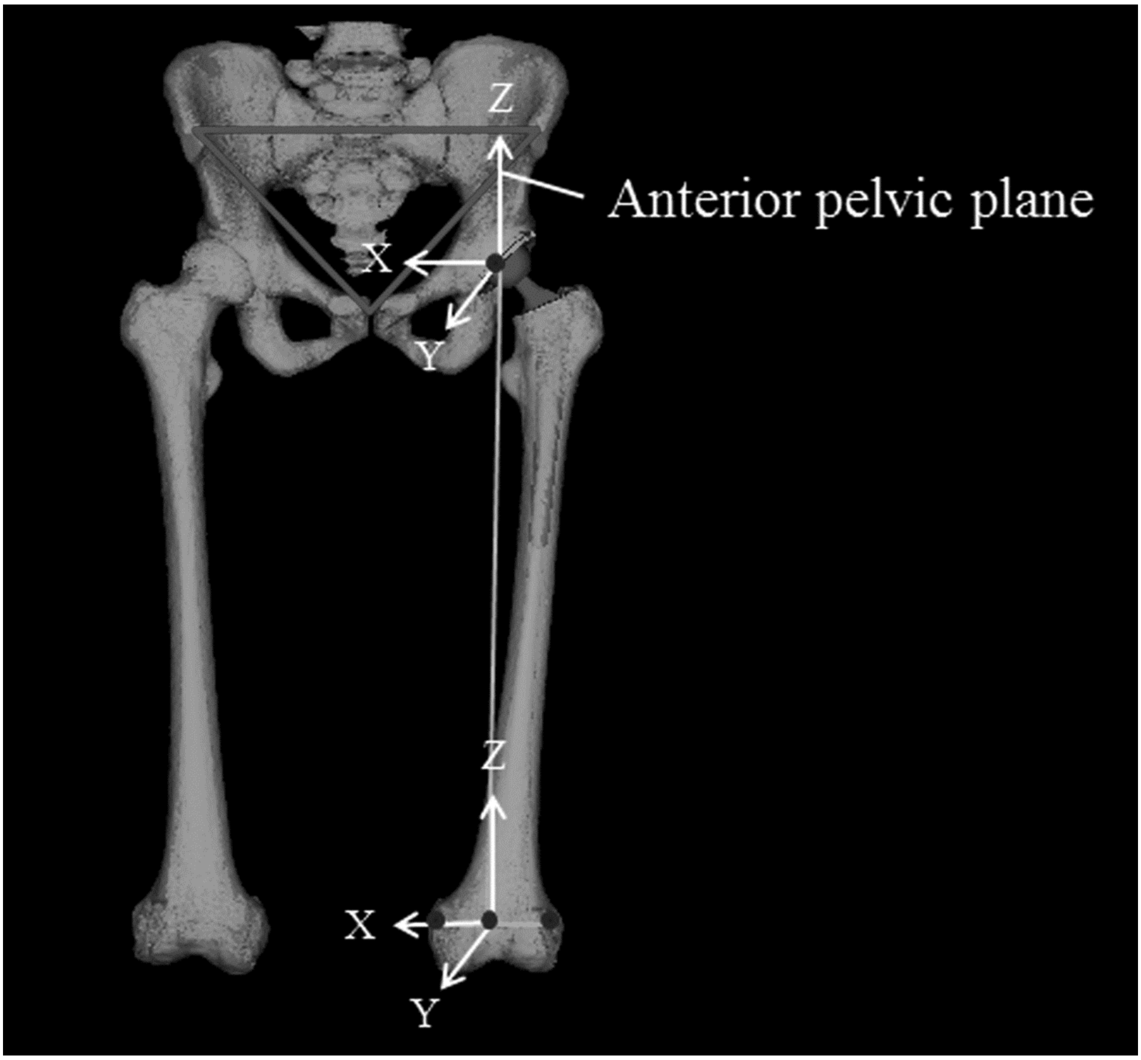

Fig. 2

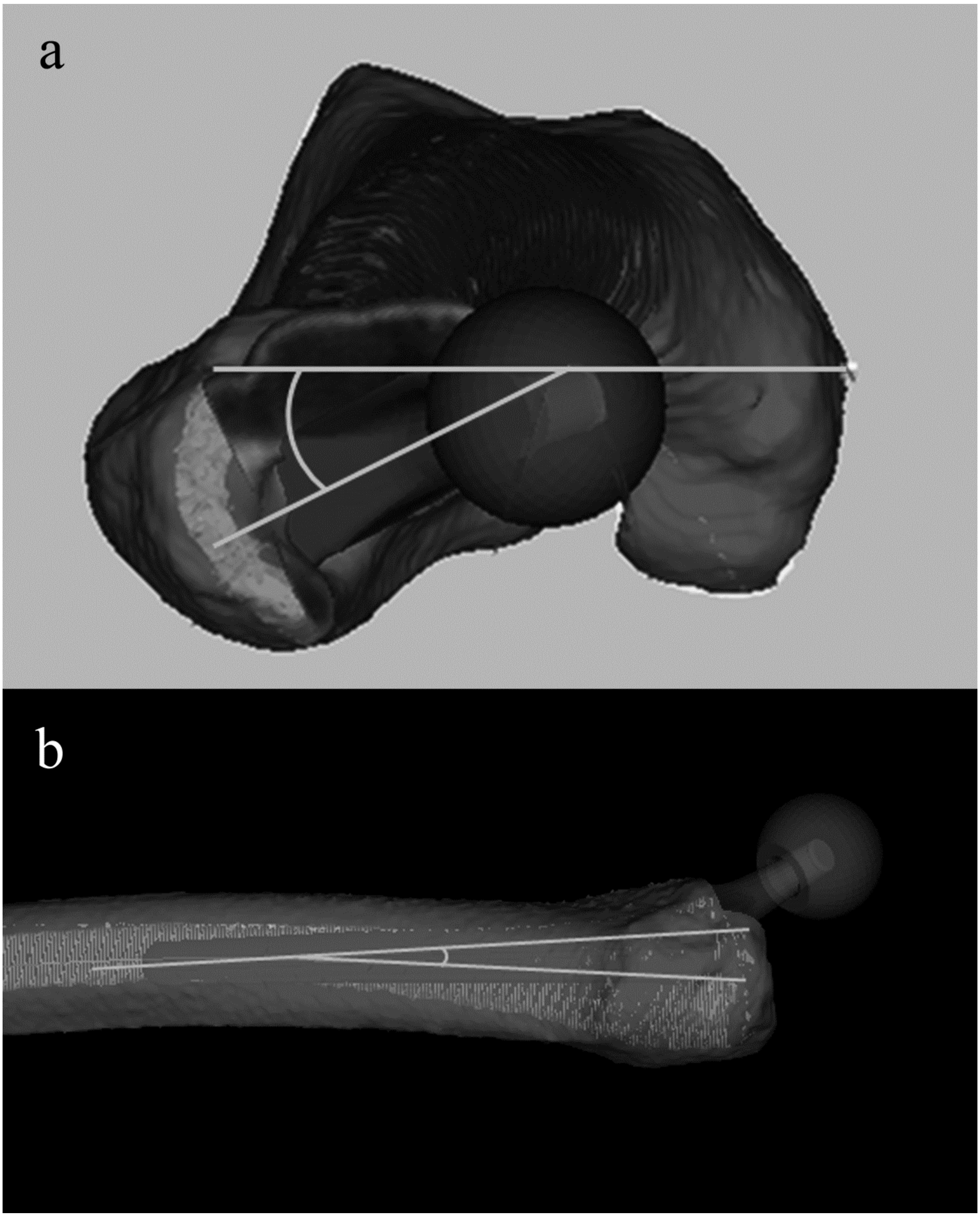

Fig. 3

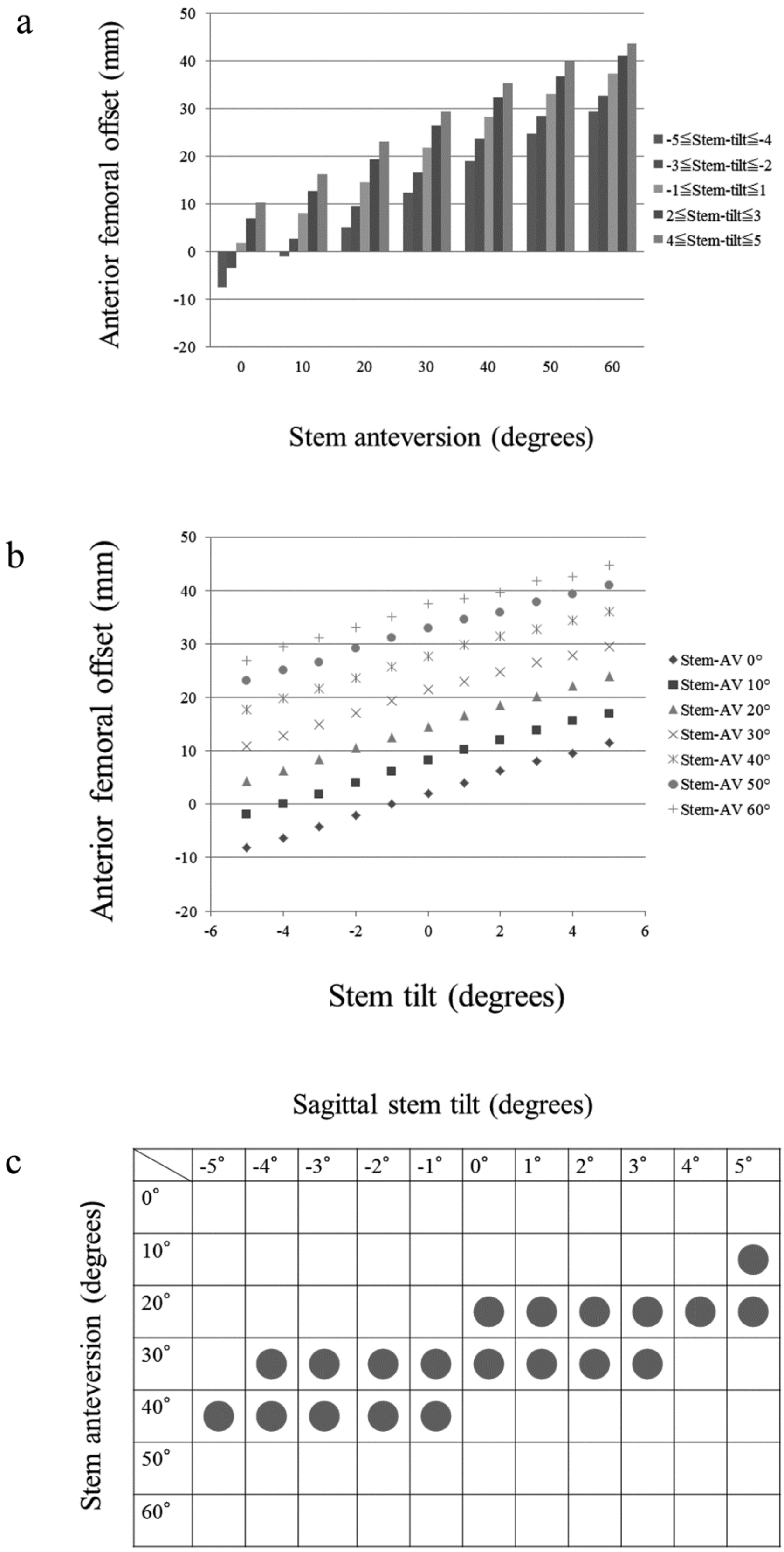
a
Anterior femoral offset (mm)
Stem anteversion (degrees)
-5≦Stem-tilt≦-4
-3≦Stem-tilt≦-2
-1≦Stem-tilt≦1
2≦Stem-tilt≦3
4≦Stem-tilt≦5
b
Anterior femoral offset (mm)
Stem tilt (degrees)
Stem-AV 0°
Stem-AV 10°
Stem-AV 20°
Stem-AV 30°
Stem-AV 40°
Stem-AV 50°
Stem-AV 60°
Sagittal stem tilt (degrees)
c
Stem anteversion (degrees)
-5° -4° -3° -2° -1° 0° 1° 2° 3° 4° 5°
0° 10° 20° 30° 40° 50° 60°

Fig. 4

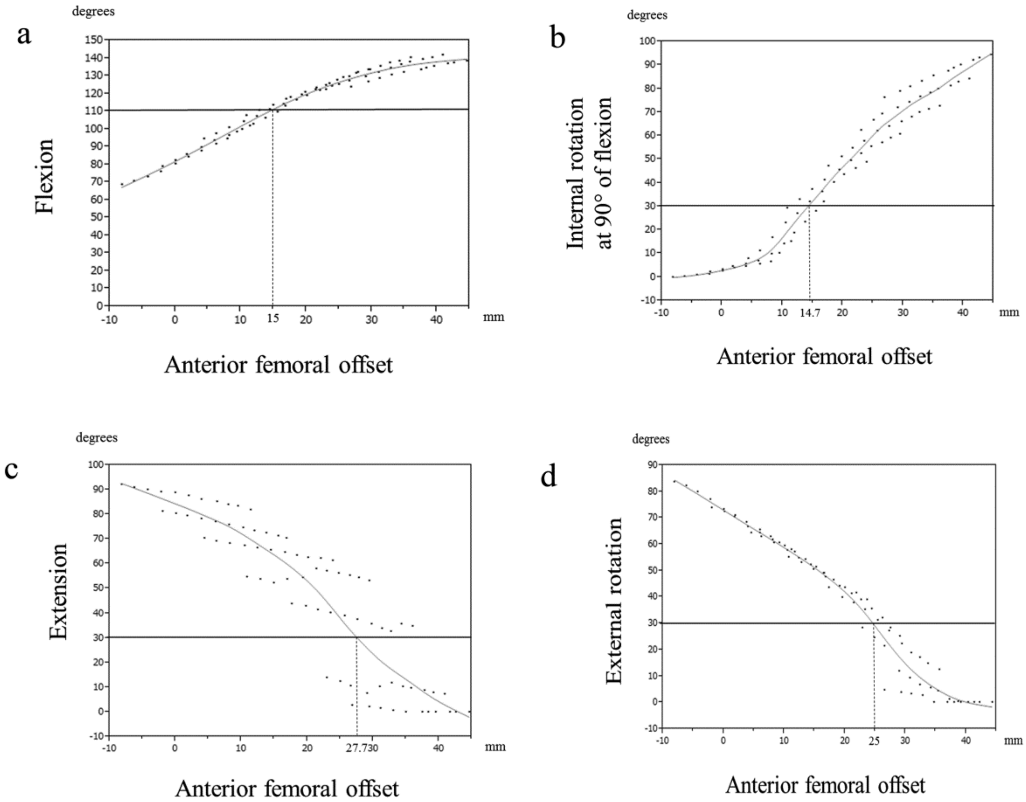
a
degrees
Flexion
Anterior femoral offset
mm
b
degrees
Internal rotation at 90° of flexion
Anterior femoral offset
mm
c
degrees
Extension
Anterior femoral offset
mm
d
degrees
External rotation
Anterior femoral offset
mm

Fig. 5

Table 1. The neck length in each model when stem-AV and stem-tilt were changed (mm)

		Stem-tilt										
		-5°	-4°	-3°	-2°	-1°	0°	1°	2°	3°	4°	5°
Stem-AV	0°	1.7 ± 3.1	1.7 ± 3.1	1.7 ± 3.1	1.7 ± 3.1	1.7 ± 3.1	1.7 ± 3.1	1.7 ± 3.1	1.7 ± 3.1	1.7 ± 3.1	1.7 ± 3.1	1.7 ± 3.1
	10°	1.7 ± 3.1	1.7 ± 3.1	1.7 ± 3.1	1.7 ± 3.1	1.7 ± 3.1	1.7 ± 3.1	1.7 ± 3.1	1.7 ± 3.1	1.7 ± 3.1	1.7 ± 3.1	1.7 ± 3.1
	20°	3.9 ± 2.6	3.9 ± 2.6	3.9 ± 2.6	3.9 ± 2.6	3.9 ± 2.6	3.9 ± 2.6	3.9 ± 2.6	3.9 ± 2.6	3.9 ± 2.6	3.9 ± 2.6	3.9 ± 2.6
	30°	6.9 ± 3.1	6.9 ± 3.1	6.9 ± 3.1	6.9 ± 3.1	6.9 ± 3.1	6.9 ± 3.1	6.9 ± 3.1	6.9 ± 3.1	6.9 ± 3.1	6.9 ± 3.1	6.9 ± 3.1
	40°	8.3 ± 2.0	8.3 ± 2.0	8.3 ± 2.0	8.3 ± 2.0	8.3 ± 2.0	8.3 ± 2.0	8.3 ± 2.0	8.3 ± 2.0	8.3 ± 2.0	8.3 ± 2.0	8.3 ± 2.0
	50°	8.1 ± 2.1	8.1 ± 2.1	8.1 ± 2.1	8.1 ± 2.1	8.1 ± 2.1	8.1 ± 2.1	8.1 ± 2.1	8.1 ± 2.1	8.1 ± 2.1	8.1 ± 2.1	8.1 ± 2.1
	60°	8.6 ± 1.0	8.6 ± 1.0	8.6 ± 1.0	8.6 ± 1.0	8.6 ± 1.0	8.6 ± 1.0	8.6 ± 1.0	8.6 ± 1.0	8.6 ± 1.0	8.6 ± 1.0	8.6 ± 1.0

Mean ± SD (range)