Original article

Three-dimensional kinetic simulation before and after rotational acetabular osteotomy

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【Key words】

rotational acetabular osteotomy, range of motion, femoroacetabular impingement, simulation, three-dimensional computed tomography

The authors declare that they have no conflict of interest.

Abstract

Background

Some reports indicate that one of major causes of clinical failure after periacetabular osteotomy is development of secondary femoroacetabular impingement (FAI).

To assess the impact of range of motion on the increase in FAI following rotational acetabular osteotomy (RAO), we performed FAI simulations before and after RAO.

Methods

We evaluated 12 hips that had undergone RAO (study group), and 12 normal hips (control group). The study group was evaluated before and after surgery. Morphological parameters were evaluated to assess acetabular coverage. Acetabular anteversion angle, anterior CE angle, alpha angle, and combined anteversion angle also were measured. Impingement simulations were performed using 3D-CT. The range of motion which causes bone-to-bone impingement was evaluated in flexion (flex), abduction, external rotation in flex 0°, and internal rotation in flex 90°. The lesions caused by impingement were evaluated.

Results

Radiographic measurements indicated improved postoperative acetabular coverage in the study group. The crossover sign was recognized pre- and postoperatively in every case in the study group and in no cases in the control group. In the simulation study, flexion, abduction and internal

rotation in flex 90° decreased postoperatively. Impingement occurred within internal rotation 45° in flex 90° in two preoperative and nine postoperative cases. The impingement lesions were anterosuperior of the acetabulum in all cases. There was a correlation between anterior CE angle, CE angle, acetabular anteversion angle and hip flexion angle. Also there was correlation between the anterior CE angle, combined anteversion angle and angle of internal rotation in flex 90°.

Conclusions

In the postoperative simulation there was a tendency to reduce the range of motion in flexion, abduction, and internal rotation in flex 90° due to impingement. Since there are more cases which cause impingement within a 45° internal rotation in flex 90° after RAO, we consider there is a potential for increased FAI after RAO.

Introduction

Hip dysplasia is one of the most common causes of secondary osteoarthritis (OA) in young adult patients. Various reports have described periacetabular osteotomies to prevent progression from dysplasia to secondary OA, such as Bernese periacetabular osteotomy [1] and Ninomiya and Tagawa's rotational acetabular osteotomy (RAO) [2]. Periacetabular osteotomy (PAO) is now a common surgical procedure and an effective treatment option for symptomatic acetabular dysplasia [3].

In a periacetabular osteotomy, the osteotomised acetabular fragment is rotated anterolaterally, which improves acetabular coverage and also restores the center of rotation of the femoral head both medially and distally [2]. It helps restore normal hip biomechanics, decreases symptoms, improves function, and prolongs the longevity of the hip joint [4, 5]. There have been several studies about the biomechanical effects of periacetabular osteotomy and assessments of acetabular morphology using three-dimensional (3D) computed tomography (CT) [6, 7]. However, few reports have addressed the impact of PAO on range of motion (ROM) and changes in ROM before and after PAO. Most previous studies evaluated hips in a static state and it was technically difficult to duplicate kinetic motion.

Some reports indicate that one of the major causes of clinical failure is the development of secondary femoroacetabular impingement (FAI) after acetabular reorientation. Myers et al. [8]

described the risk of a secondary anterior femoroacetabular impingement after PAO. Siebenrock et al. [9] reported 29% of hips (17 of 58) experienced symptomatic impingement after PAO and pointed out that excessive lateral and anterior correction may lead to FAI. Thus, it is important to use kinetic simulation to evaluate the influence of PAO on ROM, because FAI occurs in dynamic motion.

Recent advancements in imaging and computer technology allow us to simulate ROM of the hip joint using 3D-CT and special software. The purpose of our study was to evaluate morphological features in patients before and after RAO and to simulate ROM in patients before and after RAO.

Materials & Methods

Subjects

With the approval of our Institutional Review Board and informed consent obtained from all patients, we reviewed retrospectively collected data for 12 hips in 12 patients who underwent RAO between June 2006 and January 2013, with available computed tomography acquired before and after the surgery. The control group was 12 normal hips in 12 patients whose contralateral hips had been treated in our hospital. All patients were female; mean patient ages were 40 years in the study group and 37 years in the control group, and mean body mass indexes were 21.8 in the study group and 20.7 in the control group (Table 1). We selected only female patients because in Japan, secondary OA of the hip due to hip dysplasia occurs in about 90% of all cases, and most patients are female. In the study group, 3 hips were Tönnis Grade [10] 0, 6 were Grade 1 and 3 were Grade 2. All surgeries were performed by a single surgeon (senior author, KT). Using the RAO technique of Ninomiya and Tagawa [2], we rotated the acetabular fragment, aiming at a 0° acetabular roof angle and an anterior rotation of about 10 degrees, evaluating posterior coverage by CT. All procedures included an intraoperative anteroposterior view radiograph of the pelvis to determine whether the acetabular fragment was rotated as called for in the preoperative plan. CT scans were performed from the pelvic to the femoral condyle on all patients before and after the surgery.

Morphological study

The lateral center-edge (CE) angle [11], Sharp angle [12], acetabular head index [13], acetabular roof angle [14], and crossover sign [15] were evaluated on the anteroposterior view radiographic images of the pelvis for both the study and the control groups. The anterior CE angles [16] also were evaluated by CT. The acetabular anteversion angle was defined as the direction of the acetabular opening in the axial plane and measured at the level centered on the femoral head.

On the femoral side, the femoral anteversion angle and neck shaft angle were measured according to previously described methods [17]. The alpha angles [18] were determined on axial oblique images taken in the plane of the femoral neck using multi-planar reconstruction CT. Also the combined anteversion angle, the determined sum of the anteversion angle of both femur and acetabular which was used in total hip arthroplasty, was evaluated.

ROM study

Range of motion simulations were performed using ZedHip (version 5.5; LEXI, Tokyo, Japan) preoperative planning software for total hip arthroplasty (Fig 1). In brief, we created 3-D models of the patient's hip using computed tomography data. The functional pelvic coordinate system previously described [19], adjusted for pelvic anteroposterior tilt in the supine position, was used as a substitute for the anterior pelvic plane. The unit vectors of the system were defined as follows. The mediolateral axis was the same as the anatomical pelvic plane, through the bilateral anterior superior iliac spines and the midpoint of bilateral pubic tubercles. The anteroposterior axis was perpendicular to the CT table. The craniocaudal axis was perpendicular to the anteroposterior and mediolateral axes.

The femoral coordinate systems were defined as the retrocondylar plane. The anteroposterior axis was perpendicular to the posterior femoral plane that included the most posterior point of the greater trochanter and the posterior femoral condyles. The craniocaudal axis was parallel to the posterior femoral plane including the femoral head center and the midpoint of the medial and lateral femoral epicondyles. The mediolateral axis was perpendicular to the craniocaudal and anteroposterior axis.

The neutral position of the hip was determined when both the pelvic and femoral coordinate systems were parallel. The range of motion of the hip joint was determined as a relative angle between the two coordinate systems.

The range of motion which causes bone-to-bone impingement was evaluated in flexion, abduction, external rotation in 0° flexion, internal rotation in 90° flexion, internal rotation in 90° flexion and 10° adduction, and internal rotation in 90° flexion and 20° adduction. The lesions caused by impingement were evaluated using the clock system. In brief, the locations of the acetabular rim were quantified with an overlying clock system. 0 o'clock was defined as the top of the acetabular rim based on anterior pelvic plane. The location of the anterior edge, the posterior edge was defined as 3 o'clock and 9 o'clock. All acetabula were assumed to be on the right side.

Statistical analysis

Descriptive data are shown as mean ± standard deviation (SD). The Wilcoxon signed-rank tests and Mann-Whitney U tests were used to compare paired and unpaired data. Differences were defined as significant when p was <0.05. Correlation analysis was performed to examine the relationship between the morphological parameter and the range of motion using the Pearson linear correlation coefficient (r). A coefficient > 0.40 was defined as moderate and over correlation.

Results

All postoperative radiographic measurements indicated improved acetabular coverage in the study group (Table 2). The postoperative acetabular coverages in the study group were larger than in the control group, although there were no significant differences. The crossover sign was recognized in each case in the images obtained before and after surgery for the study group. There were no positive crossover signs in the control group. The anterior CE angle improved postoperatively and some cases coverage became greater than in normal hips. In postoperative hips, the acetabular anteversion angle was reduced compared to preoperative and normal hips. In the study group there were no cases of preoperative retroversion and postoperative retroversion occurred in only one case, with an acetabular anteversion angle of less than 0 degrees.

In the simulation study, the range of motion after RAO decreased flexion from 133.4° to 105.9° in the preoperative study group. In nine postoperative simulations impingement occurred up to 120° flexion, the normal range of flexion previously reported (Table 3). Abduction decreased in the postoperative study group, from 63.2° to 48.5°, but this range of motion was the same for the control group. There was no significant difference in external rotation before and after surgery in the study group. Internal rotation in 90° flexion decreased from 55.0° to 25.4° postoperatively in the study group. In two preoperative and nine postoperative cases impingement occurred within 45 degrees of internal rotation in 90° flexion, which is the normal range reported in previous publications. In all cases, internal rotation in 90° flexion decreased as adduction increased. Impingement lesions, which were caused by internal rotation in 90° flexion, so called ‘anterior FAI,’ were on the anterosuperior quadrant of the acetabulum in all cases. The average of the impingement lesions was at 1.1 o’clock (Before RAO / After RAO / Control: 34.0°/33.4°/31.3°). There were no significant differences among the three groups. There was a correlation between anterior CE angle (r;-0.5133, $p<0.001$), CE angle (r;-0.5237, $p<0.001$), acetabular anteversion angle (r; 0.4345, $p<0.001$), and hip flexion angle. Also there was a correlation between the anterior CE angle and angle of internal rotation in 90° flexion. Furthermore, there were correlations between the anterior CE angle, combined anteversion angle, and the angle of internal rotation in 90° flexion and 10° adduction , and the angle of internal rotation in 90° flexion and 20° adduction (Table 4).

【Discussion】

In our study, we evaluated morphological features and range of motion before and after RAO using a 3D-CT simulation. Our results indicate that anterior coverage after RAO was sometimes greater than in normal hips. In the postoperative simulation, there was a tendency toward a reduced range of motion in flexion, abduction, and internal rotation in 90° flexion due to impingement. The correlation between anterior CE angle and flexion, internal rotation in 90° flexion, internal rotation in 90° flexion and 10° adduction, and internal rotation in 90° flexion and 20° adduction leads us to consider that this tendency is caused by increased anterior coverage after RAO.

Some published reports have addressed range of motion after PAO. Ziebarth et al. [20] reported that flexion, internal rotation decreased postoperatively in patients who underwent periacetabular osteotomy. On the other hand, Hasegawa et al. [21] found no significant change in range of motion in eccentric RAO. However, to our knowledge, there are few reports of the influence of range of motion following PAO. In our cases, flexion, abduction, and internal rotation decreased postoperatively compared to preoperative and normal hips. So, postoperatively there was a tendency toward reduced ROM. Also, since impingement occurred until about 20° internal rotation in 90° flexion in the postoperative study group compared to more than 30° internal rotation in 90° flexion in the control hips, we consider there is a strong potential for increased FAI after RAO.

We have been able to evaluate kinetic motion using 3D simulations for some ten years. Several authors have reported clinical or simulation data of ROM in normal hips or those with FAI. Nakahara et al. [19] showed 126.2° of flexion and 44.9° of internal rotation at 90° flexion in normal hips using 3D simulations. Tannast et al. [22] developed software for the noninvasive three-dimensional assessment of FAI and reported 121° of flexion and 35° of internal rotation at 90° flexion in normal hips. Our simulation analysis matches well with previously reported clinical or simulation data on the range of motion in normal hips, demonstrating that this simulation system is helpful in a clinical setting (Table 5).

In relation to FAI cases, Kubiak-Langer et al. [23] evaluated the range of motion in 28 hips with anterior FAI using a 3-D CT-based method and reported 105° of flexion and 11° of internal rotation at 90° flexion. Several authors have reported on hip range of motion in FAI (Table 5). In our simulation, flexion was equivalent to clinical cases of FAI, but internal rotation was wider than that found in previous studies. We consider that this was related to a larger femoral anteversion angle in the study group than in the control group.

There have been some reports about femoroacetabular impingement after PAO. Siebenrock et al. [9] reported 29% (17 of 58 hips) had symptomatic impingement after PAO and pointed out the excessive lateral and anterior correction may lead to FAI. Myers et al. [8] reported the risk of a secondary impingement after PAO. Steppacher et al. [4] reported a survival rate of 60.5% and identified a postoperative impingement sign as a predictor of poor outcomes following the periacetabular osteotomy. Specifically regarding RAO, Yasunaga et al. reported that postoperatively, 42.6% had a positive crossover sign and 63.5% had a positive posterior wall sign [14]. They found no significant correlations between a positive crossover sign and radiographic progression of osteoarthritis, although anterior impingement signs increased after RAO. In our current study, impingement occurred within 45° internal rotation in 90° flexion more often in the postoperative study group than in the preoperative study group. Previous reports indicated that impingement between femur and reoriented acetabulum actually occurs after PAO. However, no reports mentioned about the clinical features of the patients caused impingement after PAO. Our study showed there were correlations between combined anteversion angle and the angle of internal rotation in 90° flexion and 10° adduction, and the angle of internal rotation in 90° flexion and 20° adduction. The average combined anteversion angle was larger in the after-RAO group than in the control hips. However, the cases in which impingement occurred within 45° internal rotation in

90° flexion after RAO had smaller combined anteversion angles than those in the control hips. It can be said that small combined anteversion is one of the risk factors of anterior impingement after PAO.

However, it is uncertain whether anterior impingement caused secondary OA in our patients. Albers et al. [24] found that proper acetabular reorientation and the creation of a spherical femoral head improves long-term survivorship in PAO. Nassif et al. [25] have reported periacetabular osteotomy and combined femoral head-neck junction osteochondroplasty. In our patients, the average alpha angle was greater than 55° (normal value less than 50°) and the femoral anteversion angle was larger than in normal hips. A larger alpha angle would decrease internal rotation angle in 90° flexion. On the other hand, a larger femoral anteversion angle would increase internal rotation angle in 90° flexion. Previous reports have shown that females, especially those with a dysplastic hip, have a larger femoral anteversion angle [18]. We suggest this larger femoral anteversion angle might reduce the occurrence of secondary OA due to FAI in females compared to males.

To prevent the incidence of FAI after RAO, we might also consider the pelvic and femoral morphology. Cases which have a smaller femoral anteversion angle require special care because in such cases the combined anteversion angle might be reduced postoperatively. Also, we could consider the preoperative anterior coverage. A previous report showed a wide variety of deficiency types and degrees of acetabular dysplasia [26]. In some of our cases the anterior CE angle varied from small to large. In cases of dysplasia with normal anterior CE angles, rotating the acetabular fragment anterolaterally as one would do in cases with smaller anterior CE angles might increase the risk of secondary FAI. We should preoperatively evaluate the anterior coverage using false profile radiography or the anterior CE angle by computed tomography to plan the degree of anterior rotation. Individualized preoperative planning that includes femoral and pelvic morphology can prevent FAI. Furthermore, we hope that the 3D simulation which we performed after surgery can also be applied to the preoperative planning. Further development of the 3D simulation system is needed in order to plan for adequate rotation of the acetabular which fulfills the normal range of motion and sufficient acetabular coverage.

Our study has several limitations. First, we did not compare the simulation data and range of motion in a clinical setting. However, there have been reports that assessed ROM using CT-based simulation in normal hips and FAI (Table 3) and our simulation analysis matches well with previously reported clinical or simulation data on the range of motion of normal hips. Second, the range of motion simulations did not consider impingement of the soft tissue and compensation of lumbar vertebra. In fact, there have been some cases in which soft tissue impingement might have occurred before bone-to-bone impingement and some cases have contracture, so the physical range of motion might be smaller than that in the simulation. Third, the center of the rotation of the femoral head was defined as the center of the spherical approximation of the femoral head. So, in the case with an elliptical femoral head, impingement was detected earlier than in a clinical situation. Simulation also can be difficult in cases with joint space narrowing. Further development of the simulation system is needed to represent actual motion.

In conclusion, the postoperative simulation showed a tendency toward reduced range of motion due to impingement in flexion, abduction, and internal rotation in 90° flexion. Since there are more cases which cause impingement within a 45° internal rotation in 90° flexion after RAO, we consider there is a potential for increased FAI after RAO. FAI might occur after RAO in cases which have a smaller femoral anteversion angle or sufficient anterior coverage preoperatively. Individualized preoperative planning for RAO which takes femoral and pelvic morphology into consideration can prevent FAI.

Table and Figure legends

Table 1. Patient demographic data

Table 2. Morphological measurements of the study and control groups

Table 3. Range of motion in the study and control groups

Table 4. The coefficients of correlation between morphological parameters and directions of motion

Table 5. Hip range of motion in normal and FAI hips as reported in the literature

Fig 1. A screen shot of the ROM simulation using ZedHip preoperative planning software

(a, b) Before RAO, range of motion simulations were performed in flexion and internal rotation in 90° flexion.

(c, d) After RAO, impingement occurred in the anterosuperior quadrant of the acetabulum in flexion and internal rotation in 90° flexion.

Fig 2. The radiographs of a 29 year-old woman who underwent RAO are shown.

(a) The preoperative AP radiograph showed deficient lateral coverage.

(b) The AP radiograph showed sufficient lateral coverage without signs of progression of OA.

In the simulation study, flexion decreased from 130.0° to 98.0° and internal rotation in 90° flexion decreased from 29.5° to 11.5°.

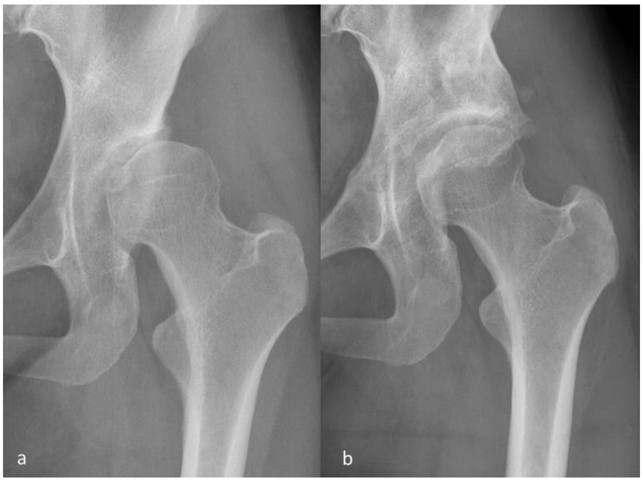

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Table 1. Patient demographic data

Parameter	Study group n=12	Control group n=12	p Value
Age at surgery (years)	36.5 ± 9.7 (27 - 48)	40.3 ± 10.7 (28 - 64)	0.398
Side (right/left)	6/6	8/4	
Height (cm)	156.3 ± 5.6 (146 - 164)	158.0 ± 8.3 (139 - 169)	0.410
Weight (kg)	53.4 ± 6.6 (41.0 - 64.4)	51.8 ± 10.7 (38.5 - 80.0)	0.289
Body mass index (kg/m^2)	21.8 ± 2.4 (16.6 - 24.8)	20.7 ± 3.1 (17.6 - 28.0)	0.195

Table 2. Morphological measurements of the study and control groups

Morphological measurements	Before RAO	After RAO	p Value*	Normal hips	p Value**
Lateral CE angle (°)	0.2 ± 9.3	33.3 ± 8.2	< 0.01	30.0 ± 3.1	0.100
	(−17 - 12)	(21 - 39)		(25 - 36)	
Sharp angle (°)	51.2 ± 3.5	41.1 ± 4.7	< 0.01	42.1 ± 2.9	0.276
	(48 - 56)	(36 - 53)		(37 - 48)	
Acetabular head index (%)	51.9 ± 11.8	90.8 ± 14.0	< 0.01	80.8 ± 4.3	< 0.05
	(43 - 69)	(62 − 109)		(74 - 87)	
Acetabular roof angle (°)	31.0 ± 9.3	2.9 ± 6.1	< 0.01	6.5 ± 3.0	0.069
	(22 - 40)	(−9 - 11)		(0 - 12)	
Cross over sign (number of case)	1	1		0	
Anterior CE angle (°)	23.0 ± 15.5	40.8 ± 16.9	< 0.05	32.7 ± 7.7	0.161
	(- 9.4 - 43.5)	(18.1 - 68.2)		(19.3 - 48.6)	
Acetabular anteversion angle(°)	25.8 ± 7.0	19.8 ± 15.2	0.170	25.7 ± 4.7	0.215
	(11.9 - 37.5)	(−18.8 - 38.4)		(19.0 - 37.5)	
Femoral anteversion angle (°)	34.7 ± 13.7 (21.3 - 65.1)			22.0 ± 6.4 (11.7 - 33.2)	< 0.01
Combined anteversion angle (°)	58.8 ± 14.1	52.3 ± 16.0	0.137	46.9 ± 8.1	0.259
	(41.7 - 90.6)	(27.1 - 81.0)		(30.7 - 65.7)	
Neck-shaft angle (°)	144.1 ± 5.8			134.7 ± 4.5	< 0.01
	(133.6 - 155.6)			(128.3 - 142.9)	
α angle (°)	54.9 ± 5.3			56.6 ± 6.2	0.479
	(49.0 - 68.0)			(50.3 - 73.0)	

All values are mean ± standard deviation (range)

*Difference between Before RAO and After RAO; **difference between After RAO and Normal hips

Table 3. Range of motion in the study and control groups

Parameter	Before RAO	After RAO	p Value*	Normal Hips	p Value**
Flexion	133.4° ± 10.5°	105.9° ± 12.8°	<0.01	122.0° ± 13.6°	<0.05
	(116.5 - 153.0)	(84.5 - 121.5)		(95.5 - 143.5)	
Abduction	63.2° ± 25.8°	48.5° ± 14.2°	<0.05	57.0° ± 15.8°	NS
	(20.5 - 83.5)	(34.0 - 81.0)		(37.0 - 76.0)	
External rotation in 0° flexion	35.3° ± 14.5°	39.5° ± 13.9°	0.534	25.2° ± 17.4°	<0.05
	(4.0 – 55.0)	(20.0 – 52.5)		(5.0 - 52.0)	
Internal rotation in 90° flexion, 0° adduction	55.0° ± 30.4°	25.4° ± 17.5°	<0.05	40.2° ± 21.4°	NS
	(23.5 - 86.5)	(0 - 51.5)		(11.5 - 64.5)	
Internal rotation in 90° flexion, 10° adduction	51.3° ± 30.1°	21.7° ± 17.1°	<0.05	33.5° ± 22.9°	NS
	(21.5 - 80.5)	(0 - 43.5)		(0 - 60.5)	
Internal rotation in 90° flexion, 20° adduction	46.8° ± 32.0°	18.7° ± 15.7°	<0.05	32.8° ± 22.8°	NS
	(7.5 - 70.0)	(0 - 39.5)		(0 - 56.5)	
Impingement lesion of Internal rotaion in 90° flexion	34.0° ± 14.9°	33.3° ± 27.9°	NS	31.3° ± 10.5°	NS
	(1.1 o`clock)	(1.1 o`clock)		(1.0 o`clock)	

All values are mean ± standard deviation (range)
*Difference between Before RAO and After RAO; **difference between After RAO and Normal hips
NS; no significant difference

Table 4. The coefficients of correlation between morphological parameters and directions of motion

Morphological parameter	Direction of motion	r	p Value
Anterior CE angle	Flexion	-0.5133	<0.001
	Internal rotation in 90° flexion	-0.4045	<0.001
	Internal rotation in 90° flexion, 10° adduction	-0.4242	<0.001
	Internal rotation in 90° flexion, 20° adduction	-0.4699	<0.001
Femoral anteversion angle	Internal rotation in 90° flexion	0.4408	<0.001
	Internal rotation in 90° flexion, 10° adduction	0.4594	<0.001
	Internal rotation in 90° flexion, 20° adduction	0.4807	<0.001
Combined anteversion angle	Internal rotation in 90° flexion, 10° adduction	0.5831	<0.001
	Internal rotation in 90° flexion, 20° adduction	0.5993	<0.001
Acetabular anteversion angle	Flexion	0.4345	<0.001
Lateral CE angle	Flexion	-0.5237	<0.001
Acetabular head index	Flexion	-0.4629	<0.001

Table 5. Hip range of motion in normal and FAI hips as reported in the literature

Authors, Year	Type of Measurement	Normal hip/ FAI/ After PAO	Flexion(°)	Internal Rotation(°) in 90° flexion
Ahlberg et al.[27], 1988	Clinical	Normal hip	130.8 ± 14.0	36.7 ± 12.2
Roaas et al.[28], 1982	Clinical	Normal hip	120.3 ± 8.3	32.6 ± 8.2
Tannast et al.[22], 2006	CT-based simulation	Normal hip	121 ± 11.8	35 ± 12
Nakahara et al[19].,2011	CT-based simulation	Normal hip	126.2 ± 10.3	44.9 ± 14.8
Siebenrock et al.[29], 2003	Clinical	FAI	99 (90-110), no standard deviation	11(0-30) no standard deviation
Wettstein et al.[30],2006	Clinical	FAI	108 ± 13	7 ± 12
Kubiak-Langer et al.[23], 2007	CT-based simulation	FAI	105.2 ± 9.7	11.1 ± 6.9
Ziebarth et al.[20], 2010	Clinical	After PAO	94.9 ± 9.9	22 ± 13
Current study	CT-based simulation	Normal hip	122.0 ± 13.6	40.2 ± 21.4
		After RAO	105.9 ± 12.8	25.4 ± 17.5