Comparison Between Hand Rasping and Robotic Milling for Stem Implantation in Cementless Total Hip Arthroplasty

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Abstract: We evaluated the effects of conventional hand rasping and robotic milling on the clinical and radiographic results of cementless total hip arthroplasty, with the same computed tomography (CT)–based 3-dimensional preoperative planning using a ROBODOC workstation (Integrated Surgical Systems, Davis, Calif). The robotic milling group consisted of 78 hips, and the hand-rasping group 78 hips. The radiographic findings from the preoperative planning and postoperative CT data were evaluated using the most accurate CT images reconstructed by the ROBODOC workstation. The robotic milling group showed significant superior Merle D'Aubigne hip score at 2 years. In the robotic milling group, there were no intraoperative femoral fractures, and a radiographically superior implant fit was obtained. Hand rasping had the potential to cause intraoperative femoral fractures, undersizing of the stem, unexpectedly higher vertical seating, and unexpected femoral anteversion causing inferior implant fit. **Key words:** ROBODOC, ORTHODOC, femoral canal preparation, comparison between hand rasping and robotic milling, cementless total hip arthroplasty.

Fit and fill of cementless femoral stems in the femoral canal are important factors for stable fixation and good clinical results in many types of cementless total hip arthroplasty (THA) [1-6]. As one of the options to obtain optimal fit and fill of cementless femoral stems, the ROBODOC system (Integrated Surgical Systems, Davis, Calif) was developed [7,8]. This system consists of a preoperative planning computer workstation (ORTHODOC, Integrated Surgical Systems, Davis, Calif) and a robotic arm equipped with a high-speed milling device to prepare the femoral canal. This system is an active robot that moves a milling device automatically, independent of an operator, according to preoperative planning [7]. ORTHODOC provides precise 3-dimensional information on fit and fill of the femoral stem in the femoral canal using computed tomography (CT) images and helps the surgeon to decide the optimal position and size of a femoral stem. Computed tomography–based planning is more accurate than conventional x-ray template preoperative planning because magnification and shape of the femoral canal on x-rays are highly variable depending on the x-ray technique [9-11]. Based on CT-based planning, the milling path for preparation of the femoral canal can be visualized using ORTHODOC, so that the surgeon can ensure that the path avoids interference with important structures such as the greater trochanter. After approval of the plan by the surgeon, ROBODOC precisely executes femoral canal milling according to the plan, using robotic machining intraoperatively [7,8].

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Submitted October 30, 2004; accepted January 1, 2006.
No benefits or funds were received in support of the study.
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0883-5403/06/1906-0004$32.00/0
doi:10.1016/j.arth.2006.01.001

In previous studies comparing robotic implantation of a femoral stem with conventional manual implantation [7,12], differences in outcome could be attributed to 2 factors. The first factor is the difference in preoperative planning between the conventional x-ray template method and the CT-based 3-dimensional preoperative planning. The second factor is the difference in surgical procedure between conventional hand rasping and robotic milling. There have been no previous reports of a pure comparison between conventional hand rasping and robotic milling using the same CT-based 3-dimensional preoperative planning.

The purpose of the present study was to compare clinical and radiographic results between hand rasping and robotic milling, based on the same 3-dimensional preoperative planning using ORTHODOC.

Materials and Methods

From September 2000 to September 2002, a total of 156 primary cementless THAs were performed on 140 patients at our 2 institutions. The indications were good bone quality (Dorr type A or B) [13] and Crowe class I, II, or III (0%-100% subluxation of the hip) [14]. Patients with poor bone quality (Dorr type C) were excluded because of the need for use of cement. Patients with Crowe class IV (>100% subluxation of the hip) were excluded because of the need for subtrochanteric osteotomy to be included in the surgery. Each patient was randomly assigned into the hand-rasping or robotic milling group. The patients' demographics are given in Table 1. The robotic milling group comprised 73 patients who underwent 78 primary THAs using the 2-pin–based procedure of the ROBODOC system. The diagnoses of the robotic milling group were as follows: degenerative arthritis secondary to hip dysplasia in 74 hips, osteonecrosis in 3 hips, and rheumatoid arthritis in 1 hip. The hand-rasping group comprised 67 patients who underwent 78 primary THAs. The diagnoses of the hand-rasping group were as follows: degenerative arthritis secondary to hip dysplasia in 73 hips, osteonecrosis in 4 hips, and rheumatoid arthritis in 2 hips. There was no significant difference in age (Mann-Whitney *U* test) or sex ratio (χ^2 test) between the 2 groups. This study was approved by the Institutional Internal Clinical Research Committees of our 2 institutions. Informed consent was obtained from all patients after the nature of the procedure had been fully explained.

Table 1. Demographics of Patients Used for Comparison

	No. of Patients (Femora)	Sex (Male/Female)	Age (y)*
Robotic milling group	73 (78)	14: 64†	58 (27-81)‡
Hand-rasping group	67 (78)	14: 64†	58 (29-77)‡

*Values represent average (range).
†Difference was not statistically significant (χ^2 test).
‡Difference was not statistically significant (Mann-Whitney *U* test).

All THAs were performed via the posterolateral approach, with the patient in the lateral decubitus position. VerSys fiber metal taper hydroxyapatite-coated femoral stems (Zimmer, Warsaw, Ind) were used in all THAs. The VerSys fiber metal taper femoral stem is a straight stem, with a symmetry plane that contains the femoral stem axis and the neck axis. The femoral stem has 2 variations in the proximal metaphysis: standard and large metaphysis.

In the robotic milling group, CT images of the femur were taken after 1 locator pin was inserted into the greater trochanter of the affected femur and the other locator pin was inserted into the lateral condyle. Three-dimensional preoperative planning (described hereinafter) was performed based on the CT data on the ORTHODOC, and the milling path was transferred to the robot controller. Intraoperatively, the 2 groups had the same length of skin incision for the hip (12-15 cm), except for the extra skin incision for the knee pin. After the leg was secured in the leg holder and the femur was rigidly attached to the robot base with the femoral external fixator, intraoperative pin-based registration using the 2 locator pins was performed. The robot milled the inside of the femoral canal according to the preoperative plan. Surgeons inserted and impacted the femoral stem manually.

In the hand-rasping group, CT images of the femur were taken preoperatively. The CT data were transferred to the ORTHODOC, which was used for the 3-dimensional preoperative planning described below. After surgeons obtained information about the position and size of the femoral stem, the femur was prepared using a handheld rasp. Surgeons inserted and impacted the femoral stem manually.

Three-dimensional preoperative planning in the 2 groups was performed as follows [15,16]. Because 3 arbitrarily selected orthogonal planner reconstructed images of the CT data could be displayed on ORTHODOC, the center of the femoral head was at first located using a circle drawing tool to encompass the femoral head contour. The femur was reoriented on the workstation to obtain the

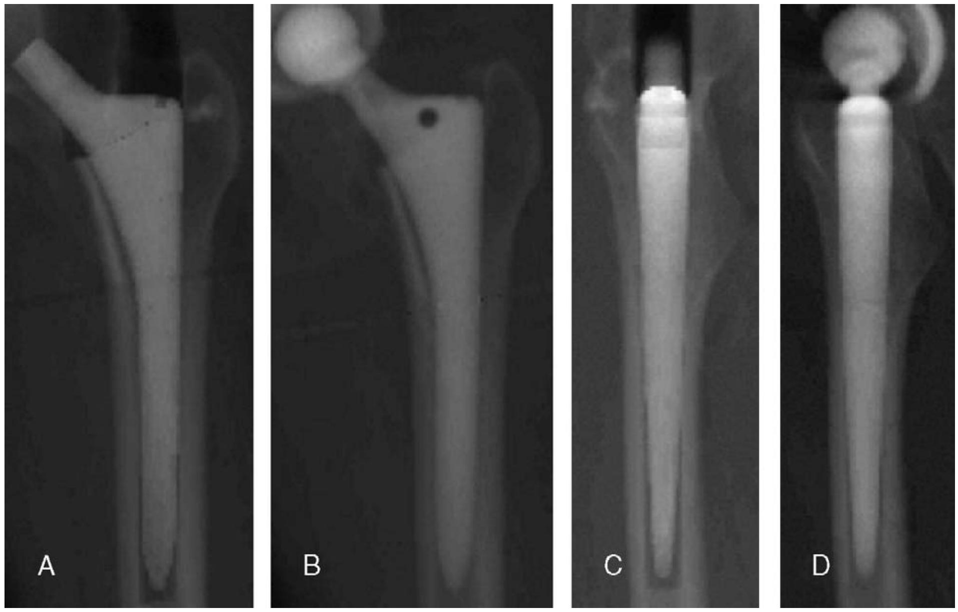

Fig. 1. A 47-year-old woman with degenerative arthritis underwent THA using the ROBODOC system. A, Anteroposterior synthetic radiograph from preoperative planning. B, Anteroposterior synthetic radiograph reconstructed from postoperative CT data. C, Lateral synthetic radiograph from preoperative planning. D, Lateral synthetic radiograph reconstructed from postoperative CT data.

coronal plane that passed through the head center and the proximal femoral medullary axis. Then, the sagittal plane through the medullary axis was obtained. A femoral stem of the maximum size that would not overream the endosteal cortical bone was selected and virtually implanted into the femoral canal. The type of proximal metaphysis (standard or large metaphysis) was chosen, which would achieve the required limb length. Each preoperative plan was discussed by 2 of the senior authors until a consensus was obtained.

The clinical results for each patient were assessed according to the Merle D'Aubigne hip score [17], in which up to 6 points each are given for pain, motion, and gait. These scores were obtained preoperatively, 3 months postoperatively, and 2 years postoperatively. We monitored the operative time, femoral canal preparation time, estimated blood loss, donation of allogeneic blood, intraoperative femoral fractures, and complication. Intraoperative femoral fractures were classified according to the Vancouver classification [18]. Allogeneic blood units were transfused based on a variety of criteria, including clinical symptoms, hemodynamic stability, and whether the hematocrit fell below 24%. The decision whether to perform a transfusion was made by the operating surgeon. In the hand-rasping group, the femoral canal preparation time was defined as the duration of the hand rasping. In the robotic milling group, the femoral canal preparation time was defined as the combined duration of positioning of the robot, registration, and milling. Physical therapy with full-weight bearing, as tolerated, was initiated on the third postoperative day. We recorded the duration of rehabilitation required to gain the ability to walk

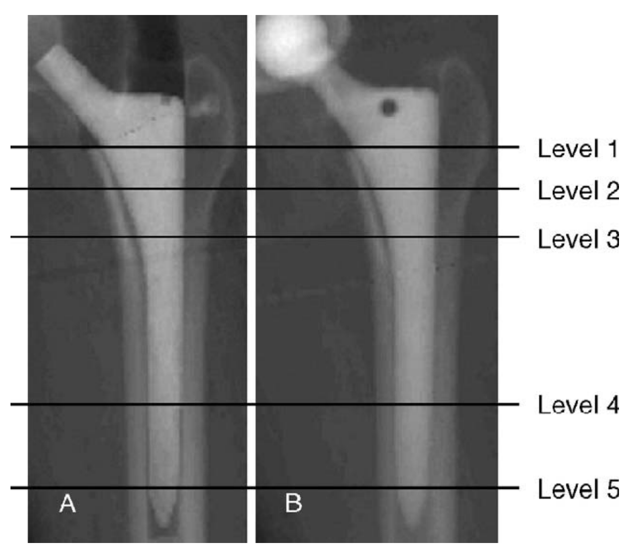

Fig. 2. The 5 lines indicate levels 1 to 5. A, Anteroposterior synthetic radiograph from preoperative planning. B, Anteroposterior synthetic radiograph reconstructed from postoperative CT data.

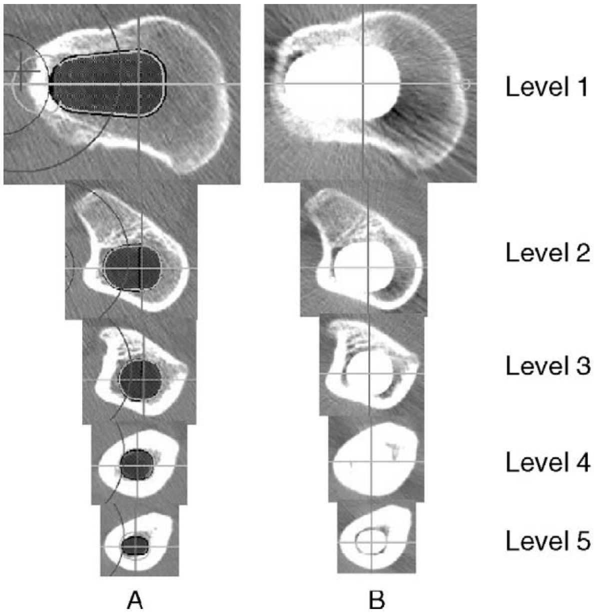

Fig. 3. Axial cross-sectional images of the proximal femur perpendicular to the symmetry plane of the femoral stem were reconstructed at levels 1 to 5. A, Axial images from preoperative planning. The line around the cross-sectional image of the femoral stem shows the milling path of the ROBODOC. The milling path in the metaphyseal stem is undersized by 0.5 mm, and the milling path in the diaphyseal stem is oversized by 0.5 mm, to achieve proximal tight fixation. B, Axial images reconstructed from postoperative CT data.

more than 6 blocks, corresponding to 500 m, without a cane [19]. Clinical measurements were compared between the 2 groups.

Radiographic evaluation using reconstructed CT images was performed preoperatively and at 1 month after THA. We reconstructed anteroposterior synthetic radiographs of the proximal femur parallel to the symmetry plane of the femoral stem (Figs. 1 and 2), lateral synthetic radiographs of the proximal femur perpendicular to the symmetry plane of the femoral stem (Fig. 1), and axial images of the femur perpendicular to the femoral stem axis (Fig. 3), using the ORTHODOC and the CT data. These reconstructed CT images were created using both preoperative and postoperative CT data. The synthetic anteroposterior radiographs were used to evaluate the mediolateral alignment of the femoral stem (angle between the femoral stem axis and the proximal femoral canal axis), the medial gap between the medial endocortical bone and the femoral stem, the lateral gap between the femoral stem and the lateral cortical bone, and the mediolateral canal filling ratio of the femoral stem (percentage of canal occupied by the femoral stem) at the following 5 levels (Fig. 2): the lower corner of the femoral neck cut (level 1), the center of the lesser trochanter (level 2), 1.5 cm distal from the center of the lesser trochanter (level 3), 4.5 cm proximal from the femoral component tip (level 4), and 1.5 cm proximal from the femoral component tip (level 5). Synthetic lateral radiographs were used to evaluate anteroposterior alignment of the femoral stem (angle between the femoral stem axis and the proximal femoral canal axis). Axial images of the femur were used to evaluate the vertical seating (vertical distance from the femoral stem shoulder to the center of the lesser trochanter) and canal fill ratio of the femoral stem (ratio of femoral stem area to the total medullary cavity area) at all 5 levels (Fig. 3). Femoral anteversion was defined as the angle between the stem neck axis and the table plane including the posterior condyles and the most prominent posterior point of the greater trochanter [20,21]. The observers who performed the radiographic analysis were blinded to which group each patient belonged.

The type and size of each implanted femoral stem was compared with those chosen in the preoperative plans. Differences in the radiographic measurements between values from preoperative

Fig. 4. A 77-year-old woman with degenerative arthritis underwent THA using a handheld rasp and had an intraoperative femoral fracture. A, Anteroposterior synthetic radiograph of the proximal femur from preoperative planning. B, Anteroposterior synthetic radiograph reconstructed from CT data obtained 1 month postoperatively.

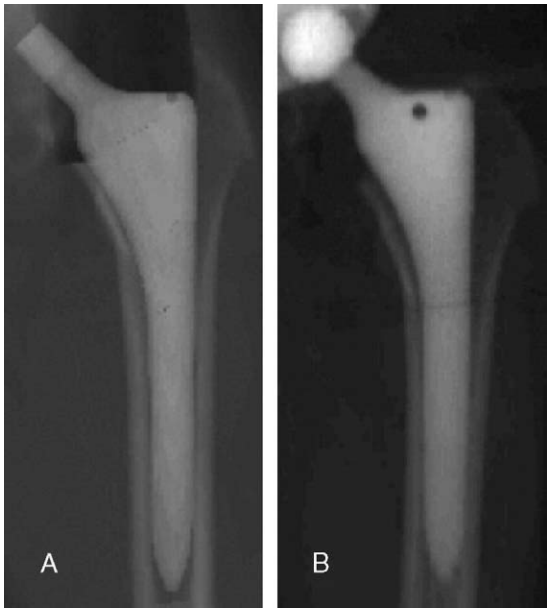

Fig. 5. A 53-year-old man with degenerative arthritis underwent THA using a handheld rasp. A, Anteroposterior synthetic radiograph of the proximal femur from preoperative planning. B, Anteroposterior synthetic radiograph reconstructed from CT data obtained 1 month postoperatively.

planning and measurements from postoperative CT images were compared between the 2 groups. We calculated Pearson's correlation coefficient for the difference in vertical seating and the absolute value of the difference in femoral anteversion between the preoperative plan and the postoperative CT images to evaluate the effect of larger differences in femoral anteversion on unexpectedly higher vertical seating. Next, we compared the mediolateral canal filling ratio, the canal fill ratio, and the alignment of the femoral stem from preoperative planning or postoperative CT images between the 2 groups. Finally, the clinical results and the differences in radiographic measurements between values from preoperative planning and measurements from postoperative CT images were compared between the 2 groups, after excluding the 2 patients with intraoperative femoral fracture and those for whom there was a difference in the type and size of the femoral stem between the preoperative plans and the postoperative results.

Radiographic evaluation included measurement of implant-bone interface. The implant-bone interface was estimated on the 2-year postoperative radiograph as stable bony ingrowth, stable fibrous ingrowth, or unstable, using the criteria of Engh et al [4].

For statistical analysis, we used the unpaired *t* test, the Mann-Whitney *U* test, the χ^2 test, and the Pearson's correlation coefficient. Differences were considered significant when the *P* value was less than .05.

Results

One patient of the robotic milling group was lost at the final follow-up. Four patients of the hand-rasping group were lost at the final follow-up. One patient (2 hips) of the hand-rasping group died with lung cancer during follow-up period. Complete clinical follow-up including evaluation on the 2-year postoperative radiograph was available for 77 hips in the robotic milling group and 72 hips in the hand-rasping group. Radiographic evaluation using reconstructed CT images obtained preoperatively and at 1 month after THA was available for all the hips. The mean follow-up was 2.3 years (range, 2-3.6 years).

Clinical Results

There were no significant differences in Merle D'Aubigne hip scores preoperatively or 3 months postoperatively between the 2 groups (Mann-Whitney *U* test) (Table 2). There was significant difference in Merle D'Aubigne hip score 2 years postoperatively between the 2 groups (Mann-Whitney *U* test) (Table 2). There were significant

Table 2. Comparison in the Clinical Results

	Robotic milling group		Hand-rasping group		
	Mean	Range	Mean	Range	*P*
Merle D'Aubigne hip score					
Preoperative	10.1	6-14	9.8	5-16	.4828
3 mo	15.8	13-18	15.3	11-18	.0556
2 y	17.4	14-18	17.1	14-18	<.05
Operative time (min)	122	70-205	102	50-193	<.0001
Femoral canal preparation time (min)	42	27-80	23	15-45	<.001
Estimated blood loss (mL)	527	150-1400	694	230-2665	<.01
Duration of gaining walking ability (d)	14	7-31	16	7-46	.0552

Table 3. Comparison in the Duration of Gaining Walking Ability, Thigh Pain, Fracture, and Agreement

	Robotic milling group	Hand-rasping group	*P*
Duration of gaining walking ability (d)			
≦13	41	28	
≧14	37	50	<.05
Thigh pain at 1 mo			
Positive	4	11	
Negative	74	67	.0573
Thigh pain at 3 mo			
Positive	2	3	
Negative	76	75	.6494
Intraoperative femoral fracture			
Positive	0	5	
Negative	78	73	<.05
Agreement of the type and size of the stem			
Agreement	78	71	
Disagreement	0	7	<.01

differences in operative time (unpaired *t* test, $P < .0001$), femoral canal preparation time (unpaired *t* test, $P < .001$), and estimated blood loss (unpaired *t* test, $P < .01$) (Table 2). However, no patient received a transfusion of allogeneic blood. There were no significant differences in the time required to gain the ability to walk more than 6 blocks without a cane (Mann-Whitney *U* test) (Table 2).

The number of patients who gained the ability to walk more than 6 blocks without a cane within 13 days was significantly greater in the robotic milling group than in the hand-rasping group (χ^2 test, $P < .05$) (Table 3). There were no significant differences in thigh pain at 1 and 3 months between the 2 groups (χ^2 test) (Table 3).

There were 5 intraoperative femoral fractures in the hand-rasping group (Fig. 4) and none in the robotic milling group (Table 3); the difference in intraoperative femoral fracture between the 2 groups was significant (χ^2 test, $P < .05$). All the patients who had an intraoperative femoral fracture were females. All fractures occurred during the final insertion of the femoral stem. All fractures were undisplaced linear cracks (type A_2 in the Vancouver classification) [18]; that is, there were no severe fractures such as types A_3, B, and C in the Vancouver classification. All 5 patients with fractures were treated by cable cerclage, which consisted of removing the femoral stem, applying cerclage, and reinserting the femoral stem. Postoperatively, the 5 patients with fractures underwent

Table 4. Comparison in Differences Between Preoperative Planning and Postoperative CT Images

	Robotic milling group		Hand-rasping group		
	Mean	SD	Mean	SD	*P*
Medial gap (mm)					
Level 1	0.03	0.17	0.84	1.09	<.0001
Level 2	0.03	0.27	0.52	0.52	<.0001
Level 3	0	0.29	0.35	0.45	<.0001
Level 4	−0.02	0.19	0.03	0.21	.1471
Level 5	0.09	0.32	0.14	0.37	.3329
Lateral gap (mm)					
Level 1	−0.3	1.37	0.03	2.73	.353
Level 2	−0.24	1.26	0.28	2.26	.0797
Level 3	−0.23	0.81	0.17	1.62	.055
Level 4	−0.09	0.21	−0.04	0.2	.1718
Level 5	0	0.34	0.1	0.33	.0836
Mediolateral canal filling ratio (%)					
Level 1	0.7	2.8	−1.8	5.3	<.001
Level 2	1.3	4.0	−2.0	6.9	<.001
Level 3	1.7	3.4	−1.4	6.9	<.001
Level 4	1.4	1.7	0.3	2.6	<.01
Level 5	0.1	3.0	−1.0	3.0	<.05
Canal fill ratio (%)					
Level 1	4.4	3.3	2.2	4.5	<.001
Level 2	0.6	4.1	−0.7	5.6	.0903
Level 3	1.9	4.5	0.9	5.5	.205
Level 4	1.5	3.8	1.1	5.1	.5645
Level 5	0.6	4.5	1.1	5.9	.529
Mediolateral alignment (°)	0.2	1.1	0.1	1.4	.5994
Anteroposterior alignment (°)	0.1	1.4	0.9	1.4	<.001
Femoral anteversion (°)	−0.3	2.5	−3.9	8.5	<.001
Vertical seating (mm)	0.9	1.7	3.9	3.4	<.0001

Table 5. Comparison in Preoperative Planning or Postoperative CT Images

	Robotic milling group		Hand-rasping group		
	Mean	SD	Mean	SD	*P*
Preoperative planning					
Mediolateral canal filling ratio (%)					
Level 1	73	6.0	74	5.9	.5585
Level 2	80	7.5	80	6.8	.9231
Level 3	85	6.5	85	5.1	.9033
Level 4	91	3.2	92	2.5	.4783
Level 5	88	3.4	87	3.0	<.05
Canal fill ratio (%)					
Level 1	46	6.4	46	5.1	.8794
Level 2	58	8.2	57	7.5	.42
Level 3	67	9.0	65	8.2	.1053
Level 4	76	8.1	76	9.5	.9917
Level 5	61	9.1	61	11	.9325
Mediolateral alignment (°)	0.3	1.1	0.1	0.7	.1608
Anteroposterior alignment (°)	0.4	1.3	0.6	1.1	.2191
Postoperative CT images					
Mediolateral canal filling ratio (%)					
Level 1	74	6.0	72	6.1	.0536
Level 2	81	7.2	78	7.4	<.01
Level 3	86	6.2	83	6.9	<.01
Level 4	93	2.9	92	2.3	.4534
Level 5	88	2.8	86	2.9	<.0001
Canal fill ratio (%)					
Level 1	51	6.8	49	6.1	<.05
Level 2	59	8.3	56	7.6	.0655
Level 3	69	8.4	66	7.9	<.05
Level 4	78	7.8	77	8.5	.741
Level 5	61	7.6	62	9.4	.7726
Mediolateral alignment (°)	0.3	1.2	0.2	1.4	.4116
Anteroposterior alignment (°)	0.5	1.2	1.5	1.5	<.0001

conditioning consisting of 6 weeks of graduated weight bearing.

We had no serious complications such as sciatic nerve palsy, deep vein thrombosis, and infection. No revisions were performed at the final follow-up.

Agreement of the Type and Size of the Femoral Stem

In the hand-rasping group, there was significant disagreement between the type and size of stems that were implanted and those that were chosen in the preoperative plans (χ^2 test, $P < .01$) (Table 3).

Differences in Radiographic Measurements Between Preoperative Planning and Postoperative CT Images

Measurements for all hips are shown in Table 4. There were significant differences in the following measurements between preoperative planning and postoperative CT images: the medial gap at levels 1 to 3 (unpaired *t* test, $P < .0001$); the mediolateral canal filling ratio at levels 1 to 3 (unpaired *t* test, $P < .0001$), level 4 (unpaired *t* test, $P < .01$), and level 5 (unpaired *t* test, $P < .05$); the canal fill ratio at level 1 (unpaired *t* test, $P < .001$); anteroposterior alignment (unpaired *t* test, $P < .001$); femoral anteversion (unpaired *t* test, $P < .001$); and vertical seating (unpaired *t* test, $P < .0001$). The difference in vertical seating between the preoperative planning and postoperative CT images weakly correlated with the absolute value of the difference in femoral anteversion ($r = 0.37$).

Comparison of the Mediolateral Canal Filling Ratio, the Canal Fill Ratio, and the Alignment of the Femoral Stem from Preoperative Planning or Postoperative CT Images

Measurements for all hips are shown in Table 5. There was no significant difference in the mediolateral canal filling ratio, canal fill ratio, and alignment of the femoral stem from preoperative planning, except for the mediolateral canal filling ratio at level 5 (unpaired *t* test). However, the robotic milling group had a significantly better mediolateral canal filling ratio from postoperative CT images at levels 2, 3 (unpaired *t* test, $P < .05$), and 5 (unpaired *t* test, $P < .0001$). The robotic milling group also had a significantly better canal fill ratio from postoperative CT images at levels 1 and 3 (unpaired *t* test, $P < .05$). There was a significant difference in anteroposterior alignment from postoperative CT images (unpaired *t* test, $P < .0001$).

Comparison After Excluding Patients with Femoral Fracture and Patients with Disagreement in the Type and Size of the Femoral Stem

In 7 patients in the hand-rasping group, the implanted femoral stem was of a smaller size and type than the stem selected in the preoperative planning. After excluding these 7 patients and the 5 patients with intraoperative femoral fracture, only 1 clinical result changed and showed no significant difference in the time required to gain the ability to walk more than 6 blocks without a cane. However, the robotic milling group still had significantly better radiographic results than the hand-rasping group in the medial gap at levels 1 to 3, mediolateral canal filling ratio at levels 1 to 5, canal fill ratio at level 1, anteroposterior alignment, femoral anteversion, and vertical seating.

Radiographic Results on the 2-Year Postoperative Radiograph

All the hips of both groups demonstrated stable bony ingrowth according to the criteria of Engh et al [4].

Discussion

In the present study, we compared the clinical effectiveness of robotic milling and hand rasping. There was no significant difference in the Merle D'Aubigne hip score between the 2 groups at 3 months. These findings are consistent with the reports of Bargar et al [7] and Honl et al [12]. There were no significant differences in thigh pain or the time required to gain the ability to walk more than 6 blocks without a cane. However, the number of patients who gained the ability to walk more than 6 blocks without a cane within 13 days was significantly greater in the robotic milling group than in the hand-rasping group. Moreover, there was a significant difference in the Merle D'Aubigne hip score 2 years postoperatively between the 2 groups. These may be due to inferior radiographic accuracy of femoral canal preparation using a handheld rasp.

The operative time and femoral canal preparation time were significantly greater for the robotic milling group. The mean difference in both the operative time and femoral canal preparation time was 19 minutes. Thus, the increased surgical time of the robotic milling group was due to the increased femoral canal preparation time. This increased surgical time is consistent with the report of Bargar et al [7]. The estimated blood loss was significantly smaller for the robotic milling group. However, no patient in either group received a transfusion of allogeneic blood. Therefore, there appears to have been no significant difference in blood loss.

The radiographic evaluation in the robotic milling group was clearly superior to that of the hand-rasping group. At levels 1 to 3, differences in the medial gaps between the preoperative plan and postoperative CT images were significantly smaller in the robotic milling group than in the hand-rasping group (Fig. 5). In the robotic milling group, there were no significant differences in the lateral gaps between the preoperative plan and postoperative CT images. This may be due to the limitations of the rasping device. The rasp can cut the endocortical bone parallel to the orientation of the rasp. In fact, the lateral endocortical bone and the medial endocortical bone in the diaphysis can be cut, but the medial endocortical bone in Adams' arch cannot be completely cut and may have caused the significantly greater differences in vertical seating in the hand-rasping group. Moreover, the greater difference in femoral anteversion may be one of the causes of the higher vertical seating. The absolute value of the difference in femoral anteversion weakly correlated with the unexpectedly higher vertical seating. This suggests that a greater difference in femoral anteversion can cause impingement of the femoral stem on the medial endocortical bone, resulting in unexpectedly higher vertical seating of the femoral stem. Consistent with the present findings, Gossé et al [22] found unexpectedly higher seating of the femoral stem in their hand-rasping group. Higher seating of the tapered stem in patients who undergo hand rasping can result in poorer fit and fill. In fact, at levels 1 to 5, the mediolateral canal filling ratios of the robotic milling group were significantly better than those of the hand-rasping group. At level 1, the canal fill ratios of the robotic milling group were significantly better than those of the hand-rasping group. Inferior proximal fit and fill can affect the magnitude of stress shielding and long-term clinical results. In contrast, robotic milling of the medial endocortical bone in Adams' arch can achieve as accurate a fit, fill, and vertical seating as in the preoperative planning.

A large difference between the preoperative plan and postoperative CT images may not always cause worse fit, fill, and alignment. There is a need for further studies of the value of preoperative planning in THA. In the present study, except for the mediolateral canal filling ratio at level 5, there was no significant difference in fit, fill, or alignment of the femoral stem on the preoperative plan between the 2 groups. However, the robotic milling group had significantly better fit, fill, and alignment on postoperative CT images than the hand-rasping group. The hand-rasping group had a significantly greater difference between preoperative planning and postoperative CT images than the robotic milling group, and such differences appear to have caused the worse fit, fill, and alignment. Preoperative planning using ORTHODOC appears to be optimal.

Differences in anteroposterior alignment and femoral anteversion were significantly smaller in the robotic milling group than in the hand-rasping group. The femoral stem tended to be inserted less antevertedly in the hand-rasping group. There is a complex interaction among acetabular anteversion, acetabular abduction, and femoral anteversion in determining the safe range of motion of the hip from prosthetic impingement [23,24]. An unexpected change in the femoral anteversion can cause instability of the hip, resulting in dislocation.

An advantage of robotic milling is its prevention of intraoperative femoral fractures. This finding is consistent with a report by Bargar et al [7]. With cementless femoral stems, the frequency of intraoperative femoral fracture reportedly ranges from 2% to 20% of cases [7,25-27]. In the present series, intraoperative femoral fractures occurred in the hand-rasping group at a rate of 6%. In contrast, there were no intraoperative femoral fractures in the robotic milling group. All present fractures were undisplaced linear cracks (type A_2 in the Vancouver classification) [18]; that is, no severe fractures were observed. Cementless tapered designs that depend on tight proximal fit appear to be associated with a higher incidence of proximal fractures [26]. Insertion of the final stem can result in a fracture caused by the wedging effect proximally as the surgeon attempts to achieve a press fit [25-27]. Rasping may cause cancellous bone to become tight, as in impaction bone grafting, reducing resistance to fractures during insertion of the final stem. Larger differences in femoral anteversion may also cause impingement of the femoral stem on the medial endocortical bone at an unexpected high level, resulting in femoral fractures in some cases [27]. In the present series, the surgeon tried to achieve a tight fit with the femoral stem according to the CT-based planning. In 9% of the hand-rasping group, undersized stems were selected because the surgeons felt too tight to go further enlargement of the femoral canal. The fracture rate associated with rasping performed according to CT-based planning may be a factor for fractures.

Of the patients in the hand-rasping group, 15% had either undersized implantation or intraoperative femoral fracture. After exclusion of those patients, the robotic milling group still had better radiographic results than the hand-rasping group. Even if the size and type of femoral stem chosen in the preoperative plan could be inserted by a handheld rasp without intraoperative femoral fracture, the accuracy of stem implantation according to the preoperative plan could be inferior to that obtained by robotic milling. These differences in radiographic findings may affect the long-term outcome.

New technology should also be evaluated in terms of cost-effectiveness. The cost of a complete ROBODOC system is approximately US$600 000 [7]. In contrast, the cost of a hand-rasping implant system is much lower. The present study showed no significant difference in the near-term clinical results between hand rasping and robotic milling. However, the robotic milling group had no intraoperative femoral fractures and had better fit, fill, and alignment in the radiographic findings. These advantages can help delay or eliminate costly repeat surgery in the longer term [28]. Moreover, the volume of intraoperative pulmonary embolisms can be reduced by robotic milling in the near term [29]. Therefore, a complete cost-benefit evaluation of robotic surgery requires consideration of longer-term outcomes.

The present study had 1 limitation: the short duration of follow-up. The robotic milling group showed superior radiographic findings according to the reconstructed CT images and significant superior Merle D'Aubigne hip score at 2 years. However, all the stems in the 2 groups achieved stable bony ingrowth at 2 years. It may be difficult to draw some conclusions about the advantages and disadvantages of the robotic milling or hand-rasping systems with a 2-year follow-up. In future studies, we will use longer-term follow-up periods to clarify whether the better radiographic results and elimination of fractures achieved by robotic milling will lead to significant long-term improvement.

The present study compared the outcomes of hand-rasping and robotic milling with 3-dimensional preoperative planning using the ORTHODOC system. The radiographic findings in the preoperative planning and postoperative results were evaluated using the most accurate reconstructed CT images. The robotic milling group showed significant superior Merle D'Aubigne hip score at 2 years. The results also showed that robotic milling had the advantages of no intraoperative femoral fractures and showed radiographically superior implant fit to delay or eliminate costly repeat surgery in the longer term. Hand rasping has the potential of intraoperative femoral fractures, undersizing of the femoral stem, unexpectedly higher vertical seating, and unexpected femoral anteversion to cause inferior implant fit and instability.

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