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Surgical Technique

Robotic-Arm Assistance Simplifies Hip Arthrodesis Conversion to Total Hip Arthroplasty

Henry Fu, MBBS(HK), MMedSc(HK), FRCSEd, FHKCOS, FHKAM (Orthopaedic Surgery) [a, *],
Chun Hoi Yan, MBBS(HK), FRCSEd, FHKCOS, FHKAM (Orthopaedic Surgery) [b],
Amy Cheung, MBBS(HK), FRCSEd, FHKCOS, FHKAM (Orthopaedic Surgery) [a],
Man Hong Cheung, MBBS(HK), FRCSEd, FHKCOS, FHKAM (Orthopaedic Surgery) [b],
Vincent Wai Kwan Chan, MBBS(HK), FRCSEd, FHKCOS, FHKAM (Orthopaedic Surgery) [a],
Ping Keung Chan, MBBS(HK), FRCSEd, FHKCOS, FHKAM (Orthopaedic Surgery) [a],
Kwong Yuen Chiu, MBBS(HK), FRCSEd, FHKCOS, FHKAM (Orthopaedic Surgery) [b]

[a] *Department of Orthopaedics and Traumatology, Queen Mary Hospital, Hong Kong*
[b] *Department of Orthopaedics and Traumatology, The University of Hong Kong, Hong Kong*

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A B S T R A C T

Hip fusion takedown to total hip replacement is a challenging operation. Neck osteotomy and acetabular component placement are technically demanding and often require fluoroscopic guidance. Robotic arm–assisted total hip arthroplasty enhances accuracy of preoperative planning and provides navigated guidance for neck osteotomy and haptic guidance on acetabular reaming and cup implantation. Fluoroscopic guidance is replaced by real-time navigation and on-screen data. This article describes how robotic arm assistance can simplify this complex operation.

Introduction

Ankylosing spondylitis (AS) is prevalent in South East Asia with prevalence rate between 0.18% and 0.54% [1]. Progressive kyphotic spinal deformity and inflammatory hip arthritis are typically seen in teenage male patients. One of the devastating sequelae of burnt out AS is hip ankylosis which causes significant functional limitations. These patients are often keen to regain mobility.

Fusion takedown with conversion to total hip arthroplasty (THA) is a viable surgical option but is associated with high complication rates [2-4]. Correct indications should be adhered to before fusion takedown as patients often have a pain-free and stable hip joint to begin with. Indications for fusion takedown include a poor fusion position, back pain, knee pain, severe functional limitation from hip immobility, and significant leg-length discrepancy [4,5]. Hip abductors are typically atrophic, and patients may end up with persistent limping and require walking aids after surgery. Preoperative workup including magnetic resonance imaging (MRI) or electromyographyto assess hip abductor muscle function is valuable to predict postoperative outcome.

Whitehouse and Duncan analyzed the surgical difficulties and categorized them as exposure, neck osteotomy, acetabular preparation, and femoral fixation [6].

Exposure difficulty correlates with the fusion position and surgical approach. For posterolateral approach with the hip fused in an externally rotated position, the greater trochanter will be obscuring the femoral neck posteriorly.

Neck osteotomy is challenging in fused hip with the risk of iatrogenic fracture of the acetabulum during in situ neck osteotomy

* Corresponding author. 5/F Professorial Block, 102 Pokfulam Road, Hong Kong. Tel.: +852 22554257.
E-mail address: drhfu@ortho.hku.hk

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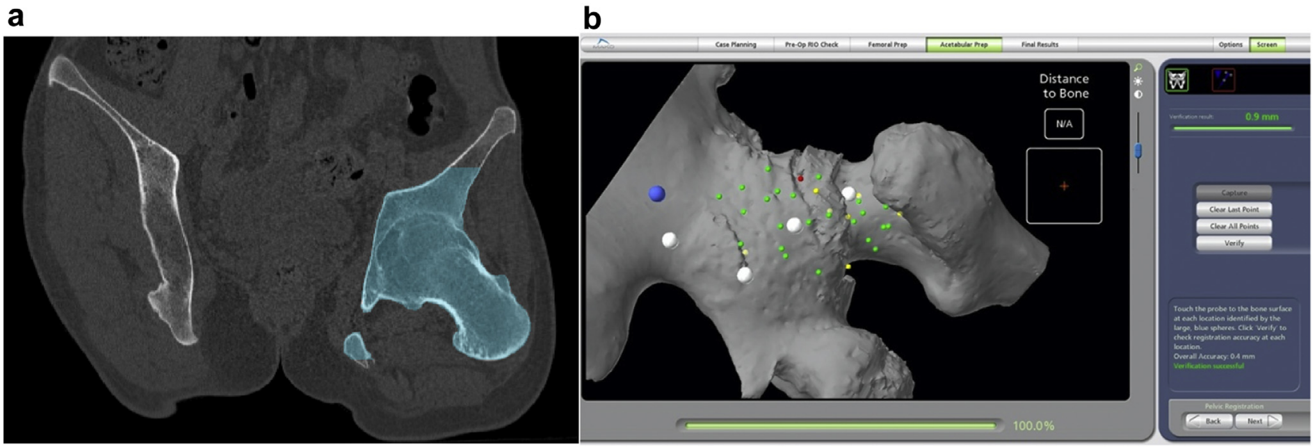

Figure 1. (a) Segmentation and (b) registration of the proximal femur and acetabulum in en bloc manner.

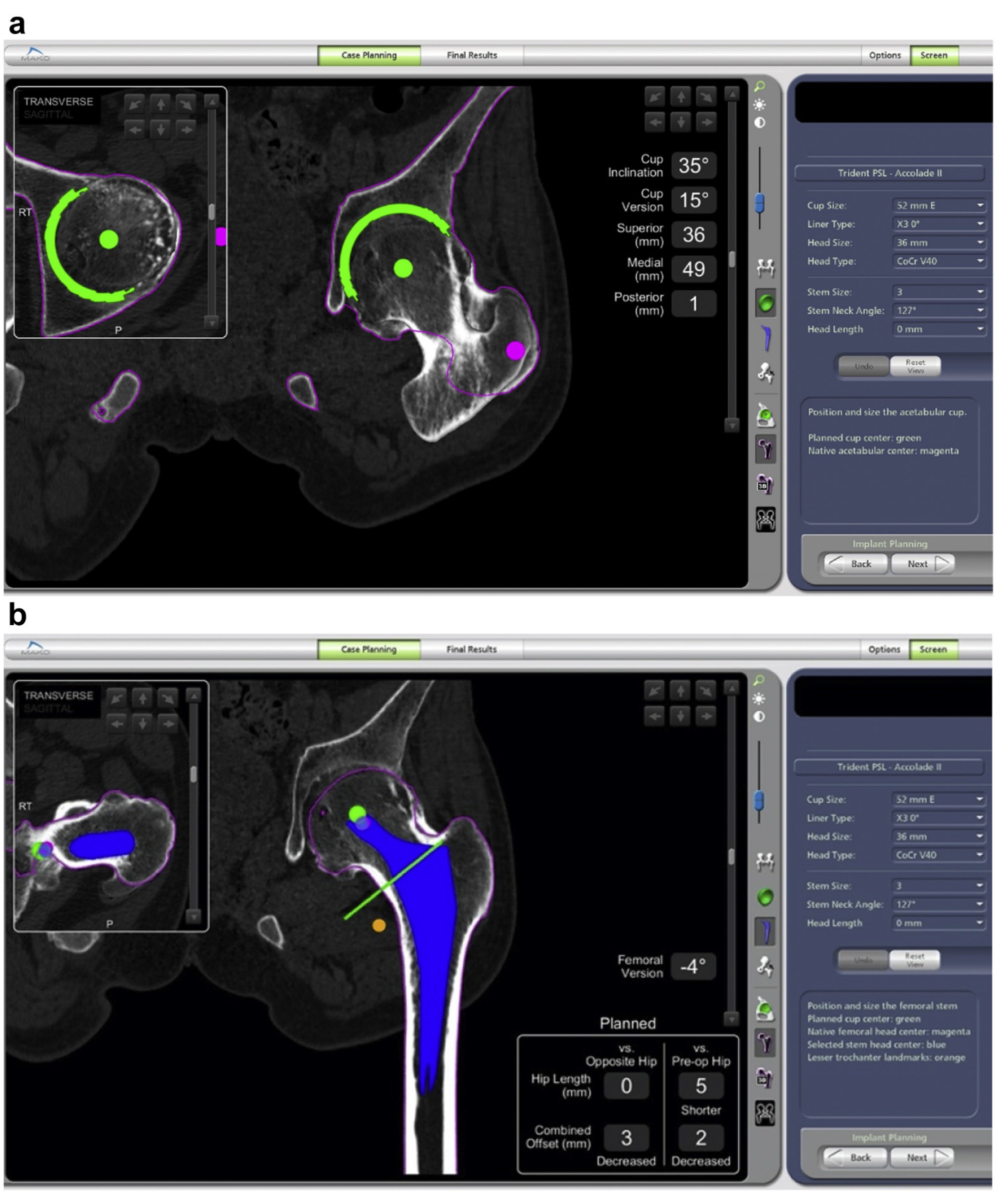

Figure 2. Preoperative planning for (a) acetabular and (b) femoral components on computed tomography images. Acetabular component anteversion of 15° and inclination of 35° were planned in view of pelvis hyperextension. Femoral retroversion of 5° was observed in this individual.

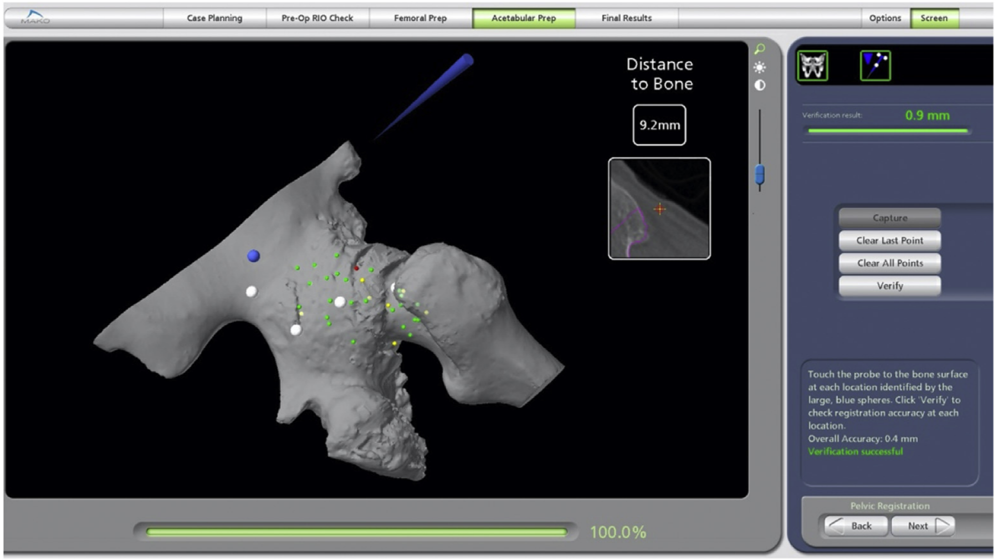

Figure 3. Verification of pelvic rotation by localizing the anterior superior iliac spine with the hip probe.

[7]. A trochanteric osteotomy is a viable option [8] but could lead to complications including delayed union or abductor weakness resulting in Trendelenburg gait. Fluoroscopic guidance is often required.

Acetabular preparation is considered the major challenge in takedown fusion. Localization of the true native acetabulum relies on the identification of bony landmarks including the teardrop, foveal fat pads, and the ischium, which are often not easily recognizable in an ankylosed hip. Repeated intraoperative fluoroscopy is often required to guide reaming and acetabular cup positioning, but is less efficient and inconsistent with 2-dimensional images.

Femoral preparation difficulties include distorted proximal femur anatomy with difficult identification of the femoral canal.

Robot-assisted THA surgical technique

The Mako Robotic Arm–Assisted Surgery System (Mako Surgical Corp., Stryker, Fort Lauderdale, FL) has gained popularity in recent years with United States Food and Drug Administration approval in 2015 for its THA application. The system uses a robotic arm guided by a 3-dimensional computer model created from patient-specific computed tomography (CT) scans. The CT images are loaded onto the computer console where the surgical team plans the acetabular component sizing and placement based on patient specific CT scans. Through navigation technology and registration of checkpoints, the patient's bony anatomy is matched with their CT scans, allowing the plans to be executed accordingly. This robotic system is a semiautomated system where the surgeon maintains control of the robotic arm, working within the preplanned boundaries. If the surgeon were to ream outside boundaries, the robotic arm will provide auditory and haptic feedback to the user and ultimately shut off the robotic arm. With fusion takedown where much attention is required to identify the acetabular cup placement, the robotic system can provide accurate localization in 3-dimensional space, simplifying this critical step.

Preoperative planning

CT scans of the pelvis, proximal femur, and knee are performed as per protocol, but segmentation of the pelvis and proximal femur should be performed en bloc instead of separately (Fig. 1). This deviation from usual protocol requires authorization by the operating surgeon. Landmark placement should also be adjusted in the preplan such that the initial 3 acetabular alignment points are now outside of the acetabulum to facilitate in situ registration but on identifiable bony prominences to maintain accuracy.

Tang and Chiu [9] described the tendency for pelvic hyperextension in patients with AS and lumbar spine kyphotic deformity. Anatomical placement of the acetabular component will result in excessive anteversion and inclination, therefore increasing the risk of anterior dislocation. In general, a smaller anteversion and lower inclination should be targeted in patients with pelvic

Table 1
Patient demographics for reported cases of arthrodesis conversion.

Case number	1	2	3
Age	26	70	34
Gender	Male	Female	Male
Diagnosis	AS with fibrous ankylosis	AS with bony ankylosis	AS with fibrous ankylosis
Preoperative Fusion Position	40° Flexion 15° Abduction 15° External rotation	10° Flexion 20° Abduction 10° External rotation	10° Flexion 5° Adduction 10° External rotation

Table 2
Radiological outcome of acetabular cup placement comparing preoperative planning, intraoperative verification, and postoperative results of reported cases.

Case number	1	2	3
Cup anteversion (postoperative/intraoperative/planned)	16°/16°/15°	23°/19°/17°	15°/16°/17°
Cup inclination (postoperative/intraoperative/planned)	38°/35°/35°	40°/37°/37°	38°/34°/35°

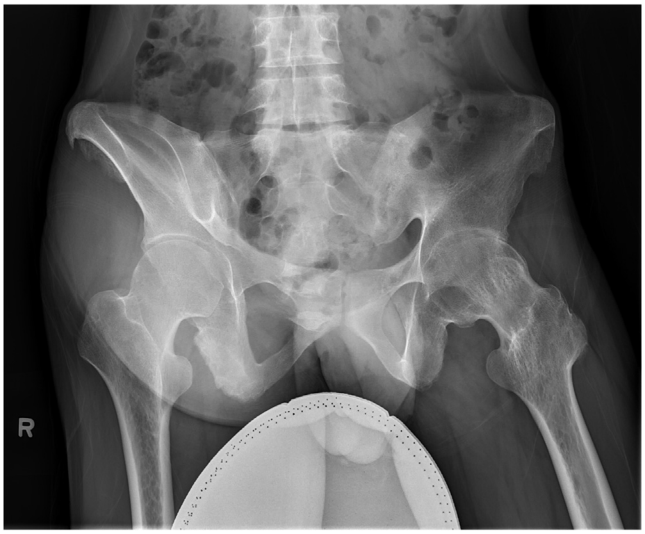

Figure 4. Preoperative radiograph of patient 1 with ankylosing spondylitis with evidence of left hip ankylosis and pelvic hyperextension.

hyperextension. Orientation of the acetabular component can be accurately planned on robotic software. Another advantage of preoperative CT is that native femoral version can be accurately assessed (Fig. 2), allowing the surgeon to target a patient-specific combined anteversion.

Surgical technique

Posterior approach using Mako express femoral workflow is described here.

The patient is placed in the lateral decubitus position, with the pelvis stabilized to the operating table. Pelvic positioning is less critical with robotic THA than the conventional method. Three bone pins are inserted over the iliac crest with the pelvic array attached. With the pelvis stabilized throughout the operation, the operating table can be tilted to allow better visualization from behind the greater trochanter without dislocating the hip. An electrocardiography lead is adhered to the patella as a constant reproducible femoral checkpoint before draping.

Surgical exposure is performed down to the femoral neck and acetabulum. The sciatic nerve is identified and protected throughout the procedure. Femoral proximal landmark is placed over the greater trochanter, followed by registration of proximal and distal landmarks over the tip of the patella. The pelvic checkpoint is placed over the posterosuperior part of the acetabulum away from the site of reaming and intended supplementary screw insertion.

Rather than dislocating the hip, in situ registration is performed first before osteotomy. The acetabulum together with the femoral head and neck are registered en bloc. The first 3 acetabular alignment points should be as accurate as possible to ensure correct rotational alignment with the virtual model. The subsequent 32 registration points should be as widely distributed over the ilium, femoral neck, and the ischium as possible and registered on hard cortical bone rather than soft tissue. The 8 verification points can then be taken to confirm the rotational alignment; while doing so, the surgeon can position the probe over the anterior superior iliac spine to verify the rotation (Fig. 3).

With the conventional technique, neck cut is often performed under fluoroscopic guidance to avoid iatrogenic injury to the anterior column. With robotic guidance, neck osteotomy can be completed using guidance of the hip probe on the verification screen. The hip probe can provide real-time feedback on the level of the neck cut and direction of neck cut (Fig. 6). The direction and location can be marked with diathermy.

After neck cut, the femur is displaced anteriorly to expose the acetabulum, and the robotic arm can then be brought in for reaming. Under haptic guidance, the robotic arm–controlled reamer can concentrically ream away the entire femoral head down to the planned true acetabulum. Although single-sized reaming can theoretically be performed, starting with a smaller sized reamer (downsize by 4-6 mm) will provide a larger working boundary minimizing interruption by the robotic arm constraint. Once majority of the bone has been removed by the small reamer, the actual size reamer can be used to prepare a spherical bone bed

Figure 5. Preoperative planning (radiograph view) for patient 1 showing ideal fitment with a 52-mm acetabular cup.

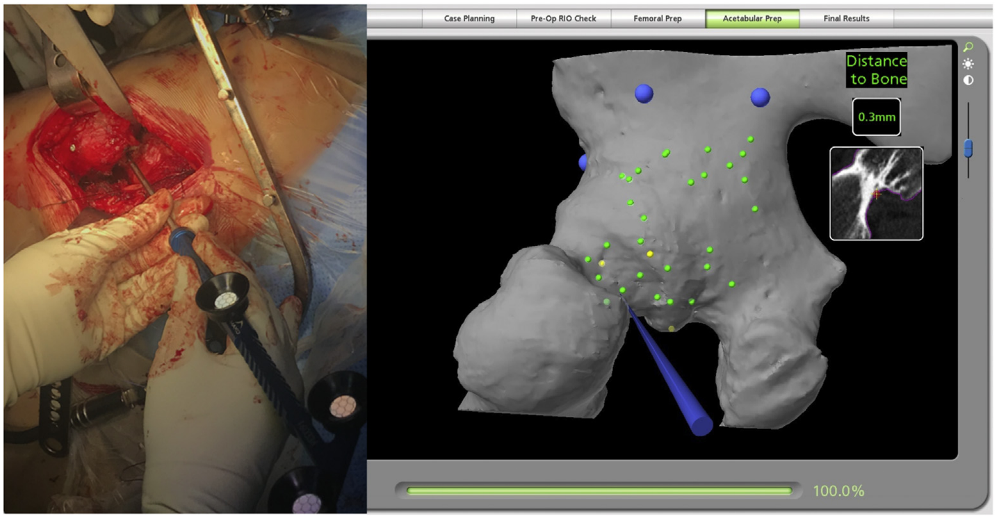

Figure 6. Hip probe used as a real-time navigation tool to guide orientation of neck cut.

for implantation. Trial impaction and fluoroscopic verification can be performed as needed but is not a must. The acetabular shell is subsequently impacted under robotic arm guidance. Anteversion and inclination angles are locked while the impaction depth can be captured sequentially. The offset impactor handle may be used to facilitate the posterior approach where the femur comes in line with impaction. Once a satisfactory depth is achieved (0-1 mm proudness), the impactor handle is carefully disengaged from the cup. The cup position with respect to version, inclination, and depth can be assessed using the probe. Supplementary screws are inserted as needed, and the liner is impacted.

Femoral preparation is performed manually. The femoral canal is often sclerotic and difficult to identify in chronic ankylosis. Box chisel and small-diameter power reamers are used to find the canal, followed by usual reaming and broaching up to the planned stem size. With robotic assistance, once the trial stem, trial head, and neck are in place, the hip can be reduced and assessed for the leg length and offset. These can be adjusted accordingly before actual femoral components are inserted and verified once again.

Postoperatively, patients are allowed for full weight-bear walking without posterior hip precautions. Oral indomethacin of 25 mg 3 times daily is prescribed for 6 weeks as heterotopic ossification prophylaxis.

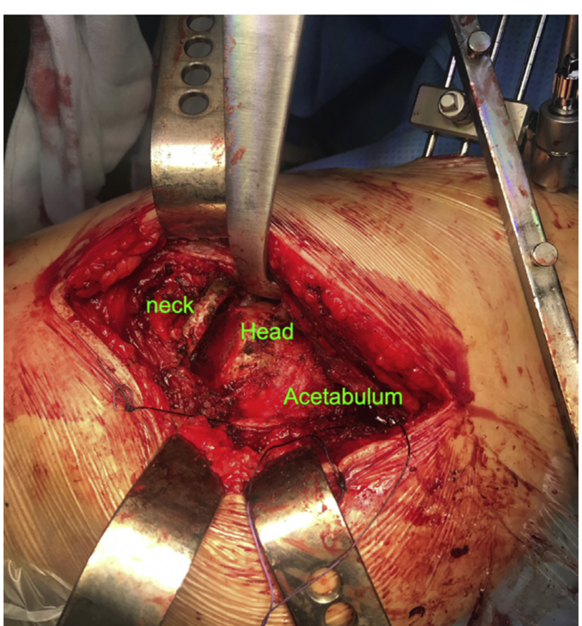

Figure 7. In situ neck osteotomy also showing the femoral head remains immobile inside the acetabulum.

Case illustration

We report 3 robotic arm–assisted THAs for spontaneous hip ankylosis due to ankylosing spondylitis operated between July 2019 and March 2020 using the posterolateral approach with Mako express workflow. All 3 patients had complete ankylosis clinically although 2 patients only had fibrous ankylosis radiologically. All operations were performed by a single surgeon competent with both conventional and robotic THA but had no prior experience performing conversion of an ankylosed hip to THA. Table 1 summarizes patient demographics and outcomes of these patients while Table 2 summarizes the radiological outcomes of the 3 cases.

Case 1

A 26-year-old male patient with ankylosing spondylitis with left hip ankylosis for 3 years in 40° flexion, 15° abduction, and 15° external rotation underwent robotic arm–assisted total hip replacement. Indication for surgery was back pain and poor hip function. Preoperative CTs and radiographs showed fibrous ankylosis with pelvic hyperextension (Fig. 4) and a native femoral retroversion of 4°. MRIs showed mild fatty infiltration of the gluteus medius.

Preoperative planning on CT scans showed ideal fitment with a 52-mm cup, allowing 2-mm anterior, posterior, and medial walls to remain. Native femoral version was 4° retroversion with templating showing optimal fitment with size 3 stem. Acetabular cup placement was planned for 15° anteversion in view of hyperextended pelvis, while inclination was aimed at 35° in view of pelvic

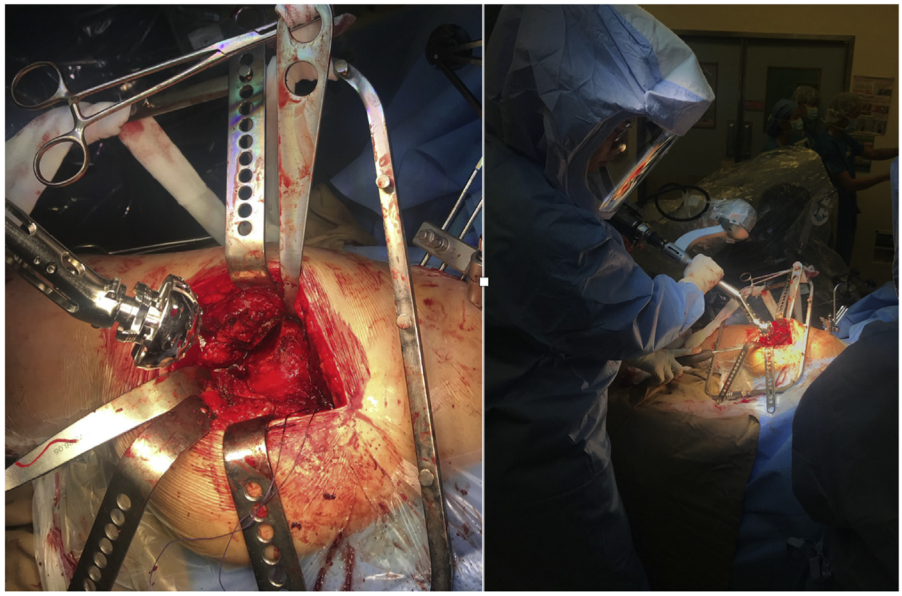

Figure 8. Robotic arm–controlled reamer placed directly into the surgical field to ream away the femoral head.

hyperextension. The radiograph planning view allows the surgeon to visualize what the postoperative radiograph may look like (Fig. 5).

Express workflow robotic THA was performed using the posterior approach. After tracker placement, the operating table was tilted forward, making the patient more prone, enhancing exposure of the posterior femoral neck. Registration of the acetabulum, femoral head, and neck regions was completed en bloc. Neck osteotomy was then navigated using the hip probe (Fig. 6). Single neck cut osteotomy was performed (Fig. 7). Robotic arm–assisted acetabular reaming was completed sequentially with a 48-mm reamer to remove most of the femoral head, followed by a 52-mm reamer down to the planned cup position (Fig. 8). Owing to the large amount of reaming material from the femoral head, direct visualization is not possible, but the robotic arm's haptic guidance will ensure a correct depth and direction of reaming (Fig. 9). Once reaming is completed and the acetabulum irrigated, the bed revealed punctate bleeding bone and intact periphery (Fig. 10). A 52-mm cementless cup (Stryker Trident,Peripheral Self Locking PSL, Stryker, Mahwah, NJ) was impacted under robot guidance to control for anteversion and inclination. Impaction was continued until the cup was fully seated at 1 mm proud from the plan. Cup stability was confirmed to be good with manual assessment; therefore, no supplementary screws were used. The cup was verified to be seated at 1 mm proud with an inclination of 35° and anteversion of 16° (Fig. 11). No intraoperative fluoroscopy was used. A 32-mm metal-backed ceramic liner was used in view of the young age.

The femoral canal was prepared manually with a straight reamer followed by sequential broaching to size 3 and manually producing 5° anteversion. The cementless component (Accolade II, Stryker, Mahwah, NJ size 3 with 127° offset) was inserted with 32 mm + 0 ceramic hip ball. The leg length was 1 mm longer and combined offset was decreased by 7 mm compared with the contralateral side because of medialization of the cup (Fig. 12).

Skin to skin operation time was 110 minutes.

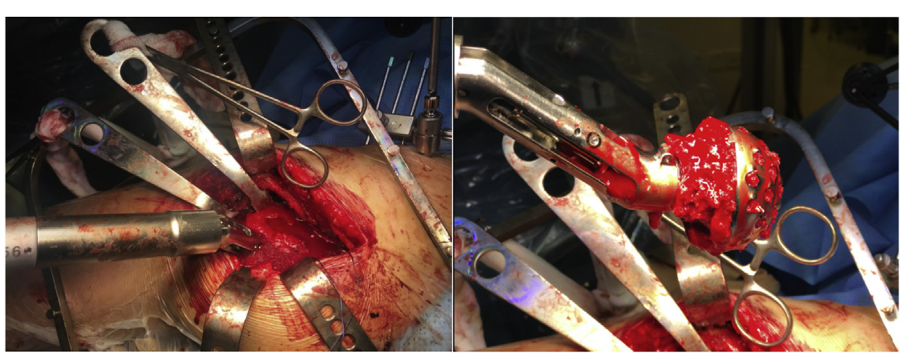

Figure 9. Acetabular reaming can be performed entirely under robotic arm guidance without direct visualization (obscured by reaming material); the entire femoral head can be reamed away.

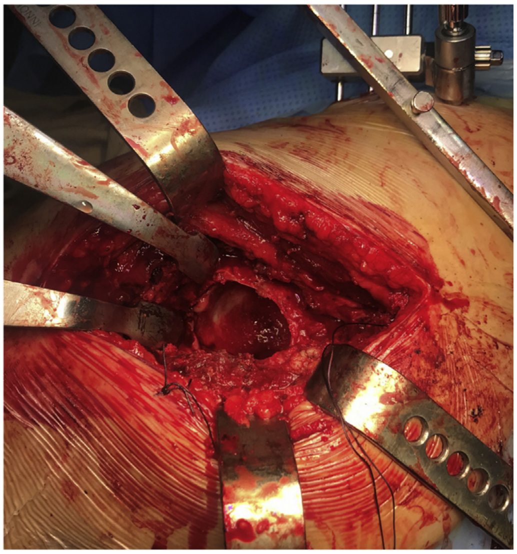

Figure 10. Intraoperative photograph demonstrating concentric acetabular reaming with preserved anterior and posterior acetabular walls. Bleeding cancellous bone bed was encountered circumferentially.

The patient was allowed full weight-bear walking immediately and was discharged on postoperative day 3 being able to walk with a stick independently.

The postoperative radiograph (Fig. 13) and CT scans showed a cup inclination angle of 38° and anteversion of 16°. The acetabular component position was consistent with planning in relation to the ilioischial line and tear drop. At 6 months, there was grade 2 heterotopic ossification over the superolateral aspect, but clinically, the patient's range of motion was maintained.

On 6 months' follow-up, there were no complications. The flexion range was 0°-70° (Fig. 14). He managed to walk unaided for 30 minutes on level ground with Harris Hip Score improving from 65 to 85 (Table 3).

Case 2

This is a 70-year-old lady with ankylosing spondylitis and bilateral spontaneous hip fusion. She underwent left hip fusion takedown to total hip replacement using conventional instruments in May 2015. The initial surgery was complicated by femoral nerve neuropraxia and grade 3 heterotopic ossification despite indomethacin. During the latest follow-up at 4 years postoperatively, her left hip flexion range was only 0°-40°.

Her right hip had bony ankylosis at 10° flexion, 20° abduction, and 10° external rotation for more than 30 years (Fig. 15). Indications for conversion to THA were back pain and functional limitation. Preoperative CT scans showed bony ankylosis of the right hip, and MRI showed mild fatty infiltration over the gluteus muscles.

Robotic arm–assisted THA was performed in October 2019. Preoperative planning revealed an ideal acetabular component size of 46 mm with native femoral anteversion of 12°. The cup inclination angle and anteversion were planned at 37° and 17°, respectively (Fig. 16). A posterolateral approach was used. Single neck cut osteotomy was performed under navigation guidance. Sequential reaming with 2 sized reamers was used (42 mm and 46 mm). A 46-mm cup was impacted under robotic arm guidance. Intraoperative verification of the cup position showed inclination of 37° and anteversion of 19°. A highly cross-linked polyethylene with no lip was inserted. The femoral side was completed using a manual technique with a 32-mm cobalt chrome head after native femoral anteversion. The leg length was 2 mm longer, and combined offset was decreased by 5 mm when compared with contralateral. Operative time was 155 minutes (skin to skin). No fluoroscopy was used throughout the surgery.

Postoperative radiograph (Fig. 17) and CT scans measured cup anteversion of 23° and an inclination angle of 40°. There was no evidence of heterotopic ossification at 6 months.

The Harris Hip Score improved from 65 preoperatively to 87 at postoperative 6 months.

The left hip flexion range was 0°-70°, abduction 30°, adduction 30°, external rotation 20°, and internal rotation 20° (Table 4).

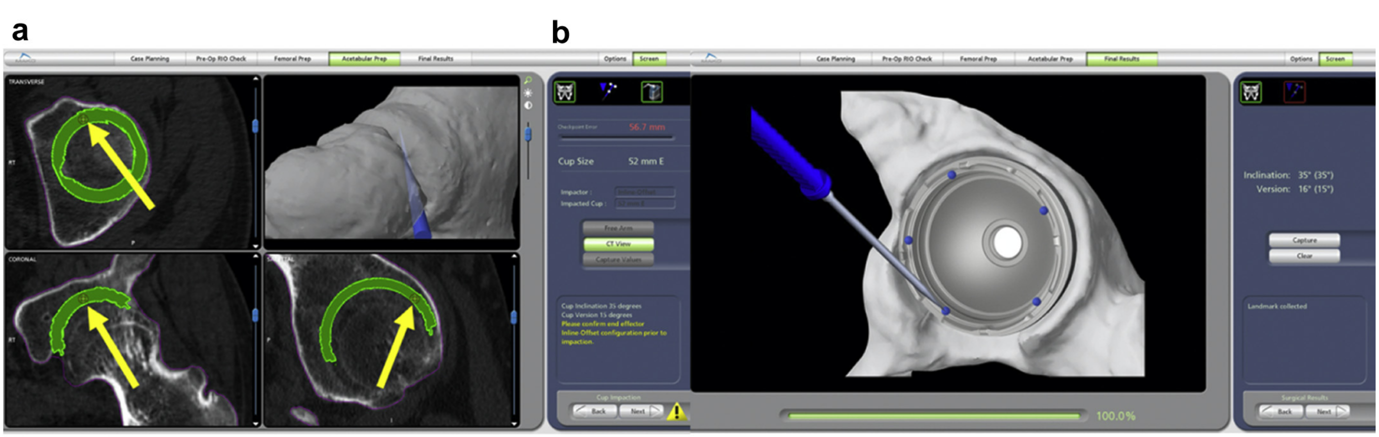

Figure 11. Verification of the cup position using hip probe avoids the need for fluoroscopy. (a) The hip probe is used to verify the actual cup position with respect to preoperative CT plans on all 3 planes. (b) Surgical results of the cup plane view to verify the cup inclination and anteversion by registering 5 points along the rim.

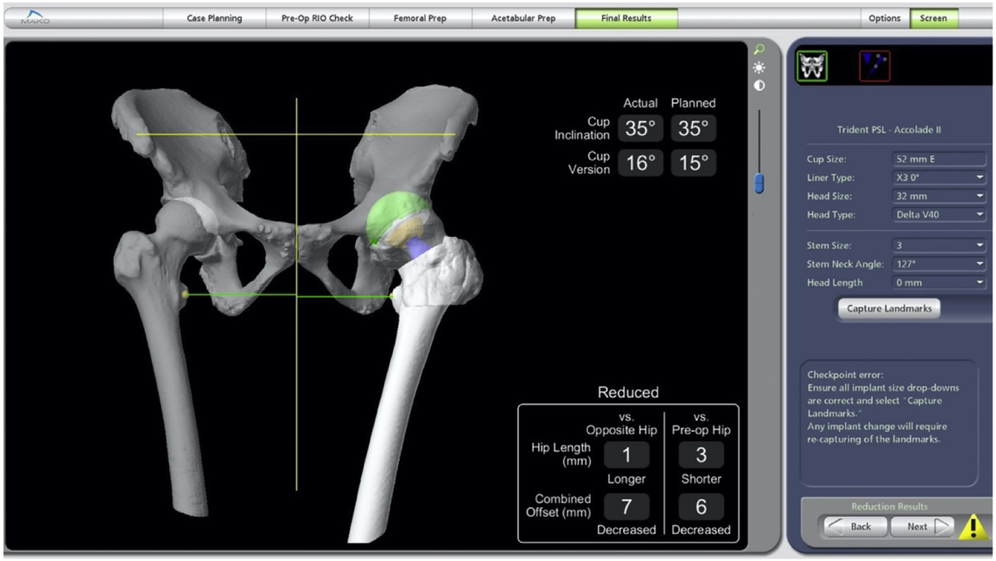

Figure 12. Verification of the limb length and combined offset after implantation for case 1.

Case 3

The last patient is a 34-year-old man with ankylosing spondylitis with fibrous ankylosis of his right hip. His right hip was ankylosed at 10° flexion, 5° adduction, and 10° external rotation preoperatively with radiological evidence of fibrous ankylosis (Fig. 18). The indication for conversion to THA was the suboptimal fusion position and severe functional impairment. Preoperative CT scans showed fibrous ankylosis of his left hip, and MRIs showed satisfactory abductor muscle quality.

Robotic arm–assisted THA was performed in March 2020 using the same techniques described previously. A 54-mm acetabular cup was planned with an inclination angle of 35° and anteversion of 17° (Fig. 19). The native femoral anteversion was 5° with size 5 stem producing ideal fitment.

Single neck cut osteotomy was performed with the navigation technique described previously. Sequential reaming with 2 sized reamers was performed (48 mm and 54 mm). The cementless acetabular cup was impacted under robotic arm guidance with

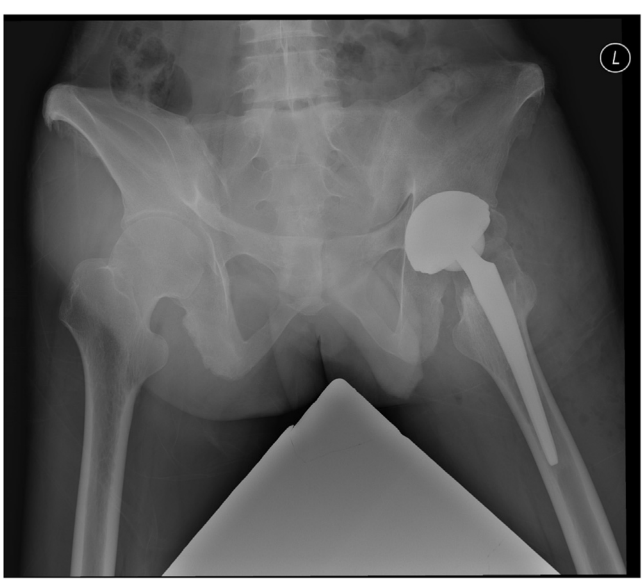

Figure 13. Postoperative radiograph of patient 1.

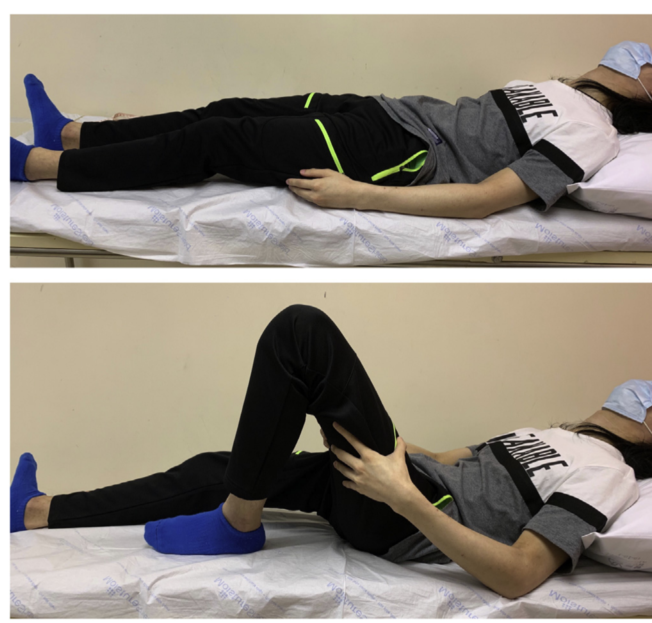

Figure 14. Patient 1 at postoperative 6 wk demonstrating an extension-flexion range of 0°-70°.

Table 3
Key operative details of reported cases.

Case number	1	2	3
Neck osteotomy	Single	single	single
Reamer sizes used (mm)	48, 52	42, 46	48, 54
Acetabular component size (mm)	52	46	54
Trial	Nil	nil	nil
Bearing	Ceramic on ceramic	Metal on HXLPE	Ceramic on HXLPE
Supplementary screws	0	2	0
Intraoperative fluoroscopy	Nil	Nil	nil
Operative time(min)	110	155	168

HXLPE, highly cross-linked polyethylene.

proudness of 0 mm and a verified inclination angle of 34° (−1° from plan) and anteversion of 16° (+1° from plan). Excellent cup stability was achieved, and thus, no supplementary screws were inserted. A highly cross-linked polyethylene liner with 10° lip placed at 10 o'clock was used to produce a high combined anteversion to prevent posterior dislocation.

The femoral side was performed manually with sequential broaching to the planned size. A size 5 high-offset cementless femoral stem with a 36 mm −2.5 mm ceramic head was inserted to produce a leg length of −1 mm and combined offset of −4 mm compared with the contralateral hip.

Operative time was 168 minutes, and no intraoperative fluoroscopy was required.

Postoperatively the patient was able to flex the hip from 0° to 40°. No complications were encountered during in-hospital stay. On discharge at postoperative day 6, he was able to walk with 1 elbow crutch independently.

Postoperative radiographs showed the cup position inclination angle of 38° and anteversion of 16°. Acetabular component placement was as planned with respect to ilioischial line and the tear drop (Fig. 20). On the latest follow-up at 3 months, his flexion range was 80° with Harris Hip Scores improvement from 38 preoperatively to 79 (Table 4). No complications were reported as of the latest follow-up.

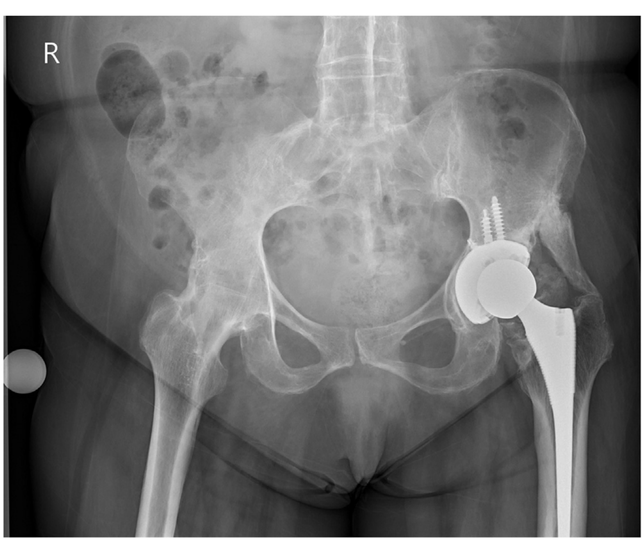

Figure 15. Preoperative radiograph of case 2 showing bony ankylosis of the right hip.

Discussion

Conversion of hip fusion to total hip replacement is a challenging operation with high complication rates. Intraoperative complications are common because of inability to dislocate the hip and difficult identification of the true acetabulum. Kim et al [7] reported complications including pelvic discontinuity, greater trochanteric fracture, calcar fracture, femoral perforation, and postoperative femoral and peroneal nerve palsies. Joshi et al [10] reported 15 nerve palsies and 5 dislocations out of 187 cases. Richards and Duncan reported an overall complication rate of 54% with 5 infections, 4 dislocations, 3 acetabular component aseptic loosening, 1 periacetabular osteolysis, and 1 pulmonary embolism in their cohort of 26 patients [11]. Complication rates are noticeably higher in patients with surgical fusion rather than spontaneous fusion [12]. In all our 3 cases of fusion takedown, no intraoperative or early postoperative complications occurred. With robotic arm–assisted THA, a navigated neck osteotomy minimizes the need for trochanteric osteotomy during exposure and lowers the risk of iatrogenic fracture over the acetabulum. One patient developed heterotopic ossification, but clinically, the range of motion was maintained.

Robotic arm–assisted THA has shown promising results in terms of accurate component placement. In a CT-based study, Nodzo et al [13] were able to demonstrate a significant correlation between the mean intraoperative and postoperative acetabular component inclination ($R^2 = 0.62$; $P < .001$) and anteversion ($R^2 = 0.76$; $P < .001$). When compared with conventional THA, studies have shown superior accuracy with the robotic technique. Domb et al [14] have shown in their case-control study involving 100 patients that robot-assisted acetabular component placement had a higher probability of lying within the Lewinnek and Callanan safe zones than conventional THA. Kamara et al [15] further compared the acetabular component placement in robotic posterior THA with fluoroscopic anterior THA and manual posterior THA and found that the probability of achieving the surgeon's target inclination (30°-50°) and anteversion (10°-30°) was significantly higher in the robotic posterior group.

The operating surgeon in our series had no prior experience with fusion takedown, but with robotic arm assistance, the acetabular radiological outcomes remained. Kayani et al [16] showed no learning curve effect with robotic arm–assisted technology for achieving the planned center of rotation, acetabular cup position, combined offset, and limb-length discrepancy. Despite the limited numbers in the present case series, we demonstrated that technology can supplement experience especially in difficult cases.

Apart from the robotic system discussed, other computer-assisted systems can also provide real-time data on the acetabular component anteversion, inclination, leg length, and offset;

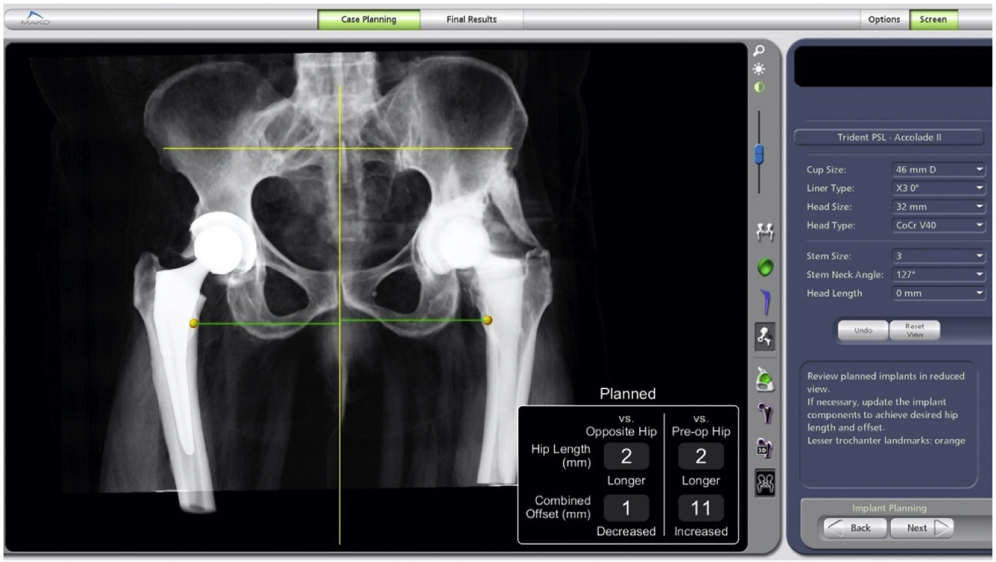

Figure 16. Radiograph view planning of the acetabular component position for case 2.

however, they do not offer any constraints on reaming. In hip ankylosis, determining the depth and direction of reaming is difficult because of distorted anatomy. The robotic arm system offers additional haptic constraint controlling the depth of reaming that has distinct benefit for fusion takedown where the entire femoral head is to be reamed away. Theoretically, any computerized system that can provide accurate planning, constraints on reaming, and cup placement should be able to produce similar results.

Drawbacks of robotic THA include cost, prolonged operative times, pin site–related complications, and lack of long-term follow-up results. Substantial upfront cost of installation, maintenance, disposables, and training of operative room personnel may increase the health burden.

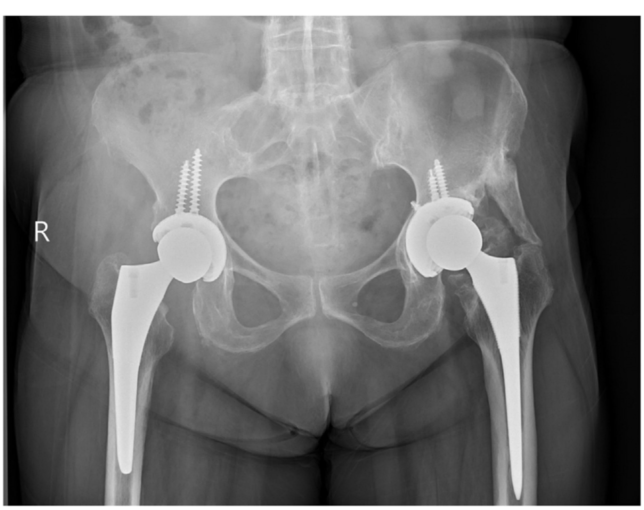

Figure 17. Postoperative 6-mo radiograph of case 2 showing good alignment with no heterotopic ossification on the right side with robotic THA.

Conclusion

Conversion of ankylosed hip to THA was traditional associated with high complication rates because of its technical difficulties. With recent development of robotic arm–assisted THA, enhanced 3-dimensional preoperative planning, precise acetabular reaming, accurate component placement, and real-time intraoperative verification significantly simplify conversion to THA for patients with spontaneous hip ankylosis. Long-term studies are warranted for long-term outcomes, but we report promising early clinical and radiological outcomes with our cases.

Conflict of Interests

K.Y. Chiu is a paid consultant for DePuy Johnson and Johnson, Smith and Nephew, Stryker Mako, Zimmer Biomet, and MicroPort; C.H. Yan is a paid consultant for DePuy Johnson and Johnson, Stryker, and Smith and Nephew and is a board member of the AAHKS International Committee and the Hong Kong Orthopaedic Association.

Table 4
Clinical outcomes.

Case number	1	2	3
Range of motion	6 mo	6 mo	3 mo
Flexion/extension	70°/0°	70°/0°	80°/0°
Abduction/adduction	30°/15°	30°/20°	25°/20°
External/internal rotation	30°/10°	30°/20°	15°/10°
Harris Hip Score			
Preoperative	65	65	38
3 mo	85	87	79
6 mo	85	88	NA
Complications	Brooker II Heterotopic Ossification	Nil	Nil

Figure 18. Preoperative planning for case 3 showing fibrous ankylosis of the right hip.

Figure 20. Postoperative radiograph for case 3 with right robot-assisted THA.

Figure 19. Preoperative planning for case 3.

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