MENTORS IN ORTHOPEDICS

ROBOTIC-ASSISTED TOTAL HIP ARTHROPLASTY: FROM PLANNING TO ROBOTIZATION

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SUMMARY

Background: Total hip arthroplasty (THA) outcomes are frequently compromised by component malpositioning, which contributes to approximately 40% of revision surgeries. Traditional manual techniques and standard navigation systems often fail to prevent medial or superior shifts in the center of rotation, potentially leading to impingement, accelerated wear, and limb length discrepancy.

Objective: This article evaluates the application of robotic-arm assisted technology in THA, focusing on preoperative planning, intraoperative execution, and clinical evidence regarding implant accuracy and patient outcomes.

Key Points: The system utilizes preoperative CT-based 3D modeling to facilitate surgeon-directed adjustments of acetabular orientation, center of rotation, and femoral offset. Intraoperative robotic guidance constrains acetabular reaming and component impaction, ensuring adherence to the plan within a reported 3.5° margin of error. Comparative data indicate that robotic assistance significantly increases the proportion of implants placed within established safe zones compared to manual or fluoroscopic methods. Furthermore, the technology facilitates bone preservation through single-stage reaming and maintains accuracy regardless of patient body mass index. While a learning curve of approximately 35 cases is noted, early functional data, including Harris Hip Scores, suggest outcomes superior to conventional techniques at one year. However, increased operative time and equipment costs remain significant factors for consideration.

Conclusion: Robotic-arm assisted THA provides a reproducible method for achieving precise component positioning and restoring hip biomechanics. It minimizes errors related to manual instrumentation and offers a data-driven approach to managing complex anatomical variations and improving surgical predictability.

KEYWORDS

Arthroplasty, Replacement, Hip; Robotic Surgical Procedures; Surgery, Computer-Assisted; Acetabulum; Treatment Outcome

As surgery goes, total hip replacements achieve some of the best outcomes; however, operated patients continue to demand even better functional results.

The short-, mid- and long-term results do not always meet expectations and are sometimes marred by complications or poor results.

A certain number of factors, such as patient demographic, surgical approach and technique, and implant type can affect the outcome of this type of surgery. Some of these factors are surgeon-dependent, affected only by the choices made during the presurgical planning stage but also by ability to follow the plan exactly and avoid implant malposition.

Looking at the possible causes of failure, especially those dependent on the surgeon, we believe that one of the worst offenders is the implant placement.

Malpositioning is linked to a higher rate of dislocation, impingement within or around the implant which can cause pain or affect functional outcomes, accelerated implant wear, unequal length and, ultimately, a higher rate of revision. It is in fact responsible for up to 40% of revisions.[1]

Presurgical planning, and the use of hip navigation systems in some cases, has improved implant position.

However, these tools do not fully control the position of the implant and there is still significant room for error by the surgeon when it comes to reaming and orientation.

Reviews of navigation data, comparing the Lewinnek safe zone against scan outcomes, show a consistent albeit involuntary tendency to a medial and superior shift in centre of rotation[2,3], a surgical issue that existed well before the advent of image-guided techniques and navigation systems.

There has been lively debate in recent years as to the design and suitability of a robotic tool for ensuring the surgery is as accurate as possible in terms of implant position. This same period saw the introduction of the Mako THA system (Stryker®, Mahwah, USA) designed to help surgeons accurately place components in perfectly accordance with the presurgical plan, taking into account numerous factors such as the choice of whether to restore the centre of rotation, preservation of bone stock, leg length adjustments, global offset management, and the absence of any internal or external impingement especially with the psoas.

It takes us one step closer to the ultimate goal of improving short-, mid- and long-term results.

FROM PLANNING TO ROBOTISATION

The robotic arm comes with software with the ability to plan implant placement using patient-specific anatomic markers and native acetabular geometry, centre of rotation, femoral version, offset and comparative length of the operated hip.

For a total hip arthroplasty (THA), the patient data are collected in advance using a preoperative CT scan with the ability to calibrate the field (knees can be included in the field in order to assess femoral version). Once the CT scan is complete, the specialist Segmentation Team creates a patient-specific virtual 3D model of the pelvis and femur. Using the surgeon's preferences, the Segmentation Team will also create an initial pre-plan and select the CT landmarks.

One of the key stages prior to the procedure the surgeon's approval of the plan proposed by the MPS (Mako Product Specialist) or engineer. The surgeon has complete flexibility, during the preoperative planning, to adjust various components of the plan based on the implant used, including:

- acetabular component orientation (Fig. 1),
- centre of rotation
- hip length
- cup overhang, especially anterior
- cemented or cementless, anatomic or straight, anteverted or neutral stem (Fig. 2)
- combined offset (Figs 2 & 3)
- combined anteversion, based on safe zone data,
- bone sparing i.e. minimization of reaming diameter by choosing a smaller cup, whilst respecting the other elements.
- leg length (Fig. 3).

Figure 1. Cup planning: size, coronal and transverse orientation, anterior overhang (red arrow), posterior overhang (blue arrow), native acetabular centre of rotation (magenta sphere), planned cup centre (green sphere).

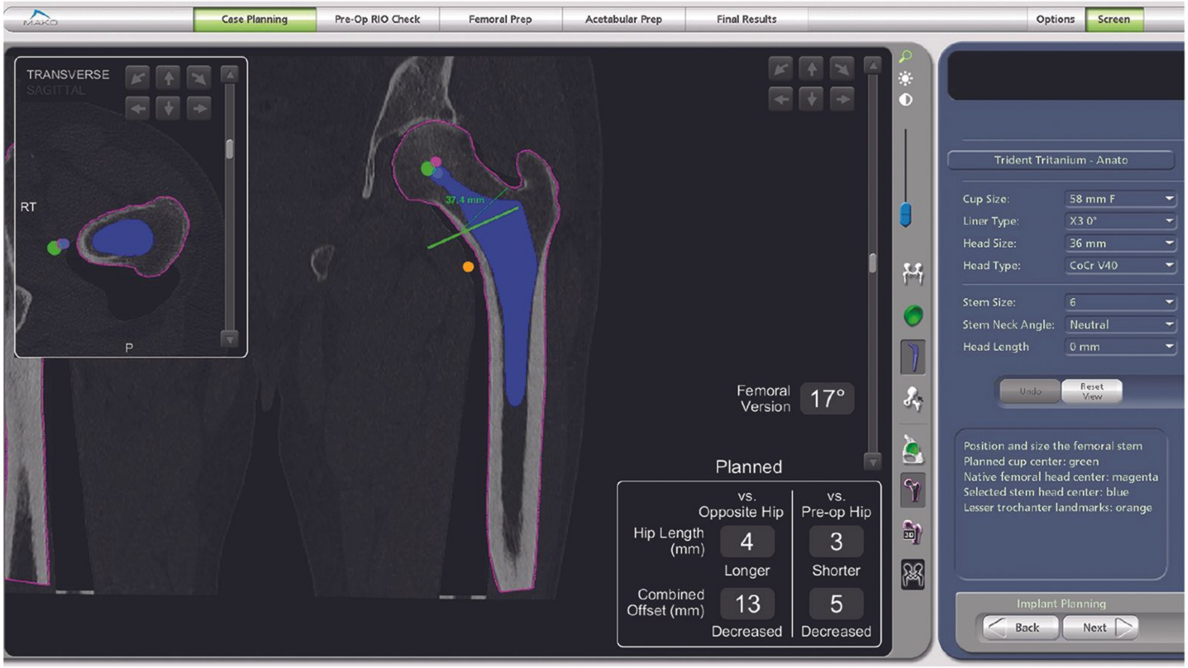

Figure 2: Stem planning. The surgeon has chosen an anatomic (Anato®, Stryker), size 6, anteverted stem with a 36/0mm head. Native centre of rotation (magenta sphere), stem (blue sphere), cup (green sphere). Length and combined offset calculated with reference to the opposite hip and pre-op hip.

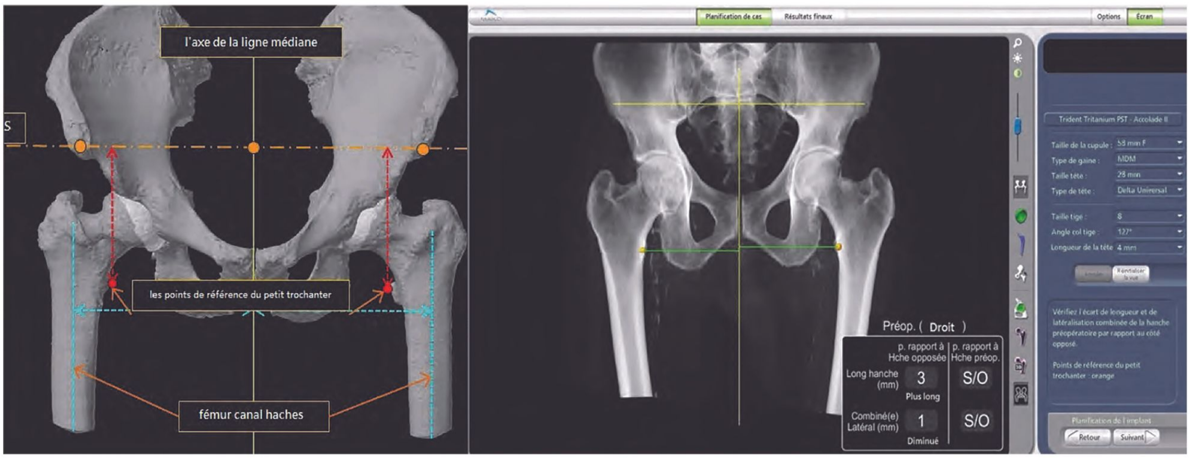

Figure 3. Hip length is the distance (mm) from the ASIS Axis to the lesser trochanter landmarks with the femurs in mechanical axis alignment. Combined offset is the distance (mm) from the Midline Axis to the femoral canal axes with the femoral canal axes aligned vertically.

These choices are unpredictable and, in all cases, will depend entirely on the surgeon's preferences when validating the final plan (Fig. 4), although changes may still be made mid-procedure based on findings or constraints.

Figure 4. Final plan and postoperative x-ray simulation.

SURGICAL TECHNIQUE

The goal of the surgical approach is to establish adequate visualization of the anatomy so that the entire surgical area is exposed. Stryker's MAKOplasty Total Hip Application® is designed to accommodate the posterolateral, anterolateral and direct anterior surgical approaches with one of two types of femoral workflow:

- express: uses robotic assistance to place the cup and navigate the femoral stem;

- enhanced: includes guided neck resection and femoral stem version.

The surgeon is responsible for ensuring the appropriate location, type and size of the incision. This choice will influence the position of the landmarks. The pelvic array is placed on the iliac crest, on the same side as the approach if posterior, or on the opposite side as the approach if anterior. The acetabular and femoral landmark placement will also depend on this choice (Fig. 5).

Figure 5. A) Setting up the robotic arm and landmarks for a Moore posterolateral or DSA approach; B) Patient set-up and pelvic array for a Direct Anterior Approach (DAA); C) robotic-assisted reaming for a DAA; D) Robotic-assisted cup impaction.

The landmarks are used to reconcile the navigation data with the anatomic data collected preoperatively and adjust the robotic arm for placement of the reamer and final implant. They are also points of reference for guiding the femoral stem. Once the femoral array is in place, the surgeon collects the preoperative length and offset of the native hip. After resecting the femoral neck, exposing the acetabulum and placing the acetabular landmark, the software correlates the checkpoint acquisition data (mapping) with the plan. If following the enhanced workflow, the femoral checkpoint acquisition will precede the acetabular checkpoint acquisition (Fig. 6).

Once the data have been reconciled, optimal reaming is ensured using the robotic arm with a single-size reamer positioned in accordance with the plan. This arm can restrict the surgeon's movements in terms of orientation, centre of rotation and depth of reaming.

It also controls the final cup impaction. Using the probe to check final cup orientation ensures that the intraoperative values never differ from the plan by more than 2° (Fig. 6).

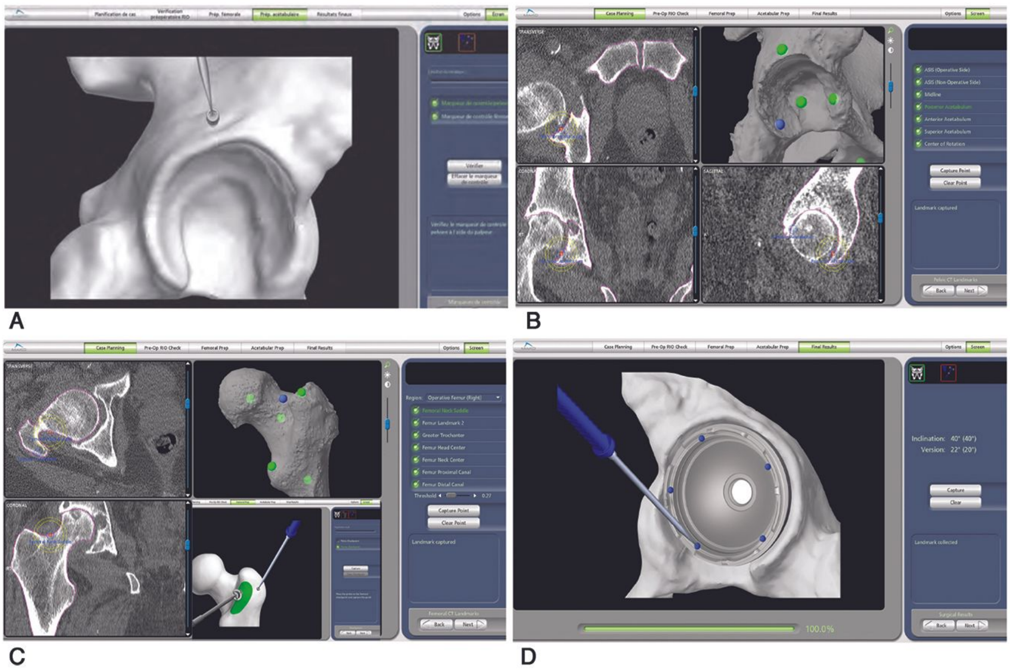

Figure 6. (a) Placing the acetabular landmark; (b) Mapping the acetabulum using the registration spheres; (c) Placing the femoral landmarks during the Enhanced workflow with proximal landmark capture; (d) Checking final cup placement using the probe.

Once the femur is prepared, stem version, lateral shift and leg length data are collected from either the trial components or the final implant and may be used to make adjustments in head length by editing the plan and checking the data using intraoperative data acquisition.

The robotic system therefore means everything is double-checked during the procedure, once by the surgeon and once by the robot.

CURRENT LEVEL OF PROOF OF THE BENEFITS OF ROBOTIC-ASSISTED HIP ARTHROPLASTY

Surgeons first began using MAKO robotic-assisted hip surgery in October 2010. Nine years on, over 100,000 total hip replacements have been performed worldwide. Concerns have been raised regarding the use of this technology, including:

- accuracy and reproducibility

- bone sparing

- managing combined anteversion

- the learning curve

- adaptability to individual patient anatomy and morphology

- benefits in terms of fewer complications and improved functional outcomes

- compatibility and influence on ERAS programmes and outpatient surgery

- medico-financial considerations.

Accuracy and reproducibility

A multi-centre study of 110 patients4 compared cup placement at three stages: preoperatively according to the plan, intraoperatively as recorded by the MAKO system and postoperatively through radiographic capture (Martell Hip Analysis Suite™, John Martell MD, Chicago, USA).

The results confirmed the accuracy and reliability of implant placement to within ±3.5° of variation in cup orientation in 95% of cases (95% confidence interval). Nodzo et al. recently concluded that an independent analysis of intraoperative data correlates with CT scan images.[5]

Domb et al. conducted a study of six surgeons at a single centre who performed a total hip arthroplasty (THA) for 1980 patients.6 The aim of this study was to analyse the effect of approach and technological assistance. Six different surgical techniques were analysed: conventional posterior, x-ray guided posterior fluoroscopy-guided anterior (DAA), navigation-guided anterior (DAA), MAKO robotic-guided anterior (DAA) and robotic-guided posterior. Considering the percentage of cups implanted in the Callanan safe zone (30°–45°; 5°–25°)7, the robotic-arm assisted procedures were significantly more accurate, all approaches combined (Fig. 7).

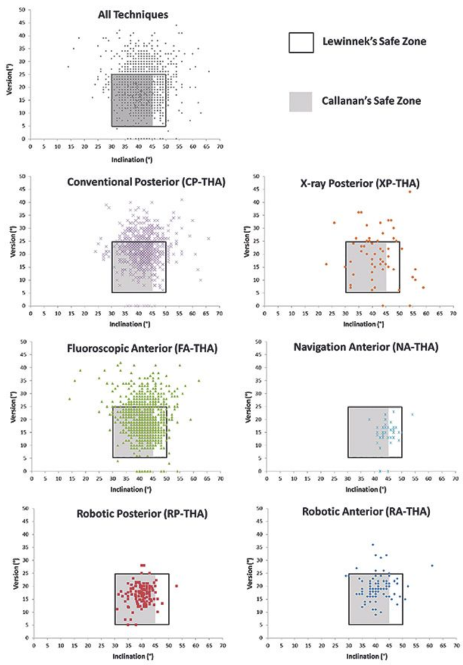

Figure 7. Distribution of cup inclination and version in relation to Lewinnek's and Callanan's safe zones, for each treatment group.6.

Adjustments in leg length, centre of rotation and combined offset have also been analysed,[5,9] with the authors reporting results accurate to 1 ± 0.7mm, and pointing out the link between implant centre of rotation position and the risk of dislocation.

Given the benefits in terms of no medial or superior shift thanks to the robotic arm constraint, the system appears to protect from the risk of dislocation.

Bone sparing

Another goal of robotization is to preserve bone stock. This is one of the factors to consider during the planning stage, based on whether the surgeon has chosen to restore the centre of rotation. Robotic guidance means this choice can be applied accurately with the use of a single-size reamer (size is determined by the choice of an iso or pressfit implant), and the depth of reaming is controlled by the system. The ability to constrain the reamer trajectory prevents any ovalization of the reaming and therefore ensures stable implantation of the final cup with the results identical to the plan. Chosen cup diameter is usually 2mm larger than the femoral head.

Suarez-Aedo et al. analysed the preservation of bone stock in a comparative study between the conventional THA approach (CTHA) (n=57) and robotic-arm assisted THA (RTHA) (n=57).[10] They confirmed the benefits of using a cup size relative to femoral head diameter. The results may suggest greater preservation of bone stock using RTHA compared to CTHA.

Managing combined anteversion

There is much debate over the validity of a safe zone[11] given the variation in native femoral anteversion and torsion[12,13,14,15] which make it hard, if not unpredictable, to determine, case by case, the ideal combined anteversion for a given patient. Certain factors such as changes in balance of the spine over time, stiffness of the lumbopelvic complex and the mechanical relationship between the spine and hip[16,17] must all be considered at the planning stage and undermine the concept of 'combined anteversion'. However, the ability to check this combined anteversion before and during the surgery is still very useful.

Marcovigi et al. evaluated the potential benefits of using robotic-assisted technology such as the MAKO system, assessing the influence of native femoral version on final stem version and combined anteversion when using straight uncemented stems.[18] They identified considerable variation in native femoral anteversion and confirmed the influence of the surgeon on stem version. However, adapting this version based on native version, whilst respecting a standardized combined anteversion, could be a reasonable alternative. We believe that our choice of either an anteverted (+7°) or neutral anatomical stem is another valid option (Fig. 8). Using the Enhanced workflow to navigate stem version is also very useful.

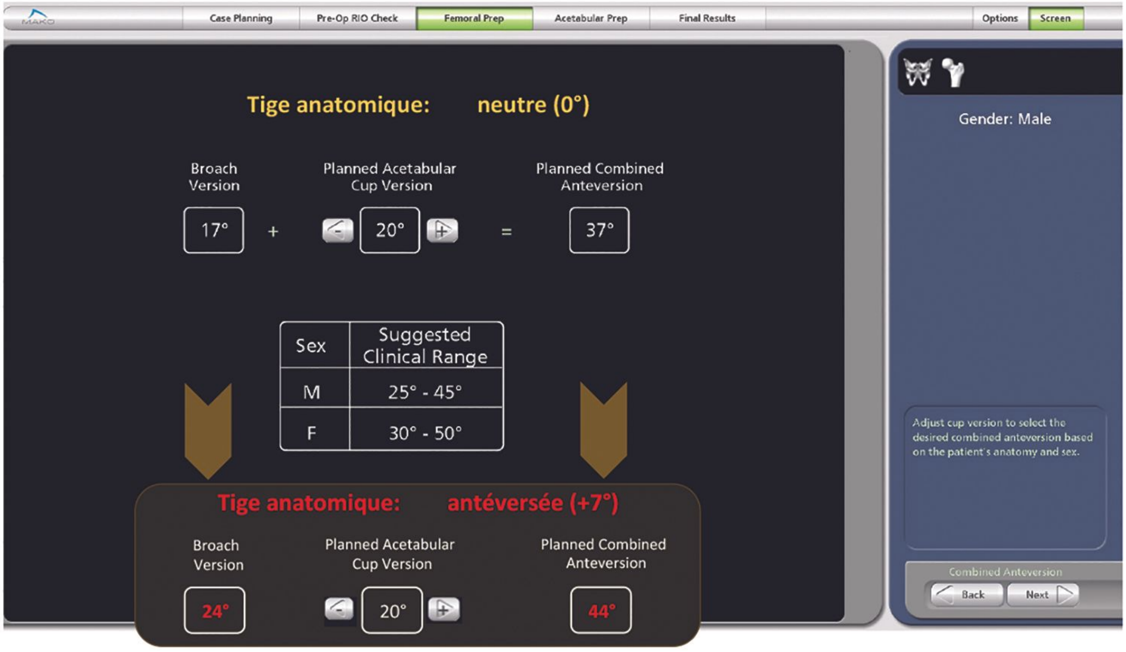

Figure 8. Combined anteversion: Selecting an anteverted or neutral femoral stem within the Enhanced workflow. The upper half of the screen shows the plan, and the lower half shows the choice of an anteverted stem based on patient sex and lumbopelvic morphology (large pelvic incidence and pelvic version) and stiffness (variation in pelvic version on EOS® images less than 10° between standing and seated).

The learning curve

In a retrospective single-surgeon study involving groups of 100 consecutive RTHA cases, Bukowski et al. looked at the effects of the learning curve on outcomes.[19] Three patient groups were analysed: G1 - the first 100 CTHA cases, G2 - the next 100 CTHA cases and G3 - the first 100 RTHA cases. At 1 year, no dislocations were reported in G3, unlike the other two groups.

Redmond et al. investigated changes in component position, duration of surgery and rate of complications since the first robotic-assisted procedure.[20] This continuous single-surgeon series also divided patients into three groups - group A of the first 35 patients, Group B of the second 35 patients, and Group C of the following 35 patients. Based on implant accuracy (percentage of safe zone outliers) and duration of surgery, the authors report a rapid learning curve of 35 cases before the procedure is mastered. However, they found no inter-group differences for technical problems (one loosened femoral array in Group A, one badly impacted cup in group A) or complications. In a recent meta-analysis, Han et al. reported a significant increase in operating time for robotic procedures versus traditional techniques.[21] Greater experience therefore means longer operating times,[22] something we have also witnessed in our practice at Nimes University Hospital.

Robotic assistance and BMI

Patient obesity can make cup placement harder. Gupta et al. examined the accuracy of acetabular cup inclination and version in the obese patient with posterior RTHA in 105 patients.[23] Three groups were defined based on body mass index (BMI, kg/m2)(<30 (n=59), 30–35 (n=34) and >35 (n=12)).

There was no statistical difference between the groups for acetabular inclination (p=0.43) or version (p=0.95). BMI is not a limiting factor for the use of robotic-assisted navigation. On the contrary, such systems increase the reliability of implant position and allow identical placement accuracy to non-obese patients.

What are the actual short-, mid- and long-term functional benefits of robotic-assisted THA?

Although most studies[21] describe robotic assistance as a reliable tool for implant accuracy, does it offer any real benefits in terms of long-term outcomes? Bukowski et al.19 report significantly superior Harris functional scores for robotic-assisted surgery (92.1 ± 1.8 vs. 86.1 ± 16.2; p=0.002) at one year. Perets et al. monitored a cohort of 162 RTHA patients over minimum of two years and also reported satisfactory short-term outcomes.[24] Although the FJS-12 (Forgotten Joint Score25) reported by this author[24] are comparable if not superior at two years compared to literature on conventional procedures, Han et al.[21] looked at six studies with a sufficient level of proof but report no significant difference. There is therefore need for further studies to provide a more robust assessment over a longer follow-up

Robotic THA, ERAS and outpatient surgery

Given the increasing number of articles on Enhanced Recovery After Surgery (ERAS) programmes, the various healthcare providers, under the auspices of the French National Health Authority (Report CNAMTS/DGS/SFAR, 2013), have a considerable interest in optimising the care pathway and clinical experience for patients undergoing this type of surgery. The shift among healthcare establishments towards outpatient surgery is also testament to this strategy. Robotization does not appear to have influenced this approach. However, when combined with data transparency it offers a high-quality process that reassures both surgeon and patient, thus reducing stress and promoting rapid recovery. Provided that robotic assistance only marginally affects hospitalization time, it is fully in line with this approach.

Cost and medico-financial study

Although the robotic system is effective in terms of implant quality and therefore long-term outcomes, the cost is currently a key consideration. Although current studies include larger cohort sizes, the follow-up periods are often not long enough, with a small number of independent studies. There is an unmet need for a medico-financial study to compare the clinical benefits against the cost, in order to help optimize the allocation of resources given the financial and social climate.

CONCLUSION

The MAKO system is potentially very useful for surgeons. It is an additional tool that allows accurate preoperative planning, optimal cup placement assisted and guided by the robot whilst ensuring good preservation of bone stock and controlling both cup orientation and centre of rotation. Any problems therefore derive from the surgeon’s choices and type of implant used.

A few issues have yet to be addressed, including:

- Optimal cup orientation

- Optimal patient-specific femoral anteversion

- Management of offset and varus etc.

- Whether and how to incorporate postural and spino-pelvic parameters.

The system can be used to apply these arbitrary choices. Although robotic surgery does not preclude all complications, the improvement in implant placement is nevertheless a useful way of minimising certain problems.

The benefits of using this tool should naturally be monitored regularly by checking the short-, mid- and long-term patient outcomes.

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