Computer-assisted total hip arthroplasty: the present and the future

Mahmoud A Hafez† & *Anthony M DiGioia III*

*†Author for correspondence
Institute for Computer Assisted Orthopaedic Surgery, Western Pennsylvania Hospital, Pittsburgh, PA 15224, USA
Tel.: +1 412 578 2267;
Fax: +1 412 605 6376;
mhafez@msn.com*

Computer technologies have revolutionized different aspects of medical practice and recently, computer-assisted orthopedic surgery (CAOS) has opened a new frontier in less invasive and more accurate surgical practice. This enabling technology has the ability to improve the accuracy and reproducibility of surgical techniques, allow new, demanding procedures that could not otherwise be performed, provide objective means with which to measure surgical performance and outcomes and supply powerful training tools. There are different modalities of CAOS, but navigation techniques are by far the most commonly used in clinical settings. Surgeons have used CAOS for total hip arthroplasty (THA) to plan precisely the alignment of the implants and provide exact real-time measurement during surgery. The capabilities of CAOS have also been coupled with the benefits of minimally invasive techniques in THA and resurfacing arthroplasty. Currently, the application of CAOS in THA is still in its infancy. However, future applications of CAOS may have a significant impact on clinical practice, similar to that of fiberoptic technology. This review outlines the scientific basis, state of the art applications and future perspective of CAOS in THA.

Keywords: accuracy, computer assisted, hip arthropathy, image-based, image-free, navigation, reproducibility, robotics, visualization

Definition & history

Computer-assisted orthopedic surgery (CAOS) can be defined as the use of computer-enabled technology at pre-, intra- and/or post-operative stages in the management of surgical conditions using active or passive systems and performed for several applications: planning, simulation, guidance, robotic, telesurgery and/or training [1].

Computer-assisted techniques first started in neurosurgery using the principles of stereotaxis, defined as the location of bodily structures using a fixed coordinate system. The application of stereotaxis was documented as early as 1906 [2]. However, CAOS was only developed following the advent of the computed tomography (CT) scan in the late 20th century and the subsequent introduction of position-tracking devices that allowed linking of the different steps of imaging, planning and surgical implementation, even when performed at different times.

The practical applications of CAOS in orthopedics began in the early 1990s using robotic techniques for femoral canal preparation in total hip arthroplasty (THA) [3]. The technical development gradually progressed from active robotics towards passive navigation systems. The earliest navigation systems were image based, using CT scans followed by systems that allowed navigation using intraoperative fluoroscopy or without any prior imaging (image free). The clinical applications of CAOS have expanded significantly in the field of arthroplasty, trauma and spinal surgery. CAOS has become an entity attracting multidisciplinary teams of surgeons, engineers and computer scientists.

Rationale for using computer-assisted surgery in total hip replacement

The development and application of a wide range of CAOS techniques could be attributed to the nature of the skeletal system, which is suited for CAOS having relatively nondeformable, readily imaged bony structures as compared with soft tissues. Orthopedic surgical procedures are reconstructive in nature and involve machinery actions such as cutting, drilling, reaming and fixation. The demand for a high degree of accuracy and reproducibility – that is not always met by conventional techniques – has paved the way for CAOS applications.

Total hip replacement (THR) is one of the most important orthopedic procedures of the last century. In the USA alone, there are more than 170,000 THA procedures performed every year and the rate is increasing steadily. It is a demanding procedure and technical errors can affect the function and the survival of the implants. Technical errors and outliers still occur and may jeopardize survival and function [4–6]. Malalignment of implants is the major contributing factor for dislocations [6,7]. In addition, malalignment of the acetabular component increases the occurrence of

Table 1. Classification of computer-assisted orthopedic surgery systems.

	Preoperative image	Intraoperative image	Image free
Active	Available*	Not available	In development#
Semi-active	Available‡	Not available	In development**
Passive	Available§	Available¶	Available‡‡

*Examples : * Active robots; ‡ Active constrained robots; § CT-based navigation and templating systems; ¶ Fluoro-based navigation systems; # Bone attached robots; ** Handheld robots; ‡‡ Image-free navigation systems. (Reproduced from [1]).*

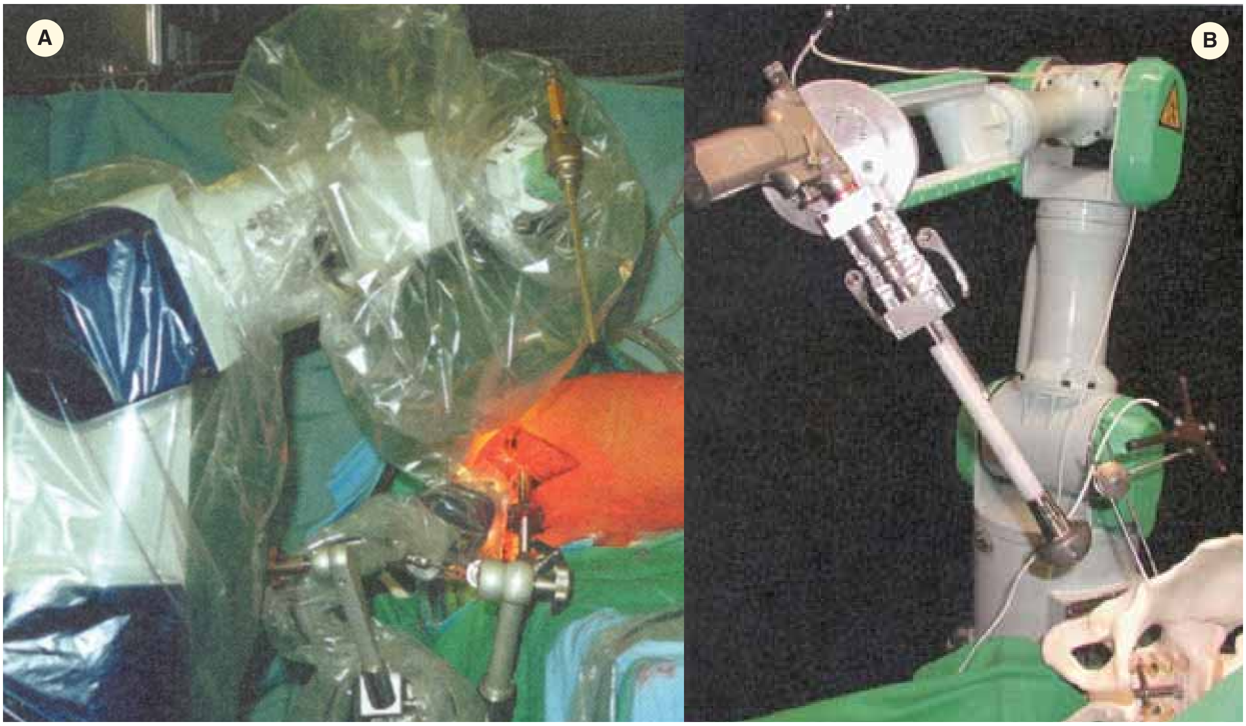
impingement and dislocation, which in turn reduces the range of motion and increases the risk of wear and failure.

Limitations of current techniques in THR

Current surgical techniques lack quantitative preoperative planning and sensitive tools to measure intraoperative surgical performance and the patients' outcome. Current techniques cannot link preoperative plans with the execution of the surgical task or link the surgical performance to postoperative outcome [8]. Conventional tools do not provide real-time feedback or accurate information during surgery.

Currently, surgeons rely on free-hand techniques or mechanical guides to align THA implants (the acetabular cup, in particular). However, these techniques have limited accuracy [5,9–13]. Saxler and colleagues assessed the accuracy of free-hand cup positioning in 105 THA procedures using a CT-based navigation system as a measurement tool [12]. Only 27 out of 105 THA procedures were positioned within the safe zone. Several authors have also reported the intraoperative motion of the pelvis as a possible cause for acetabular cup malalignment [4,13,14]. To date, standard tools are not capable of accurately measuring these variables during the actual procedure, and the accuracy of radiographic measurements of implant alignment is question-able [15,16]. Moreover, there is a trend toward less and minimally invasive surgical (MIS) techniques, making surgical procedures more challenging and subject to errors [17,18].

Figure 1. Photographs of robotic total hip arthroplasty technique (A) on a plastic bone and (B) on a patient.



Reproduced with kind permission from Springer Science and Business Media. In: *Navigation and Robotics in Total Joint and Spine Surgery* (1st Edition). Stiehl JB, Konermann WH, Haaker RG (Eds). Spinger, Berlin, Chapter 19 (Figure 7), 148, Chapter 23 (Figure 1), 169 (2004).

Figure 2. The use of a navigation system in total hip arthroplasty.

The introduction of new procedures (e.g., resurfacing arthroplasty) also brings higher demands for accuracy and skills.

There has been an increasing emphasis on the teaching and evaluation of technical skills, but traditional methods of training are currently unable to keep pace with new techniques [19].

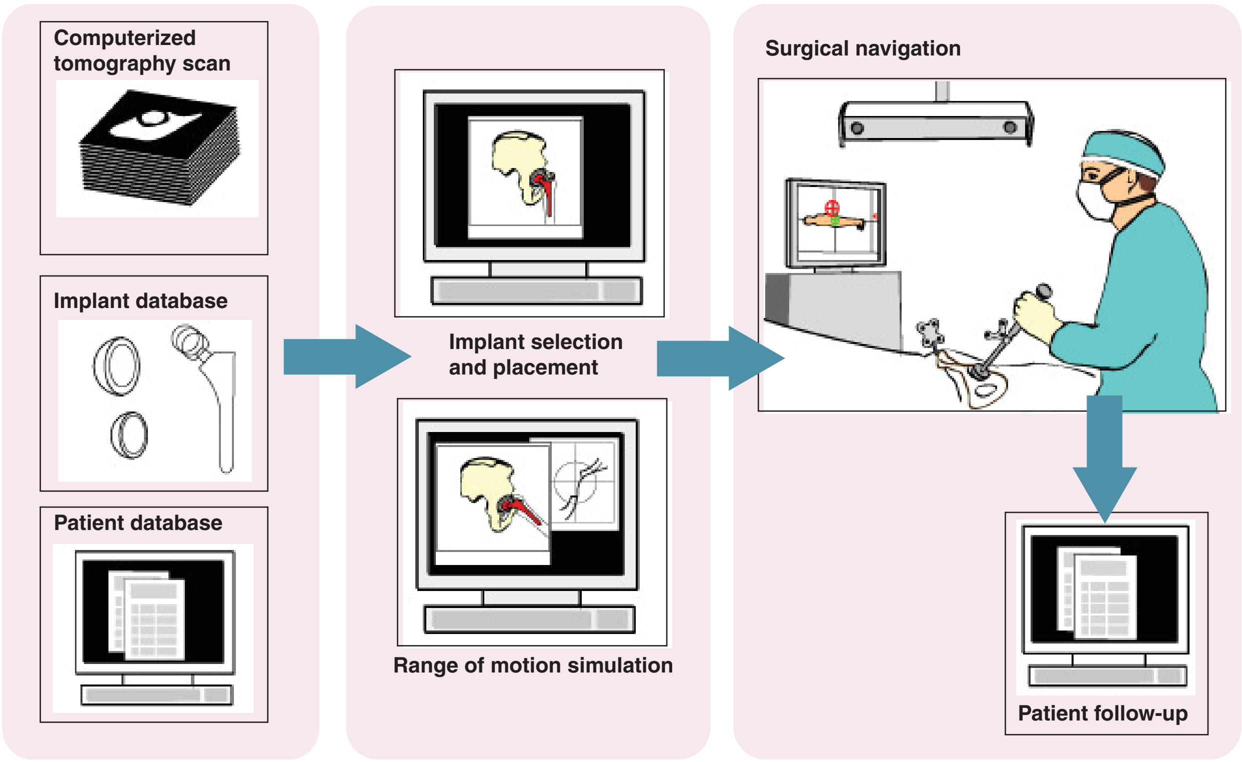
Types of CAOS systems

CAOS systems are classified in Table 1 according to their actions and the need for imaging [20].

Active systems (Figure 1) can perform a part or all of the surgical procedure. Robotic systems typically require preoperative CT scans and intraoperative registration to correlate the patients' anatomy with the preoperative images. Rigid fixation of the limb and the robot is also needed. Passive systems commonly refer to navigation techniques (Figures 2 & 3), but they also include another less common modality, 'patient-specific templating'. Navigation techniques do not perform surgical actions. They act primarily as intraoperative information systems, providing valuable feedback to surgeons with measurement and assessment of performance in real-time. Medical device agencies such as the US FDA are more inclined to approve passive rather than active systems. CT-based navigation systems are commonly used for spinal surgery and, occasionally, for arthroplasty. Fluoroscopy-based navigation systems are typically used in procedures that normally require fluoroscopy, such as trauma surgery. In addition to improving the accuracy of trauma procedures, there is the added advantage of reducing radiation exposure, which is on the rise [21]. Image-free navigation systems are most commonly used in clinical practice, particularly for total knee arthroplasty (TKA).

Patient-specific templating techniques using rapid prototyping (RP) technology are another passive modality of CAOS, but currently have limited applications. This technique allows 3D, CT-based preoperative planning and provides patient-specific templates that uniquely match the surface geometry of individual bony structures. There are few orthopedic applications of this technique in trauma surgery: pedicle screw insertion, acetabular osteotomy and TKA [22–24]. The technical differences between current CAOS systems are summarized in Table 2.

Figure 3. Schematic representation of an image-based navigation system.



Technical steps

The technical steps are variable, according to the system used and the type of procedure. There are four steps that are common to all types of navigation and robotic systems.

- Data (image) acquisition and planning can be either preoperative as in CT-based robotic and navigation systems (Figure 4), or intraoperative as in image-free or fluoro-based navigation systems. The surgeon can plan the procedure, simulate the surgery and evaluate the outcome. For image-free navigation, the data are collected intraoperatively by localizing certain landmarks and collecting points from the joint surfaces.
- Registration (Figure 5) was typically used for CT-based systems (robotic or image-based navigation) to relate the preoperative images to the patient's anatomy on the operating table. Surface registration is the gold standard, where the surgeon collects a cloud of points by touching the bone surfaces with a tracked probe. The unique shape of the bone then matches the preoperative image and planning to the position of the patient on the operating table. For image-free and fluoroscopy-based navigation, the registration process is atypical, owing to the lack of real images for the former and the intraoperative acquisition of images for the latter.
- Tracking (Figure 5) means real-time updates of the position and orientation of the bone, instruments and their movement. The tracking devices currently used are of the optical (active and passive) variety. Electromagnetic tracking has been introduced recently, but is still at the experimental stage. Clinically, it is easier to use as it requires no tracking camera or line of sight. The components of optical tracking are the tracking camera and the trackers, which need to be attached to instruments or guides and also to the bone. Trackers require rigid fixation to the bone through pins or clamps. The concepts of registration and tracking are similar to that of global positioning systems used in cars.
- The surgical action is either an active performance, as in the case of robotic surgery, or intraoperative measurement and feedback, as in the case of navigation techniques (Figure 6). Continuous and real-time information regarding the position of instruments and

implants is displayed on a monitor, allowing accurate performance and a reduction in the rate of outliers.

Clinical applications of CAOS in THR

The clinical application of CAOS in THA is confined currently to specialized centers and surgeons who are experienced in these techniques [9–11,13,25–30]. Even in these centers, the application of CAOS in THA may not be a routine procedure for every patient. Current CAOS systems involve longer operative times and introduce new equipment into the operating room (OR). As in conventional surgery, patient selection is very important. Patients with severe osteoporosis may not be suitable, as it is difficult to obtain rigid fixation of tracking pins in soft bones. It is also difficult to identify landmarks accurately in obese patients. The percentage of THA patients who are suitable for CAOS is variable, depending on the surgeon's experience, but is gradually increasing.

In THR, CAOS techniques allow surgeons to plan precisely the alignment of the acetabular and femoral components and to perform the surgery in accordance with the preoperative plan. Exact, real-time measurements provide the surgeon with valuable information, such as the degree of abduction and anteversion of the acetabular cup, the position of the stem and changes in leg length. The position of the pelvis is also computed to permit accurate measurements of the final position of the cup relative to the pelvis. DiGioia and colleagues reported the first clinical application of navigation techniques in THA [13]. Several authors have reported recently the use of different types of navigation techniques in THA; CT based [9,27,29,31,32], fluoroscopy based [26,27] and image free [11,25,28,30,33,34]. The results of these studies were encouraging and showed better accuracy of all navigation systems as compared with conventional techniques. They also showed the advantages and disadvantages of each technique. DiGioia and colleagues used a CT-based navigation system to evaluate the alignment accuracy of acetabular components, while using conventional mechanical guides, in 78 patients (82 hips) [5]. They found unacceptable acetabular alignment in 78% of hips. There were unpredictable and large variations in the initial position of patients' pelves on the operating room table and significant pelvic movement during surgery and the intraoperative range of motion testing. Jolles and colleagues assessed the alignment accuracy of 150 acetabular cups placed by ten surgeons on ten plastic models using the lateral position [10]. They found that the errors for the free-hand technique and mechanical guide were much higher than for the navigation technique. Nogler and colleagues found a more consistent and accurate placement of acetabular cup using image-free navigation techniques compared with mechanical guides [11]. Hube and colleagues compared two navigation systems; CT based (46 patients) and fluoroscopy based (107 patients) [27]. Both systems were found to be accurate, the CT-based

Table 2. Comparison between the currently available computer-assisted orthopedic surgery systems.

	Robotics	Navigation			Patient-specific templates
		Image-based CT	*Image-based fluoroscopy*	*Image free*	
Data source or imaging	Preop CT	Preop CT	Intraop x-ray	Intraop collection of kinematic and morphologic data	Preop CT
Planning	Preop 3D	Preop 3D	No preop planning but Intraop 2D assessment		Preop 3D
Spatial arrangement in OR	Robot, leg holder and clamps	Navigation cart, tracking devices			None
Registration & tracking	Registration ± tracking	Both required	Tracking + atypical registration		Not required
Intraop measurement & adjustment	No	Yes	Yes	Yes	No

CT: Computed tomography; Intraop: Intraoperative; OR: Operating room; Preop: Preoperative. (Reproduced from [1]).

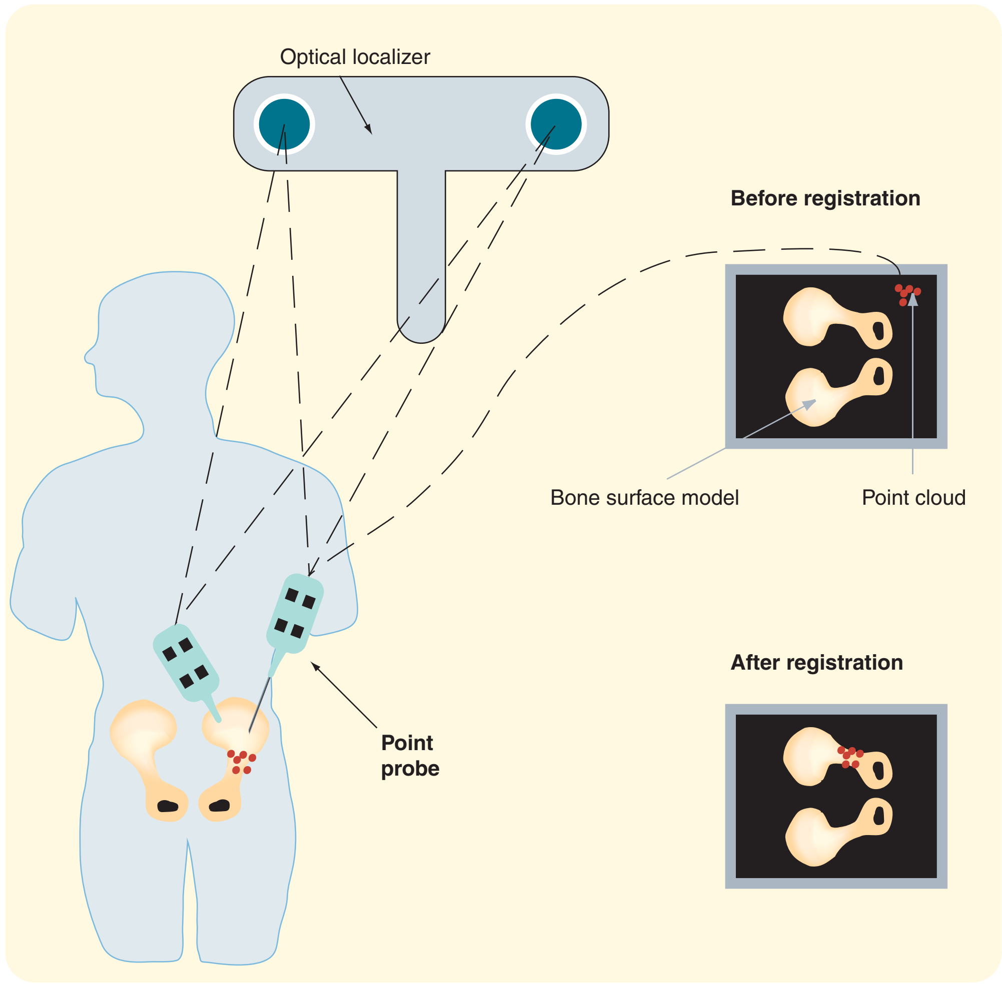
Figure 4. Computerized tomography-based preoperative planning of total hip arthroplasty allowing positioning of the femoral implant in 3D planes.

system was time consuming during preoperative planning, but it has the advantage of providing 3D anatomical feedback that is useful for cases of congenital or post-traumatic deformities. Image-free navigation techniques have the advantage of eliminating radiation exposure from CT or fluoroscopy but the accuracy of identifying landmarks, especially in obese patients, is questionable.

Seel and colleagues reported the use of CAOS techniques in planning revision surgery for recurrent dislocation [31]. The preoperative planner was used to guide the surgeon in adjusting the alignment of the acetabular component to avoid impingement and improve the stability of THR. They also used virtual x-ray (computer enhancement system) to accurately measure the alignment of the acetabular cup in 3D planes from postoperative x-rays. Barger and colleagues reported the early results of using robotic techniques in primary and revision THA that showed promising outcomes [35]. There are few reports in literature on the use of robotic techniques for THA with variable clinical outcomes [36–39]. Honl and colleagues conducted a randomized trial for 154 THA procedures, comparing conventional with robotic-assisted implantation using a Robodoc® system [38]. The robotic-assisted technology had advantages in terms of preoperative planning and the accuracy of the intraoperative procedure. Disadvantages were the high revision rate, the amount of muscle damage, which could be responsible for the higher dislocation rate, and the longer duration of surgery. They stated that this technology must be developed further before its widespread usage can be justified.

Currently, there is a growing enthusiasm among surgeons that the success of MIS in laparoscopy and arthroscopy could be transferred to joint replacement. Compared with conventional techniques, MIS has the potential to provide a better short-term outcome, with earlier recovery, shorter hospital stay and fewer short-term complications such as bleeding, stiffness and pain. The use of CAOS tools in MIS techniques may improve visualization and accuracy. There is a new trend of combining MIS with CAOS [17,18]. Few surgeons have applied this approach in hip and knee arthroplasty [18,30,40,41]. In a prospectively comparative trial, DiGioia and colleagues reported

Figure 5. Schematic of tracking and registration process.



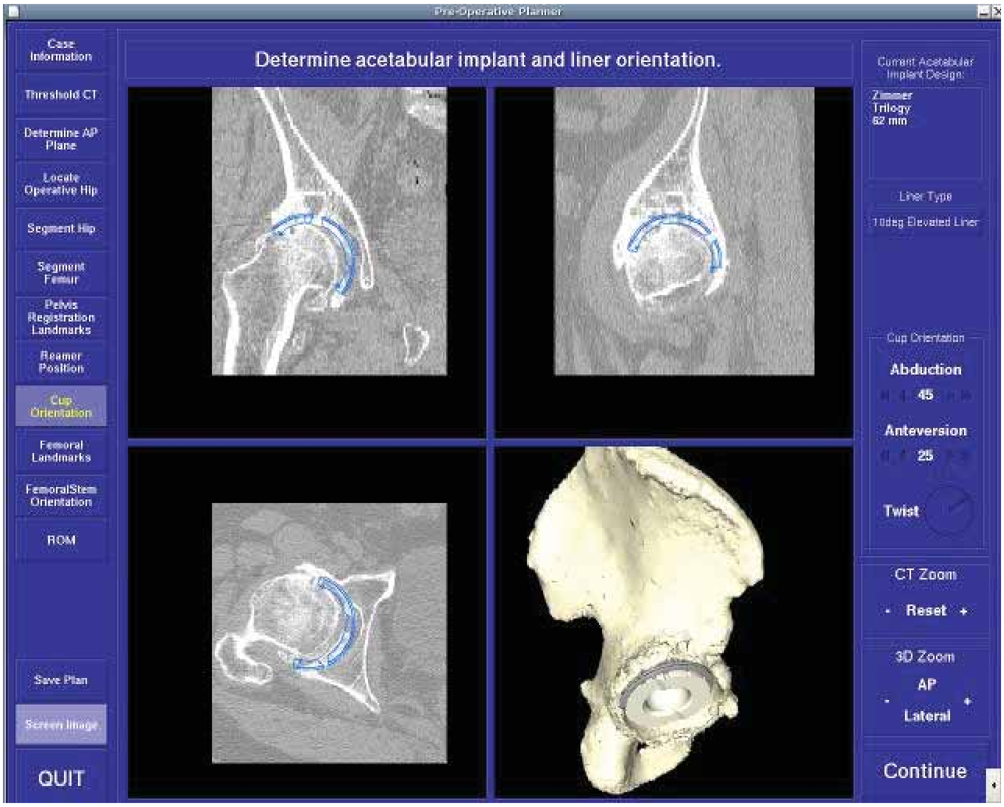
the results of using a navigation system in minimally invasive THR [18]. A total of 33 patients who had undergone a mini-incision THA were matched by diagnosis, gender, average age and preoperative Harris Hip Score (HHS) to 33 patients who had undergone THA using the traditional posterior approach. The trial showed better results for the combined approach of CAOS and MIS. At the 3-month follow-up, patients in the mini-incision group had improved significantly in limp ($p < 0.05$) and ability to climb stairs ($p < 0.01$) compared with the traditional group. At the 6-month follow-up, the mini-incision group was significantly better in terms of limp ($p < 0.05$), distance walked ($p < 0.001$) and stairs ($p < 0.001$). There was no significant difference between groups for pain, function or range of motion at the 1-year follow-up examination. Wixson and colleagues found more reproducible acetabular component placement in a series of 82 navigated THA procedures through a minimally invasive posterior approach, as compared with a cohort control of 50 conventional THR [30].

Similar to the use of surgical simulators in laparoscopic surgery, CAOS techniques can simulate surgical steps and provide more powerful training methods. They can permit real-time feedback and also allow errors to occur and be evaluated. Navigational techniques can be used as information systems for training workshops on sawbones and cadavers. Other modalities that can be used for training are augmented reality [42].

Limitations & drawbacks of CAOS

Although navigation and robotic technologies have been applied successfully to several procedures worldwide, universal acceptance has not been forthcoming. Inherent complexity, cost,

Figure 6. Intraoperative measurement and feedback to the surgeon.



Note the measurements of abduction and anteversion in the middle of the right column.

set-up time and learning curves dissuade many potential users. Current navigation techniques require the insertion of tracking targets or registration pins into bone, adding risk and extending OR time. Image-based systems may require preoperative CT or magnetic resonance imaging (MRI) scans or intraoperative x-rays, which are not part of the normal routine. There are potential pitfalls while using CAOS techniques. Errors may occur during different steps of the procedure, such as imaging, planning, data collection, tracking, registration and surgical performance [9,43–45]. Image-free navigation systems cannot determine whether the collected (input) data are correct or incorrect. This scenario can be summarized, as 'error in–error out', which is commonly referred to as 'garbage in–garbage out' [1].

Future perspective

CAOS technology is the 'surgical toolbox of the future'. In the short term, it is expected that navigation systems will be refined to be more user friendly, less expensive and have better functionality. Subsequently, more THA procedures will be performed using navigation techniques. Also, the future will reveal many promising technologies that are being investigated currently in research laboratories. Surgeons and engineers are striving to optimize current CAOS systems, introduce new technologies and broaden clinical indications. Eventually, these assisting technologies will permit the development of a new generation of surgical procedures that surgeons are not capable of performing today owing to surgical limitations. CAOS applications may have an impact on surgical practice similar to that of fiberoptic technology.

There is a trend to exploit other available imaging modalities, such as MRI and ultrasound (US). 3D fluoroscopy is a new imaging modality that can reconstruct 3D images from a series of 2D fluoroscopic views, with a reduced risk of radiation. New tracking devices are likely to appear in the near future that will replace or augment current optical trackers. Electromagnetic trackers have been already used in experimental settings, and appear to be more convenient than optical trackers as they do not require a tracking camera or line of sight. New CAOS systems have been developed and tested in laboratory settings but are awaiting clinical applications. The Precision Freehand Sculptor is a handheld robotic tool that has some features of navigation systems and may prove useful for minimally invasive procedures [46]. A bone-attached robotic system is being developed and tested for patellofemoral arthroplasty [47]. Patient-specific instrumentation is a new concept to produce templates (instruments) based on the patient's preoperative imaging. It has been used for TKA where it completely replaced conventional instrumentation [48]. Image overlay is a new technology that allows surgeons to visualize the patient's anatomy during surgery, without direct exposure, and to provide other supplementary information vital to the execution of operative procedures. This device has great promise for enabling various telemedicine applications. ORs need to be designed to accommodate different types of CAOS systems. Ergonomics should be

Executive summary

Limitations of current techniques for total hip arthroplasty

- No quantitative planning or sensitive tools to measure surgical performance and outcome.
- Cannot link preoperative plans with the execution of the surgical task or link the surgical performance to postoperative outcome. Implant malpositioning and dislocation still occur.

Definition of computer-assisted surgery

- The use of computer-enabled technology at any stage (pre-, intra- and post-operative) in the management of surgical conditions using various systems (active or passive) and applied to several applications (planning, simulation, guidance, robotic, telesurgery and/or training).

History of computer-assisted surgery

- Computer-assisted techniques first started in neurosurgery using the principles of stereotaxis.
- Currently, computer-assisted orthopedic surgery (CAOS) has become an entity that has expanded significantly in the last decade.

Rationale for using CAOS

- The skeletal system is suited for CAOS having nondeformable, readily imaged structures.
- Its surgical procedures are reconstructive, involving machinery actions such as cutting, drilling, reaming and fixation.
- The demand for a high degree of accuracy and reproducibility.
- The CAOS-enabling technology can allow more demanding procedures and better training.

Classification of CAOS

- CAOS is classified into active (robotics), semi-active and passive (navigation) systems.
- Based on the imaging requirements, the above systems are further classified into image based (preoperative or intraoperative) or image free.

Surgical techniques

- The technical steps are variable according to the system used and the type of the procedure.
- The common steps for navigation and robotics are: 1) Imaging (data collection) and planning; 2) Registration; 3) Tracking; 4) Intraoperative surgical actions and/or measurement.

Clinical applications of CAOS

- Navigation techniques are by far the most commonly used modality of CAOS.
- Unlike knee surgery, CAOS for total hip arthroplasty (THA) is still confined to specialized centers.
- Using CAOS, surgeons can measure precisely the acetabular alignment (abduction/anteversion), stem position and leg length in real time, thus improving accuracy and reproducibility.
- CAOS has also been used in minimally invasive THA and resurfacing arthroplasty.

Limitations & pitfalls of CAOS

- Inherent complexity, cost, set-up time and long learning curve dissuade many potential users.
- Potential pitfalls and errors may occur during different steps of CAOS, such as imaging, planning, data collection, tracking, registration and surgical performance.

Conclusion

- CAOS is an enabling technology that can improve accuracy and reproducibility.
- CAOS may allow new, demanding procedures that could not otherwise be performed.
- Wider acceptance of CAOS depends on the ease of use and cost effectiveness of the systems.

optimized. The environment should allow the integration of pre- or peri-operative imaging and planning with the surgical performance and facilitate training and telesurgery.

Conclusion

CAOS is an enabling technology that may have a significant impact on the outcome of surgical practice. There are several systems in current clinical use including robotics, navigation and templating techniques. CAOS tools can enable more accurate and less invasive surgical techniques. They can be used as the surgical trainers of the future, by coupling simulations with real-time evaluations of surgical performance. CAOS can also 'close the loop' in surgical practice by measuring and relating surgical techniques directly to patient outcomes. Currently, the application of CAOS in THA is still confined to experienced surgeons in specialized centers. The broad application is limited by complexity, cost, setting-up time and a long learning curve. CAOS systems need to be validated and standardized. Surgeons should be aware of the potential errors and pitfalls during clinical applications of these systems. Structured training should be available to surgeons before leaping to clinical practice. Improvements in clinical outcome have to be documented and cost effectiveness has to be analyzed before the standardization of such systems. The technology and approaches are evolving and the future will bring new CAOS systems that could be widely accepted.

Bibliography

Papers of special note have been highlighted as either of interest (•) or of considerable interest (••) to readers.

1. Hafez MA, Jaramaz B, DiGioia AM III: Computer assisted knee surgery: an overview. In: *Surgery of the Knee (4th Edition).* Insall JN, Scott N (Eds). Churchill Livingston, PA, USA, 1655–1674 (2006).
• Provides useful information on computer-assisted orthopedic surgery (CAOS).
2. Clarke RH, Horsley V: On a method of investigating the deep ganglia and tracts of the central nervous system (cerebellum). *Br. Med. J.* 2, 1799–1800 (1906).
•• Of historical importance (pioneered techniques).
3. Paul HA, Bargar WL, Mittlestadt B *et al.*: Development of a surgical robot for cementless total hip arthroplasty. *Clin. Orthop. Relat. Res.* 285, 57–66 (1992).
•• Of historical importance (pioneered techniques).
4. Asayama I, Akiyoshi Y, Naito M, Ezoe M: Intraoperative pelvic motion in total hip arthroplasty. *J. Arthroplasty* 19(8), 992–997 (2004).
5. DiGioia AM 3rd, Jaramaz B, Plakseychuk AY *et al.*: Comparison of a mechanical acetabular alignment guide with computer placement of the socket. *J. Arthroplasty* 17(3), 359–364 (2002).
• Comparative or randomized controlled trial (RCT) study.
6. Homesley HD, Minnich JM, Parvizi J *et al.*: Total hip arthroplasty revision: a decade of change. *Am. J. Orthopedics* 33, 389–391 (2004).
7. Morrey BF: Instability after total hip arthroplasty. *Orthop. Clin. North Am.* 23, 237–248 (1992).
8. DiGioia AM III, Jaramaz B: Computer-assisted tools and interventional technologies. *Lancet* 354(Suppl. SIV46) (1999).
9. Amiot LP, Poulin F: Computed tomography-based navigation for hip, knee and spine surgery. *Clin. Orthop. Relat. Res.* 421, 77–86 (2004).
10. Jolles BM, Genoud P, Hoffmeyer P: Computer-assisted cup placement techniques in THA improve accuracy of placement. *Clin. Orthop. Relat. Res.* 426, 174–179 (2004).
11. Nogler M, Kessler O, Prassl A *et al.*: Reduced variability of acetabular cup positioning with use of an imageless navigation system. *Clin. Orthop. Relat. Res.* 426, 159–163 (2004).
• Comparative or RCT study.
12. Saxler G, Marx A, Vandevelde D *et al.*: The accuracy of free-hand cup positioning – a CT based measurement of cup placement in 105 THAs. *Int. Orthop.* 28(4), 198–201 (2004).
13. DiGioia AM, Jaramaz B, Blackwell M: The Otto Aufranc Award. Image guided navigation system to measure intraoperatively acetabular implant alignment. *Clin. Orthop. Relat. Res.* 355, 8–22 (1998).
•• Landmark paper in hip CAOS.
14. Jaramaz B, DiGioia AM 3rd, Blackwell M, Nikou C: Computer assisted measurement of cup placement in total hip replacement. *Clin. Orthop. Relat. Res.* 354, 70–81 (1998).
15. Eddine TA, Migaud H, Chantelot C, Cotton A, Fontaine C, Duquennoy A: Variations of pelvic anteversion in the lying and standing positions: analysis of 24 control subjects and implications for CT measurement of position of a prosthetic cup. *Surg. Radiol. Anat.* 23, 105–110 (2001).
16. Jaramaz B, Nikou C, DiGioia AM III, Aston C: Inherent inaccuracies of conventional radiographic measurements of cup orientation. *Trans. Orthop. Res. Soc.* 24, 925 (1999).
17. DiGioia AM 3rd, Blendea S, Jaramaz B, Levison TJ: Less invasive total hip arthroplasty using navigational tools. *Instr. Course Lect.* 53, 57–64 (2004).
18. DiGioia AM 3rd, Plakseychuk AY, Levison TJ, Jaramaz B: Mini-incision technique for total hip arthroplasty with navigation. *J. Arthroplasty* 18(2), 123–128 (2003).
•• Of historical importance (pioneered techniques).
19. Kohls-Gatzoulis JA, Regehr G, Hutchison C: Teaching cognitive skills improves learning in surgical skills courses: a blinded, prospective, randomised study. *Can. J. Surg.* 47, 277–283 (2004).
20. Picard F, Moody JE, DiGioia AM 3rd *et al.*: Clinical classification of CAOS systems. In: *Computer and Robotic Assisted Knee and Hip Surgery.* DiGioia AM, Jaramaz B, Picard F, Notle L (Eds), Oxford University Press, Oxford, UK, 43–48 (2004).
21. Hafez MA, Smith RM, Matthews S *et al.*: Radiation exposure to the hands of orthopaedic surgeons: are we underestimating the risk? *Arch. Orthop. Trauma Surg.* 125, 330–335 (2005).
22. Brown GA, Firoozbakhsh K, DeCoster TA *et al.*: Rapid prototyping: the future of trauma surgery. *J. Bone Joint Surg. Am.* 85(Suppl. 4), 49–55 (2003).

23. Hafez MA, Chelule KL, Seedhom BB, Sherman KP: Computer assisted total knee replacement: could a two-piece custom template replace the complex conventional instrumentation. *Comp. Aided Surg.* 9, 93–94 (2004).
24. Radermacher K, Portheine F, Anton M *et al.*: Computer assisted orthopaedic surgery with image-based individual templates. *Clin. Orthop.* 354, 28–38 (1998).
25. Dorr LD, Hishiki Y, Wan Z, Newton D, Yun A: Development of imageless computer navigation for acetabular component position in total hip replacement. *Iowa Orthop. J.* 25, 1–9 (2005).
26. Grutzner PA, Zheng G, Langlotz U *et al.*: C-arm based navigation in total hip arthroplasty-background and clinical experience. *Injury* 35(Suppl. 1), S–A90–5 (2004).
27. Hube R, Birke A, Hein W, Klima S: CT-based and fluoroscopy-based navigation for cup implantation in total hip arthroplasty (THA). *Surg. Technol. Int.* 11, 275–280 (2003).
• Comparative or RCT study.
28. Kiefer H: OrthoPilot cup navigation – how to optimise cup positioning? *Int. Orthop.* 27(Suppl. 1), S37–S42 (2003).
29. Leenders T, Vandevelde D, Mahieu G, Nuyts R: Reduction in variability of acetabular cup abduction using computer assisted surgery: a prospective and randomized study. *Comp. Aided Surg.* 7(2), 99–106 (2002).
• Comparative or RCT study.
30. Wixson RL, Macdonald MA: Total hip arthroplasty through a minimal posterior approach using imageless computer-assisted hip navigation. *J. Arthroplasty* 20(7 Suppl. 3), 51–56 (2005).
• Comparative or RCT study.
31. Seel MJ, Hafez MA, Eckman K, Jaramaz B, Davidson D, DiGioia AM 3rd: 3D planning and virtual x-ray in revision hip arthroplasty for instability: a case study and future directions. *Clin. Orthop. Relat. Res.* In press, Jan (2006).
32. Widmer KH, Grutzner PA: Joint replacement – total hip replacement with CT-based navigation. *Injury* 35(Suppl. 1), S-A84–9 (2004).
33. Wentzensen A, Zheng G, Vock B *et al.*: Image-based hip navigation. *Int. Orthop.* 27(Suppl. 1), S43–S46 (2003).
34. Zheng G, Marx A, Langlotz U, Widmer KH, Buttaro M, Nolte LP: A hybrid CT-free navigation system for total hip arthroplasty. *Comp. Aided Surg.* 7(3), 129–145 (2002).
35. Bargar WL, Bauer A, Borner M: Primary and revision total hip replacement using the Robodoc system. *Clin. Orthop.* 354, 82–91 (1998).
• Landmark paper in hip CAOS.
36. Adili A: Robot-assisted orthopedic surgery. *Semin. Laparosc. Surg.* 11(2), 89–98 (2004).
37. Bach CM, Winter P, Nogler M, Gobel G, Wimmer C, Ogon M: No functional impairment after Robodoc total hip arthroplasty: gait analysis in 25 patients. *Acta Orthop. Scand.* 73(4), 86–91 (2002).
38. Honl M, Dierk O, Gauck C *et al.*: Comparison of robotic-assisted and manual implantation of a primary total hip replacement. A prospective study. *J. Bone Joint Surg. Am.* 85(8), 1470–1478 (2003).
• A comparative or RCT study.
39. Nogler M, Polikeit A, Wimmer C, Bruckner A, Ferguson SJ, Krismer M: Primary stability of a Robodoc implanted anatomical stem versus manual implantation. *Clin. Biomech.* 19(2), 123–129 (2004).
40. Perlick L, Bathis H, Tingart M *et al.*: Minimally invasive unicompartmental knee replacement with a nonimage-based navigation system. *Int. Orthop.* 28, 193–197 (2004).
41. Stulberg SD: The rationale for using computer navigation with minimally invasive THA. *Orthopedics* 27, 942–946 (2004).
42. Blackwell M, Morgan F, DiGioia AM 3rd: Augmented reality and its future in orthopaedics. *Clin. Orthop.* 354, 111–122 (1998).
43. Li Q, Zamorano L, Jiang Z *et al.*: Effect of optical digitizer selection on the application accuracy of a surgical localization system – a quantitative comparison between the OPTOTRAK and flashpoint tracking systems. *Comp. Aided Surg.* 4, 314–321 (1999).
44. Sugano N, Sasama T, Sato Y *et al.*: Accuracy evaluation of surface-based registration methods in a computer navigation system for hip surgery performed through a posterolateral approach. *Comp. Aided Surg.* 6, 195–203 (2001).
45. Wagner A, Schicho K, Birkfellner W *et al.*: Quantitative analysis of factors affecting intraoperative precision and stability of optoelectronic and electromagnetic tracking systems. *Med. Phys.* 29, 905–912 (2002).
46. Brisson G, Kanade T, DiGioia III *et al.*: Precision handheld sculpting of bone. In: *Computer Assisted Orthopaedic Surgery. 3rd Annual Meeting of CAOS-International Proceedings, Spain.* Langlotz F, Davies BL, Bauer A (Eds), Steinkopff Darmstadt, Heidelberg, Germany 36–37 (2003).
47. Wolf A, Jaramaz B, Lisien B *et al.*: MBARS: mini bone attached robotic system for joint arthroplasty. *Int. J. Med. Robot. Comp. Assis. Surg.* 1, 101–121 (2005).
48. Hafez MA, Chelule KL, Seedhom BB, Sherman KP: Computer assisted total knee arthroplasty using patient-specific templating. *Clin. Orthop. Relat. Res.* In press (2006).

Affiliations

- *Mahmoud A Hafez, MD, FRCS*
  Institute for Computer Assisted Orthopaedic Surgery, Western Pennsylvania Hospital, Pittsburgh, PA 15224, USA
  Tel.: +1 412 578 2267;
  Fax: +1 412 605 6376;
  mhafez@msn.com
- *Anthony M DiGioia III, MD*
  Institute for Computer Assisted Orthopaedic Surgery, Western Pennsylvania Hospital, Pittsburgh, PA 15224, USA