The International Journal of Medical Robotics and Computer Assisted Surgery

Review: Current Concepts in Computer-assisted Hip Arthroscopy

Journal:	*The International Journal of Medical Robotics and Computer Assisted Surgery*
Manuscript ID	RCS-18-0016.R1
Wiley - Manuscript type:	Review Article
Date Submitted by the Author:	n/a
Complete List of Authors:	Nakano, Naoki; Addenbrooke's Hospital, Department of Trauma & Orthopaedic Surgery Ranawat, Anil; Hospital for Special Surgery Audenaert, Emmanuel; Ghent University, Orthopaedic Surgery Khanduja, Vikas; Addenbrooke's - Cambridge University Hospital, Department of Trauma & Orthopaedic Surgery
Anatomy Keywords:	joints
Operation Keywords:	
Speciality Keywords:	orthopaedic
Technology Keywords:	computer assisted surgery
Additional Keywords:	
Abstract:	In the last 15 years, hip arthroscopy has become more popular in addressing femoroacetabular impingement (FAI) because of its minimally invasive approach. However, assessing the adequacy of bone resection when correcting FAI can be difficult because the visualisation and spatial awareness of the joint are poor. The recent development of technology in the field of computer-assisted/ navigation and robotic surgery in orthopaedics as a resource for preoperative planning and intraoperative assistance has been widely reported. As this technology is expected to upgrade surgical planning and techniques, decrease human error and improve operative results by precisely defining the divergent anatomy and kinematics of the hip joint, they could also prove beneficial in the field of arthroscopic FAI surgery. This review attempts to bring the reader up-to-date with the current developments in the field, discuss our experience with navigation and robotics and provide a platform for future research in this arena.

Review

Title: Review: Current Concept in Computer-assisted Hip Arthroscopy

Running Head: Computer-assisted Hip Arthroscopy

Authors
Naoki Nakano[1], Emmanuel Audenaert[2], Anil Ranawat[3], Vikas Khanduja[1]

Institution
[1] Department of Trauma and Orthopaedics, Addenbrooke's Hospital, Cambridge University Hospitals NHS Foundation Trust, Cambridge, UK
[2] Department of Orthopaedic Surgery and Traumatology, Ghent University Hospital, Ghent, Belgium
[3] Department of Orthopaedics, Hospital for Special Surgery, New York, USA

The work was conducted in:
Department of Trauma and Orthopaedics, Addenbrooke's Hospital, Cambridge University Hospitals NHS Foundation Trust

Corresponding Author
Mr. Vikas Khanduja MA (Cantab), MSc, FRCS (Tr & Orth)
Consultant Orthopaedic Surgeon & Associate Lecturer
Department of Trauma and Orthopaedics,
Addenbrooke's - Cambridge University Hospitals NHS Foundation Trust
Box 37, Hills Road, Cambridge, CB2 0QQ.
Tel: +44 (0) 1223 257 093
Fax: +44 (0) 1223 317 207
Email: vk279@cam.ac.uk

Key Words: computer-assisted surgery; navigation; arthroscopy; hip; review

Source of Funding: Nil
Word counts: 4,015 (From Abstract to Conclusion)
Number of figures: 2
Number of tables: 0

Abstract

In the last 15 years, hip arthroscopy has become more popular in addressing femoroacetabular impingement (FAI) because of its minimally invasive approach. However, assessing the adequacy of bone resection when correcting FAI can be difficult because the visualisation and spatial awareness of the joint are poor. The recent development of technology in the field of computer-assisted/ navigation and robotic surgery in orthopaedics as a resource for preoperative planning and intraoperative assistance has been widely reported. As this technology is expected to upgrade surgical planning and techniques, decrease human error and improve operative results by precisely defining the divergent anatomy and kinematics of the hip joint, they could also prove beneficial in the field of arthroscopic FAI surgery. This review attempts to bring the reader up-to-date with the current developments in the field, discuss our experiences with navigation and robotics and provide a platform for future research in this arena.

Introduction

Femoroacetabular impingement (FAI) occurs when the hip joint has an abnormal shape at the femoral head-neck junction (cam-type) or at the acetabular rim of the pelvis (pincer-type). It has been recognised as a major risk factor that may lead to the development of early labral and cartilage damage in the non-dysplastic hip (1-4). Several clinical studies have shown that surgical correction of these osseous abnormalities improves clinical function and relieves hip pain (3,5-7). However, in patients with FAI, due to the complex 3D shape of the offending lesion and the large soft-tissue mantle around the hip joint, the arthroscopic view of the working area can be restricted (8). In addition, evaluation of the sphericity of the femoral head in the treatment of cam-type FAI during hip arthroscopy is difficult (9,10); it is usually done by means of surgical templates (femoral spherometer gauges) during open surgical dislocation.

Recently, computer-assisted navigation and modelling have emerged as a potential solution to improve the preoperative planning for FAI, including determination of the location and size of pincer/cam lesions, as well as to increase the accuracy of intraoperative correction of the osseous deformity. In this review, we will firstly outline the recent developments of computer-assisted surgery in orthopaedics, the anatomy of FAI and the current limitations of arthroscopic FAI surgery. We will then describe the evolution of computer-assisted hip arthroscopy to address these limitations, which is divided into two parts; preoperative planning/assessment tools and intraoperative navigation programmes. Lastly, the future of robot-assisted hip arthroscopy is discussed. The aim of this review is to outline the current conditions and challenges in computer-assisted arthroscopic FAI surgery.

1. Computer-assisted surgery in orthopaedics

The purpose of computer-assisted technology in orthopaedics is to provide patient-specific tools that allow for the reliable implementation of preoperative surgical plans in the operating theatre (11). The ideal goal of this technology would be to integrate high-precision preoperative surgical plans based on prior CT or MRI with actual surgical treatment procedures, by accurate placement of operative tools with quantitative feedback to assess the execution of the surgical plan.

These days, there is little doubt that computer-assisted surgery produces more accurate and precise results, and reduces the learning curve in some types of orthopaedic surgeries, including lower limb joint replacement (total hip replacement and total/unicondylar knee replacement), anterior cruciate ligament reconstruction and trauma and spine surgery (12-16). However, there have not been enough data to support improved outcomes after these navigated operations thus far. For example, although navigated total knee replacement is one of the most popular applications of computer-assisted technology in orthopaedics, no study has been available to validate this technology and prove its long-term benefits (17). Also, while navigation technology has been reported to improve the positioning of components in unicondylar knee replacement and the acetabular cup positioning in total hip replacement, the assumed benefits of technical precision and reproducibility have not to be correlated with better objective and subjective clinical outcomes yet (14,18). The cost of these systems and the learning curve associated with these new technologies should also be solved before extended application.

2. Pathoanatomy of FAI

The term 'femoroacetabular impingement' was first used in English-language literature in 1999 (19). By definition, FAI is a result of bone abutment of the femoral neck and the acetabulum. Though two distinct types of FAI have been recognised (cam and pincer), most patients present with clinical and radiographic findings which relate to both deformities. Cam impingement refers to a decrease in the femoral head-neck offset, in other words, asphericity of the femoral head-neck junction, which causes a prominent osseous lesion that impinges on the acetabulum. The location of impingement is unique and defined by the proximal-distal, medial-lateral and circumferential margins of the loss of offset; most cam legions impinge with flexion, adduction and internal rotation of the hip. On the other hand, focal pincer impingement lesions cause abnormal edge-loading of the acetabular rim, and it can occur with focal or global acetabular retroversion, coxa profunda or protrusion acetabuli (20,21).

It is widely believed that the onset of osteoarthritis (OA) relates to the local mechanical environment of a joint (22,23). In terms of the hip, cam-type FAI is recognised as an early cause of joint dysfunction, including pain generation, degeneration and tearing of the labrum which leads to OA (20,24-27). In the patient with FAI, characteristic injury to the labrum and cartilage has been observed, and it is thought to reflect repetitive micro-trauma from the abnormal osseous morphology. The labrum has several functions, such as hip stability, cartilage nutrition, augmentation of femoral head coverage and a so-called joint sealing effect (28,29). The labrum is often the first structure to be affected by pincer impingement due to mechanical impingement between the femoral neck bone and acetabulum with subsequent degeneration or ossification. In contrast, in typical cam impingement, there is early delamination of the cartilage with labral degeneration and detachment over time, as a result of chronic repetitive stress (1).

In the surgical management of FAI, both open and arthroscopic approaches can be used. As an open technique, open surgical dislocation of the hip was described to minimise iatrogenic injury to the articular surface and obtain a wide view of the hip joint safely (30). It is, however, not without risks, including non-union after trochanteric osteotomy, avascular necrosis due to disruption of femoral head blood supply and increased morbidity with a large amount of soft tissue dissection (31). Based on this, hip arthroscopy has evolved to correct osseous morphology which causes impingement, as well as treat both chondral and labral lesions in a minimally invasive manner (32-34). Several authors have reported on arthroscopic treatments for FAI-related pathology with favourable clinical outcomes (32,35-37), but there have been no long-term outcomes. Systematic reviews assessing differences in outcomes between the arthroscopic and open treatment of FAI have also been reported (34,38), and they have concluded that open techniques to address FAI and labral tears are not superior to arthroscopic methods.

3. Current limitations of hip arthroscopy for FAI

As our understanding of FAI continues to improve, there is an increased interest in computer-assisted planning and navigation to treat abnormalities associated with FAI. The current limitations of arthroscopic FAI surgery can be divided into two perspectives: preoperative assessment and intraoperative execution. While the long-term clinical outcome may be multifactorial, a reproducible and accurate surgical correction of the deformity may be one of the few variables with FAI which is surgeon-controlled. Therefore, the challenges of preoperative characterisation of the mechanical deformities, as well as the difficulties in intraoperative exposure and correction of impingement regions, make computer-assisted surgical technologies particularly useful.

Preoperative planning

Preoperative assessment tools, which include imaging modalities such as radiography and CT and MRI scanning, are all aimed at providing the surgeon with a patient-specific reconstruction of the osseous anatomy as well as a proper diagnosis. Currently, preoperative planning for arthroscopic FAI is based on these static anatomical models which characterise cam and pincer lesions. It is important to recognise the osseous anatomical anomalies when planning arthroscopic FAI surgery; in a recent CT-beased study Dolan et al (39) reported that 90% of patients with symptomatic labral tears had structural abnormalities, such as femoral retroversion or excessive anteversion, coxa valga or acetabular dysplasia which includes lateral and/or anterior under-coverage.

Today, the alpha angle is the most used tool for the anatomical surgical planning of FAI. Alpha angle is defined by the axis of the femoral neck and a line connecting the centre of the femoral head to the anterior extent of the concavity of the femoral neck in an MRI slice which is parallel to the axis of the neck and passing through the centre of the femoral head (40). Usually, an alpha angle < 50°, or a reduction of the alpha angle by 20° (in cases where the alpha angle is very large) is recommended as a target for surgical correction, because this would result in satisfactory restoration of femoral head-neck offset (41). The alpha angle has also been shown to correlate with increased chondral damage, labral injury, decreased range of movement (ROM) and other preoperative symptoms (42,43). It is also useful in assessing surgical correction postoperatively (44). There are, however, some drawbacks to using the alpha angle as a tool. First, as the maximal loss of the head-neck offset is present at different locations in different patients (45). 2D measurement is not enough to assess the anatomical variances. Secondly, it does not take the length of the cam lesion into account. The resection should be advanced into the trochanteric fossa in the case of a large bump. Thirdly, the alpha angle does not always correlate with the clinical ROM. Brunner et al(46) reported that cam-type FAI patients with insufficient offset correction showed a slightly better internal rotation than patients with satisfactory offset restoration. Lastly, a pathological value of the alpha angle itself has been questioned. Clohisy et al (47) could not define an alpha angle threshold beyond which a pathological diagnosis could be made after evaluating the alpha angle in both FAI patients and normal controls.

Intraoperative execution

The learning curve associated with arthroscopic FAI surgery is often referred to as 'steep' (48,49). It is often difficult to undertake a preoperative plan correctly, as it requires not only a high level of arthroscopic skill and good visualisation but also precise identification of the margins of the osseous bump lesion and a proper decision on the amount of bone resection. Even in the hands of experienced hip arthroscopy surgeons, who have achieved adequate exposure, the margins of the impingement lesion are not always obvious. Patient positioning, cannulation, visualisation and osseous resection are all factors which could lead to potential technical errors.

Hip arthroscopy surgeons usually combine arthroscopic appearance with fluoroscopy to perform an intraoperative assessment of an adequate resection. The problem with this method is that both of them are a 2D modality and the 3D morphology is, therefore, constructed only in the surgeon's brain without any objective assessment. Osseous abnormalities are often under-resected, and this is a major cause for revision hip arthroscopy, accounting for up to 78% to 90% of all unsuccessful arthroscopic FAI surgery (50,51). It is common for inexperienced surgeons to stop the osseous resection once an adequate image is obtained on fluoroscopy but some cam lesions extend posteriorly or distally and further internal rotation or an accessory portal may show an inadequate resection. Surgeons should bear over-resection of the bone in mind as well. Over-resection of a pincer lesion can result in iatrogenic dysplasia due to acetabular under-coverage, and postoperative instability and dislocation have been reported to be linked to over-resection (52,53). Over-resection beyond the margins of a cam lesion can damage the cortical bone support of the femoral neck, which may lead to iatrogenic fracture (54). Moreover, in the posterolateral part of the proximal femur, the blood supply to the epiphysis can be damaged by excessive reaming, leading to avascular necrosis (55). These problems reinforce the need for computer-navigated surgical tools which guide surgeons sufficiently during the operation.

4. Current navigation technology

Preoperative computer aided assessment

When assessing the deformity and planning for surgical correction preoperatively, dynamic manipulation of the image using applied algorithms or computer software as well as virtual 3D reconstruction and visualisation of the hip joint may be beneficial for surgeons.

Some non-invasive preoperative software programmes which help surgeons localise the zone of impingement, quantify the volume of resection and predict postoperative ROM using both anatomical and kinematic data have been reported on.

- The first comprehensive preoperative assessment tools ('HipMotion') were developed by Tannast et al (56) in 2007. The system performs a CT-based 3D kinematics analysis of the hip joint to define zones of impingement and then predict improvement in ROM after a virtual resection. It was made to address the need for an accurate kinematic preoperative plan and enhanced visual guidance to the surgeon. The native preoperative ROM is calculated by collision algorithms which determine ROM based on points at which impingement occurs after defining the hip centre. Then, the system performs a virtual surgical femoral and acetabular resection which prevents an impingement within normal physiological ROM. After that, using the new parameters, virtual postoperative ROM is simulated by reconstructing the hip joint to assess the efficacy of the planned procedure (57). They used concentric range of motion simulation and did not take any hip translations at the end of range of motion into account. The system offers the advantage of calculating the volume of resection based on an impingement-free postoperative ROM, not a desirable postoperative alpha angle. Validation of this software was performed by comparing the virtually predicted ROM with the actual measured ROM of cadaveric hips. Authors also compared the virtual ROM of normal hips with FAI hips and reported that patients with FAI had significantly decreased flexion, internal rotation at 90° of flexion and abduction (56).

- Using the 3D software 'Mimics' (Materialise, Belgium) to analyse 13 hips with cam-type impingement, Audenaert et al (58,59) reported that during internal rotation in 90° of flexion, the central-medial portion of the cam lesion was found to abut against the anterosuperior quadrant of the acetabular cartilage.

Bedi et al (60) measured clinical ROM and calculated virtual ROM using Mimics in FAI patients before and after arthroscopy, and reported excellent correlation in the postoperative improvement between clinical ROM and virtual ROM, with no significant differences by paired Student's *t*-tests. Mimics is a segmentation software package and does not allow virtual range of motion simulation. Both Audenaert et al and Bedi et al used dedicated software scripts to perform the motion simulation and calculated zones of impingement, and bony shapes were segmented from the CT scan with the Mimics software.

- 'Articulis' (Clinical Graphics, Netherlands) is also a software which automatically performs the 3D segmentation of the CT scans, assesses the deformity, plans for surgical correction and carries out dynamic manipulation of the image. The reliability and accuracy of this system in determining the presence of movement limiting deformities of the femoroacetabulum was validated using a cadaveric model with artificial cam deformities (Figure 1) (61).
- The 'Dyonics PLAN Hip Impingement Planning System' (Smith & Nephew, USA) provides not only a virtual 3D reconstruction and visualisation of the hip joint but also a platform for intraoperative assistance by performing virtual correction and creating a virtual fluoroscopic image that can be compared with

intraoperative fluoroscopic images, thus verifying adequate bony resection. Milone et al (62) demonstrated the effectiveness of this software compared with traditionally reformatted CT scans and plain radiographs.

They can also be used postoperatively for the assessment of the amount of osseous shaving in the cam or pincer lesions.

There are, however, some limitations to the use of these systems. The data are based on a predefined centre of rotation around which the femoral head moves, and they therefore ignore additional translations or detected collisions. Stated another way, the software does not account for the translation which occurs with hip movement, weight-bearing and muscular activation (63). Furthermore, the CT-based model only allows for osseous impingement and its surgical correction with an osteoplasty of the acetabular and femoral bone. It does not account for impingement of periarticular soft tissues such as labrum. Soft-tissue laxity or impingement can affect ROM and clinical outcomes after surgical intervention. Therefore, these systems may overestimate the potential gains in movement that can be achieved after surgery. In addition, there have been no comparative trials to date determining the superiority of using these systems in the clinical setting.

Intraoperative navigation

Navigation programmes guide the surgeon to precisely reproduce preoperative plans intraoperatively. The components of these types of navigation systems generally consist of these three parts:

- Measurement devices to trace the surgical tool;
- display device to show information about the surgery;
- marker on the surgical tool.

Intraoperative navigation requires matching the preoperative 3D-CT scan to the intraoperative situation. This registration process to establish correspondence between both situations can be image-based (using fluoroscopy) or imageless (using a digitised pointer to mark anatomical landmarks on the bone). Both image-based and imageless protocol require an osseous pin with a calibration marker attached to it that can record the motions of the femoral segments and adjust the navigation feedback accordingly, which avoids the necessity to repeat the registration step each time the femoral position is changed. Example of intraoperative navigation is shown in Figure 2.

Developments and outcomes of various intraoperative navigation programmes have been reported recently.

- Brunner et al (46) uploaded preoperative CT images of patients into a modified version of BrainLAB Hip-CT (BrainLAB AG, Germany). A C-arm adapter ('Fluoro 3D'; Vector Vision, USA) was used to synchronise intraoperative fluoroscopy with the 3D CT dataset. This allowed real-time feedback of surgical instrument placement in relation to the femoral head-neck junction. In 50 cam-type FAI patients who were divided into a navigated arthroscopy group and a without navigation group, the navigation software did not increase the rate of operative success (ROM and non-arthritic hip scores) and surgical time was significantly longer in the navigated group. This might be partially due to the fact that this prototype software did not allow preoperative planning and thus did not highlight the zone of impingement or the amount of resected bone.
- Monahan and Shimada (64) were the first to develop an encoder linkage system to track surgical instruments during hip arthroscopy. An encoder is a device which captures tool movement and orientation and it eliminates the problem of occlusion with standard optical tracking systems. The encoder

linkages are calibrated with preoperative, patient-specific 3D imaging data so the position of the surgical tools can be verified with patient anatomy. In other words, the system displays the real-time surgical instrument position relative to patient anatomy on a screen with a preoperatively generated, patient-specific 3D image. The system incorporates soft tissue as well as bone anatomy and therefore. also serves as a useful aid for safe portal placement.

- Almoussa et al (65) reported that the same shaping accuracy of the femur could be achieved between an experienced surgeon and a novice surgeon when a navigation system was used to treat cam-type FAI. In this study, a preoperative plan was generated from CT scans and the BrainLAB navigation system, and real-time tracking was performed by surgeons using a pointer with marker arrays to ensure resection was performed according to the preoperative plan. The intraoperative images used in this study were dynamic 2D CT scans in sagittal and axial planes of the head-neck junction, rather than a single image of a virtually 3D reconstructed hip. However, the results clearly indicated that navigated arthroscopic surgery based on preoperative imaging and planning may be useful to reduce the steep learning curve of arthroscopic FAI surgery.
- Van Houcke et al (66) reported the outcome of randomised controlled trial

which compared the cam resection accuracy via the conventional hip arthroscopy technique with the navigation technique. Postoperatively, the mean maximal alpha angle improved significantly in the navigated group compared with the conventional group, especially in the 12 o' clock position. However, positioning time and radiation exposure were significantly longer in the navigated group.

Other than those studies shown above, several other studies have reported on cadaver models. Kendoff et al (67) evaluated an image-based approach in a cadaver study of six hips and found that a combined CT-fluoroscopy matching navigated procedure allowed for a reproducible registration process for navigated FAI surgery at the femoral site, with high precision at the femoral neck and head-neck junction area with mean deviations below 1 mm. Also, using 12 paired cadaver hips with a virtual cam lesion, Audenaert et al (68) reported that the estimated accuracy of image-based registration by means of 3D fluoroscopy had a mean error of 0.8 mm, while the estimated accuracy of imageless registration in the arthroscopic setting was poor, with a mean error of 5.6 mm. Ecker et al (69) developed some computer-assisted planning and navigation software which uses preoperative ROM analysis on 3D models of patients' pelvic and femoral bone so that a virtual resection can be performed. Intraoperatively, the planned virtual resection area is shown as a highlighted colour-coded distance map, which aids surgeons awareness of the depth of resection. Once the resection is started, the application alters the colour-coded map in real time to prevent excessive or inadequate osteochondroplasty.

5. Future perspectives: robot-assisted surgery

Robot-assisted surgery is definitely the ultimate surgical technology, defined as a translation from the quantitative assessment produced by navigation to an automated mechanical surgical action by a robot, i.e. a robotic arm mounted with surgical instruments that can automate the entire surgical procedure following a preoperative surgical plan. This provides a greater level of precision, allowing for unmanned or even remote surgery (9,53,70).

Today, the ‘da Vinci’ (Intuitive Surgical, USA) telerobotic platform is the most widely used robotic surgical system, and its technical specifications have attracted interest. This system allows the surgeon to sit remotely at a console and control the movements of robotic arms while viewing the operative site in 3D, and it is being used in procedures such as hysterectomies (71), prostatectomies (72) and gastric bypass (73). Currently, robotic hip arthroscopy using this system is feasible only in a cadaveric model (74). However, remote control of articulated instruments with full ROM at the tip might enable parts of the hip joint that are inaccessible with rigid instrumentation to be reached (75,76) and the strong force that the system offers may be sufficient to work effectively with bony structures and to handle the long distance between skin level and the location of surgery. It is assumed that it would be feasible to use this system to perform basic hip arthroscopy due to the basic similarity of instrument design of laparoscopic and arthroscopic surgery (74). The 'Tactile Guidance System' (MAKO Surgical, USA), which is currently used to perform partial knee and total hip replacements, has been applied in a study on robotic-assisted femoral osteochondroplasty for FAI, although it was tested in sawbone models only. Nonetheless, this system appears promising, as its precision and accuracy over freehand surgery have been proven in well-constructed experimental models by Cartiaux et al (77).

An overall limitation to robotic arthroscopy is the restricted space inside the hip joint. Therefore, future instruments for robotic hip arthroscopy in patients will have to be both small in diameter and flexible. It is clear that robotic hip arthroscopy is at a very early stage at present. However, robotic technology has the potential to revolutionise hip arthroscopy and extend the number of reachable areas of the joint as well as to enable surgeons to perform more complex and precise tasks in the restricted spaces of the hip.

Conclusion

The recent advancement of computer-assisted surgery as a resource for preoperative planning and intraoperative assistance in hip arthroscopy has provided more precise surgical planning and the potential for improved operative results. There have been several studies published describing various technologies which have shown potential for increasing surgical precision in treating FAI. However, they are not without limitations, including a steep learning curve, lack of insight into soft-tissue pathology and restriction to only concentric hips. Future comparative trials determining the efficacy of computer-assisted hip arthroscopy surgery are required.

Conflict of Interest

No benefits in any form have been received or will be received from any commercial party related directly or indirectly to the subject of this article.

Legends to figures

Figure 1

Analysis of simulated bony range of motion in Articulis and suggested preoperative resection plan on the femoral neck in order to normalise the range of motion defects

Figure 2

The femoral marker (a) and fluoroscopy (B) are calibrated using the rigid pointer. An intraoperative fluoroscopy scan limited to the proximal femur is performed (C) in order to allow for image based matching of the preoperative plan. Finally, live resection control in relation to the preoperative plan can be performed using the rigid pointer and fluoroscopy is no longer required (D)

References

1. Beck M, Kalhor M, Leunig M, Ganz R. Hip morphology influences the pattern of damage to the acetabular cartilage: femoroacetabular impingement as a cause of early osteoarthritis of the hip. *J Bone Joint Surg Br*. 2005;87(7):1012-1018.

2. Bedi A, Dolan M, Leunig M, Kelly BT. Static and dynamic mechanical causes of hip pain. *Arthroscopy*. 2011;27(2): 235-251.

3. Peters CL, Erickson JA. Treatment of femoro-acetabular impingement with surgical dislocation and debridement in young adults. *J Bone Joint Surg Am*. 2006;88(8): 1735-1741.

4. Peters CL, Erickson JA, Anderson L, Anderson AA, Weiss J. Hip-preserving surgery: understanding complex pathomorphology. *J Bone Joint Surg Am*. 2009;91 Suppl 6: 42-58.

5. Beaule PE, Le Duff MJ, Zaragoza E. Quality of life following femoral head-neck osteochondroplasty for femoroacetabular impingement. *J Bone Joint Surg Am*. 2007;89(4): 773-779.

6. Byrd JW, Jones KS. Arthroscopic femoroplasty in the management of cam-type femoroacetabular impingement. *Clin Orthop Relat Res*. 2009;467(3):739-746.

7. Laude F, Sariali E, Nogier A. Femoroacetabular impingement treatment using arthroscopy and anterior approach. *Clin Orthop Relat Res*. 2009;467(3): 747-752.

8. Mardones R, Lara J, Donndorff A, Barnes S, Stuart MJ, Glick J, *et al*. Surgical correction of "cam-type" femoroacetabular impingement: a cadaveric comparison of open versus arthroscopic debridement. *Arthroscopy*. 2009;25(2):175-182.

9. Park CN, Nawabi DH, Christopher J, Conditt MA, Ranawat AS. Robotic-assisted femoral osteochondroplasty is more precise than a freehand technique in a Sawbone model. *J Hip Peserv Surg*. 2015;2(2):136-144.

10. Nawabi DH, Nam D, Park C, Ranawat AS. Hip Arthroscopy: The Use of Computer Assistance. *HSS J*. 2013;9: 70-78.

11. Pearle AD, Kendoff D, Musahl V. Perspectives on computer-assisted orthopaedic surgery: movement toward quantitative orthopaedic surgery. *J Bone Joint Surg Am*. 2009;91 Suppl 1:7-12.

12. Haaker RG, Tiedjen K, Ottersbach A, Rubenthaler F, Stockheim M, Stiehl JB. Comparison of conventional versus computer-navigated acetabular component insertion. *J Arthroplasty*. 2007;22(2):151-159.

13. Weng YJ, Hsu RW, Hsu WH. Comparison of computer-assisted navigation and conventional instrumentation for bilateral total knee arthroplasty. *J Arthroplasty*. 2009;24(5):668-673.

14. Cobb J, Henckel J, Gomes P, Harris S, Jakopec M, Rodriguez F, *et al.* Hands-on robotic unicompartmental knee replacement: a prospective, randomised controlled study of the acrobot system. *J Bone Joint Surg Br*. 2006;88(2):188-197.

15. Seon JK, Song EK. Navigation-assisted less invasive total knee arthroplasty compared with conventional total knee arthroplasty: a randomized prospective trial. *J Arthroplasty*. 2006;21(6):777-782.

16. Voos JE, Musahl V, Maak TG, Wickiewicz TL, Pearle AD. Comparison of tunnel positions in single-bundle anterior cruciate ligament reconstructions using computer navigation. *Knee Surg Sports Traumatol Arthrosc*. 2010;18(9):1282-1289.

17. Nakano N, Matsumoto T, Ishida K, Tsumura N, Kuroda R, Kurosaka M. Long-term subjective outcomes of computer-assisted total knee arthroplasty. *Int Orthop.* 2013;37(10):1911-1915.

18. Beckmann J, Stengel D, Tingart M, Götz J, Grifka J, Lüring C. Navigated cup implantation in hip arthroplasty. *Acta Orthop.* 2009;80(5):538-544.

19. Myers SR, Eijer H, Ganz R. Anterior femoroacetabular impingement after periacetabular osteotomy. *Clin Orthop Relat Res.* 1999;(363):93-99.

20. Ganz R, Leunig M, Leunig-Ganz K, Harris WH. The etiology of osteoarthritis of the hip: an integrated mechanical concept. *Clin Orthop Relat Res.* 2008;466(2):264-272.

21. Laude F, Boyer T, Nogier A. Anterior femoroacetabular impingement. *Joint Bone Spine.* 2007;74(2):127-132.

22. Bijlsma JW, Berenbaum F, Lafeber FP. Osteoarthritis: an update with relevance for clinical practice. *Lancet*. 2011;377(9783):2115-2126.

23. Martel-Pelletier J. Pathophysiology of osteoarthritis. *Osteoarthritis Cartilage.* 2004;12 Suppl A:S31-33.

24. Ganz R, Parvizi J, Beck M, Leunig M, Nötzli H, Siebenrock KA. Femoroacetabular impingement: a cause for osteoarthritis of the hip. *Clin Orthop Relat Res.* 2003;(417):112-120.

25. Burnett RS, Della Rocca GJ, Prather H, Curry M, Maloney WJ, Clohisy JC. Clinical presentation of patients with tears of the acetabular labrum. *J Bone Joint Surg Am.* 2006;88(7):1448-1457.

26. Harris WH. Etiology of osteoarthritis of the hip. *Clin Orthop Relat Res.* 1986;213: 20-33.

27. Philippon MJ, Schenker ML. Arthroscopy for the treatment of femoroacetabular impingement in the athlete. *Clin Sports Med*. 2006;25(2):299-308, ix.

28. Ferguson SJ, Bryant JT, Ganz R, Ito K. The influence of the acetabular labrum on hip joint cartilage consolidation: a poroelastic finite element model. *J Biomech.* 2000;33(8): 953-960.

29. Ferguson SJ, Bryant JT, Ganz R, Ito K. An in vitro investigation of the acetabular labral seal in hip joint mechanics. *J Biomech.* 2003;36(2):171-178.

30. Ganz R, Gill TJ, Gautier E, Ganz K, Krügel N, Berlemann U. Surgical dislocation of the adult hip a technique with full access to the femoral head and acetabulum without the risk of avascular necrosis. *J Bone Joint Surg Br.* 2001;83(8):1119-1124.

31. Botser IB, Smith TW Jr, Nasser R, Domb BG. Open surgical dislocation versus arthroscopy for femoroacetabular impingement: a comparison of clinical outcomes. *Arthroscopy.* 2011;27(2):270-278.

32. Byrd JW, Jones KS. Hip arthroscopy in athletes: 10-year follow-up. *Am J Sports Med.* 2009;37(11):2140-2143.

33. Stevens MS, Legay DA, Glazebrook MA, Amirault D. The evidence for hip arthroscopy: grading the current indications. *Arthroscopy.* 2010;26(10):1370-1383.

34. Bedi A, Chen N, Robertson W, Kelly BT. The management of labral tears and femoroacetabular impingement of the hip in the young, active patient. *Arthroscopy.* 2008;24(10):1135-1145.

35. Byrd JW, Jones KS. Prospective analysis of hip arthroscopy with 2-year follow-up. *Arthroscopy.* 2000;16(6):578-587.

36. Byrd JW, Jones KS. Prospective analysis of hip arthroscopy with 10-year followup. *Clin Orthop Relat Res.* 2010;468(3):741-746.

37. Larson CM, Ross JR, Stone RM, Samuelson KM, Schelling EF, Giveans MR, *et al.* Arthroscopic Management of Dysplastic Hip Deformities: Predictors of Success and Failures With Comparison to an Arthroscopic FAI Cohort. *Am J Sports Med.* 2016;44(2):447-453.

38. Ng VY, Arora N, Best TM, Pan X, Ellis TJ. Efficacy of surgery for femoroacetabular impingement: a systematic review. *Am J Sports Med.* 2010;38(11):2337-2345.

39. Dolan MM, Heyworth BE, Bedi A, Duke G, Kelly BT. CT reveals a high incidence of osseous abnormalities in hips with labral tears. *Clin Orthop Relat Res.* 2011;469(3):831-838.

40. Nötzli HP, Wyss TF, Stoecklin CH, Schmid MR, Treiber K, Hodler J. The contour of the femoral head-neck junction as a predictor for the risk of anterior impingement. *J Bone Joint Surg Br.* 2002;84(4):556-560.

41. Stähelin L, Stähelin T, Jolles BM, Herzog RF. Arthroscopic offset restoration in femoroacetabular cam impingement: accuracy and early clinical outcome. *Arthroscopy.* 2008;24(1):51-57 e1.

42. Johnston TL, Schenker ML, Briggs KK, Philippon MJ. Relationship between offset angle alpha and hip chondral injury in femoroacetabular impingement. *Arthroscopy.* 2008;24(6):669-675.

43. Allen D, Beaulé PE, Ramadan O, Doucette S. Prevalence of associated deformities and hip pain in patients with cam-type femoroacetabular impingement. *J Bone Joint Surg Br.* 2009;91(5):589-594.

44. de Sa D, Urquhart N, Philippon M, Ye JE, Simunovic N, Ayeni OR. Alpha angle correction in femoroacetabular impingement. *Knee Surg Sports Traumatol Arthrosc.* 2014;22(4):812-821.

45. Pfirrmann CW, Mengiardi B, Dora C, Kalberer F, Zanetti M, Hodler J. Cam and pincer femoroacetabular impingement: characteristic MR arthrographic findings in 50 patients. *Radiology.* 2006;240(3):778-785.

46. Brunner A, Horisberger M, Herzog RF. Evaluation of a computed tomography-based navigation system prototype for hip arthroscopy in the treatment of femoroacetabular cam impingement. *Arthroscopy.* 2009;25(4):382-391.

47. Clohisy JC, Nunley RM, Otto RJ, Schoenecker PL. The frog-leg lateral radiograph accurately visualized hip cam impingement abnormalities. *Clin Orthop Relat Res.* 2007;462:115-121.

48. Konan S, Rhee SJ, Haddad FS. Hip arthroscopy: analysis of a single surgeon's learning experience. *J Bone Joint Surg Am.* 2011;93 Suppl 2:52-56.

49. Souza BG, Dani WS, Honda EK, Ricioli W Jr, Guimarães RP, Ono NK, *et al.* Do complications in hip arthroscopy change with experience? *Arthroscopy.* 2010;26(8):1053-1057.

50. Heyworth BE, Shindle MK, Voos JE, Rudzki JR, Kelly BT. Radiologic and intraoperative findings in revision hip arthroscopy. *Arthroscopy.* 2007;23(12):1295-1302.

51. Philippon MJ, Schenker ML, Briggs KK, Kuppersmith DA, Maxwell RB, Stubbs AJ. Revision hip arthroscopy. *Am J Sports Med.* 2007;35(11):1918-1921.

52. Matsuda DK. Acute iatrogenic dislocation following hip impingement arthroscopic surgery. *Arthroscopy.* 2009;25(4):400-404.

53. Ranawat AS, McClincy M, Sekiya JK. Anterior dislocation of the hip after arthroscopy in a patient with capsular laxity of the hip. A case report. *J Bone Joint Surg Am.* 2009;91(1):192-197.

54. Mardones RM, Gonzalez C, Chen Q, Zobitz M, Kaufman KR, Trousdale RT. Surgical treatment of femoroacetabular impingement: evaluation of the effect of the size of the resection. Surgical technique. *J Bone Joint Surg Am.* 2006;88 Suppl 1 Pt 1:84-91.

55. Sussmann PS, Zumstein M, Hahn F, Dora C. The risk of vascular injury to the femoral head when using the posterolateral arthroscopy portal: cadaveric investigation. *Arthroscopy.* 2007; 23(10):1112-1115.

56. Tannast M, Kubiak-Langer M, Langlotz F, Puls M, Murphy SB, Siebenrock KA. Noninvasive three-dimensional assessment of femoroacetabular impingement. *J Orthop Res.* 2007;25(1):122-131.

57. Kubiak-Langer M, Tannast M, Murphy SB, Siebenrock KA, Langlotz F. Range of motion in anterior femoroacetabular impingement. *Clin Orthop Relat Res.* 2007;458:117-124.

58. Audenaert EA, Mahieu P, Pattyn C. Three-dimensional assessment of cam engagement in femoroacetabular impingement. *Arthroscopy.* 2011;27(2):167-171.

59. Audenaert EA, Vigneron L, Pattyn C. A method for three-dimensional evaluation and computer aided treatment of femoroacetabular impingement. *Comput Aided Surg.* 2011;16(3):143-148.

60. Bedi A, Dolan M, Hetsroni I, Magennis E, Lipman J, Buly R, *et al.* Surgical treatment of femoroacetabular impingement improves hip kinematics: a computer-assisted model. *Am J Sports Med.* 2011;39 Suppl:43S-49S.

61. Röling MA, Visser MI, Oei EH, Pilot P, Kleinrensink GJ, Bloem RM. A quantitative non-invasive assessment of femoroacetabular impingement with CT-based dynamic simulation--cadaveric validation study. *BMC Musculoskelet Disord.* 2015;16:50.

62. Milone MT, Bedi A, Poultsides L, Magennis E, Byrd JW, Larson CM, *et al.* Novel CT-based three-dimensional software improves the characterization of cam morphology. *Clin Orthop Relat Res.* 2013;471(8):2484-2491.

63. Puls M, Ecker TM, Tannast M, Steppacher SD, Siebenrock KA, Kowal JH. The Equidistant Method - a novel hip joint simulation algorithm for detection of femoroacetabular impingement. *Comput Aided Surg.* 2010;15(4-6):75-82.

64. Monahan E, Shimada K. Computer-aided navigation for arthroscopic hip surgery using encoder linkages for position tracking. *Int J Med Robot.* 2006;2(3):271-278.

65. Almoussa S, Barton C, Speirs AD, Gofton W, Beaulé PE. Computer-assisted correction of cam-type femoroacetabular impingement: a Sawbones study. *J Bone Joint Surg Am.* 2011;93 Suppl 2:70-75.

66. Van Houcke J, Khanduja V, Nakano N, Krekel P, Pattyn C, Audenaert E. Accuracy

of navigated cam resection in femoroacetabular impingement: A randomised controlled trial. *Int J Med Robot*. 2017;13(4).

67. Kendoff D, Citak M, Stueber V, Nelson L, Pearle AD, Boettner F. Feasibility of a navigated registration technique in FAI surgery. *Arch Orthop Trauma Surg.* 2011;131(2):167-172.

68. Audenaert E, Smet B, Pattyn C, Khanduja V. Imageless versus image-based registration in navigated arthroscopy of the hip: a cadaver-based assessment. *J Bone Joint Surg Br.* 2012;94(5):624-629.

69. Ecker TM, Puls M, Steppacher SD, Bastian JD, Keel MJ, Siebenrock KA, *et al.* Computer-assisted femoral head-neck osteochondroplasty using a surgical milling device an in vitro accuracy study. *J Arthroplasty*. 2012;27(2):310-306.

70. Advincula AP. Surgical techniques: robot-assisted laparoscopic hysterectomy with the da Vinci surgical system. *Int J Med Robot.* 2006;2(4):305-311.

71. Soto E, Lo Y, Friedman K, Soto C, Nezhat F, Chuang L, *et al.* Total laparoscopic hysterectomy versus da Vinci robotic hysterectomy: is using the robot beneficial? *J Gynecol Oncol.* 2011;22(4):253-259.

72. Parsons JK, Messer K, Palazzi K, Stroup SP, Chang D. Diffusion of surgical innovations, patient safety, and minimally invasive radical prostatectomy. *JAMA Surg.* 2014;149(8):845-851.

73. Myers SR, McGuirl J, Wang J. Robot-assisted versus laparoscopic gastric bypass: comparison of short-term outcomes. *Obes Surg.* 2013;23(4):467-473.

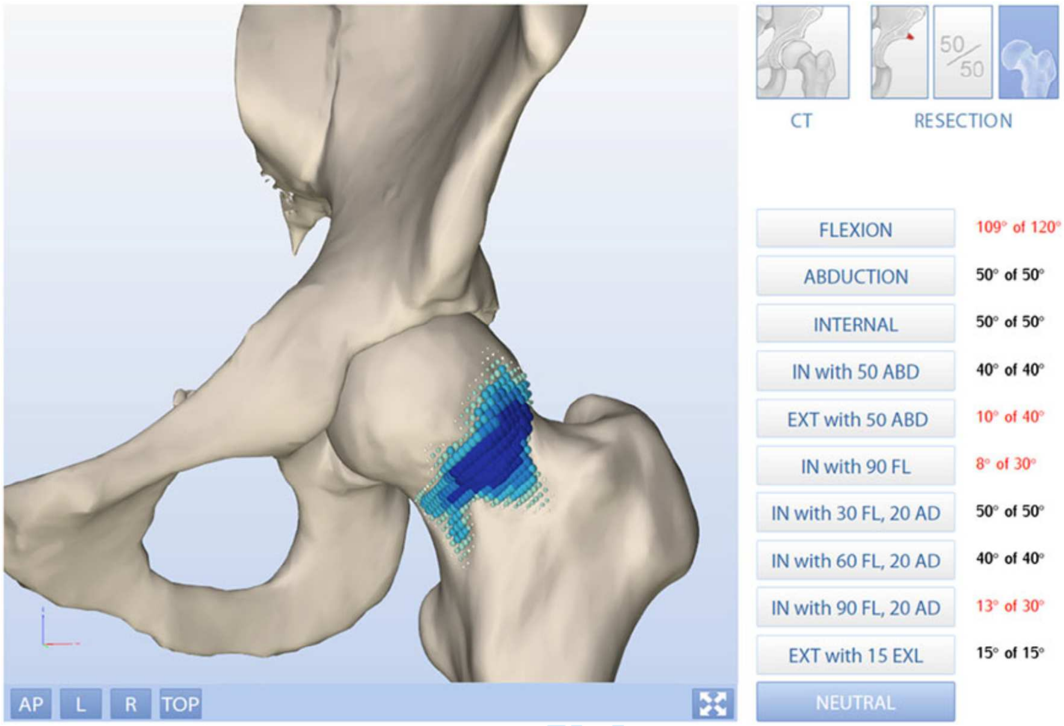
74. Kather J, Hagen ME, Morel P, Fasel J, Markar S, Schueler M. Robotic hip arthroscopy in human anatomy. *Int J Med Robot.* 2010;6(3):301-305.

75. Hagen ME, Inan I, Pugin F, Morel P. (The da Vinci surgical system in digestive surgery). *Rev Med Suisse.* 2007;3(117):1622-1626.

76. Jacobs S, Falk V. Pearls and pitfalls: lessons learned in endoscopic robotic surgery- the da Vinci experience. *Heart Surg Forum.* 2001;4(4):307-310.

77. Cartiaux O, Paul L, Docquier PL, Raucent B, Dombre E, Banse X. Computer-assisted and robot-assisted technologies to improve bone-cutting accuracy when integrated with a freehand process using an oscillating saw. *J Bone Joint Surg Am.* 2010;92(11):2076-2082.

Figure 1



FLEXION	109° of 120°
ABDUCTION	50° of 50°
INTERNAL	50° of 50°
IN with 50 ABD	40° of 40°
EXT with 50 ABD	10° of 40°
IN with 90 FL	8° of 30°
IN with 30 FL, 20 AD	50° of 50°
IN with 60 FL, 20 AD	40° of 40°
IN with 90 FL, 20 AD	13° of 30°
EXT with 15 EXL	15° of 15°

5

2

Figure 2