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REVIEW

Computer assistance in hip preservation surgery—current status and introduction of our system

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Abstract

Introduction Preservation surgery of the hip with open or arthroscopic approach has always been challenging as complex 3-D anatomy and limited surgical access make intraoperative evaluation difficult. Recent advances in computer technology offer a wide range of innovative solutions with a goal to improve accuracy and safety of corrective procedures on human joints.

Method The author critically reviews currently available literature in the field of computer assistance in hip preservation surgery. Basic features of unique planning software and navigation surgical system used in treatment of femoroacetabular impingement and hip dysplasia are introduced.

Results Currently available software provides preoperative identification of hip deformity on CT-based 3-D model and planning of the surgical correction using kinematic protocols. Real-time intraoperative 3-D orientation is possible, and execution of surgical correction can be performed either with navigation of surgical tools or with printed templates. Computer assistance in hip preservation surgery is in the developing phase. First clinical experiences of its use in treatment of femoroacetabular impingement, hip dysplasia, hip tumors, and avascular necrosis of the femoral head are promising.

Conclusion Computer assistance has been applied for treatment of several hip disorders. Technical advances are suggested and quality basic studies and clinical trials are encouraged for the novel technology to become more user friendly and widely accepted.

Keywords Hip · Computer assistance · Planning · Navigation · Hip arthroscopy · Periacetabular osteotomy

Introduction

Historically, surgical treatment of non-arthritic hip disorders has been challenging due to the limited access to the hip joint and the complexity of its anatomy. Recent technical advances made full observation of the hip via scope possible. In 2003, the concept of femoro-acetabular impingement (FAI) was introduced and instantly popularized hip arthroscopy as a therapeutic procedure [1]. Since then, hip arthroscopy has been utilized as a safe and reliable treatment of wide spectrum of hip disorders, among them FAI being most common indication [2]. Not all developmental disorders of the hip could be treated by arthroscopy. Acetabular dysplasia is one of them although there is some evidence in the literature that borderline cases may perform well after arthroscopy by addressing intra-articular secondary changes and if care of capsular integrity has been taken [3]. Nevertheless, complex reorientation periacetabular osteotomies (PAOs) remain the golden standard for treatment of moderate and severe acetabular dysplasia in adults [4–6].

Basically, failed hip preservation surgery might be a result of insufficient knowledge about pathology, lack of diagnostic and planning tools and inaccuracy of execution of correction. Recent advances in computer technology offer a wide range of innovative solutions to improve accuracy and safety of corrective surgery on human skeleton. Currently available software has enabled pre-operative motion analyses on 3-D reconstruction model of the hip. It not only does help surgeon to define deformity but also provides planning of surgical correction. Furthermore, contemporary computer technology offers several options to improve surgical execution. Correction can be performed either with intra-operative navigation or with custom 3-D printed templates.

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In this article, the author critically reviews currently available literature in the field of computer assistance in hip preservation surgery and summarizes his own clinical experience in treatment of femoro-acetabular impingement and hip dysplasia using unique planning software and surgical navigation system.

Limitations of current hip preservation surgery

The ultimate goal of hip preservation surgery is to correct pathoanatomy of the hip in order to improve biomechanical properties and to prevent further damage to the joint in longer run. To achieve good outcome, the surgeon should identify and address all structural abnormalities of the individual hip.

Shapira et al. reported in their systematic review that residual CAM, pincer and acetabular dysplasia after hip arthroscopy are responsible for secondary corrective surgery in 8.6%, 4.6% and 2.8%, respectively [7]. On the other hand, over-resection of CAM may result in detrimental biomechanical changes in the hip due to a loss of suction seal [8]. Post-operative femoral neck fracture and avascular necrosis of the femoral head present further possible worrisome complications after excessive resection of the femoral head-neck junction [9, 10]. In majority, FAI is a result of combination of focal or global acetabular over-coverage (pincer) and CAM deformity [11]. In praxis, it has been often a surgeon's subjective decision which part of the hip joint to correct and at what extend, to avoid residual impingement.

There are several surgical options to treat acetabular dysplasia. In adults, redirection of the acetabulum can be best achieved by periacetabular osteotomy (PAO). Three types of PAO have been popularized: Bernese PAO [4], curved rotational osteotomies [5] and triple pelvic osteotomies [6]. Precise pre-operative plan is mandatory to achieve good correction with PAO. PAO is technically demanding procedure because of limited visualization with surgeons having to perform some juxtarticular bone cuts out of their field of direct sight and is associated with higher complication rate.

Anatomic planning from static 2-D images

Although FAI presents dynamic mechanical conflict between the femoral head and the acetabulum, preoperative assessment of surface pathoanatomy of the hip has been based on measuring certain graphic parameters of the femoral head sphericity and the acetabular coverage from static 2-D images obtained either by X-ray, MR or CT. On the femoral side, effort has to be done to achieve as perfect sphericity of the femoral head as possible in order to preserve a sealing effect of the joint [8]. Alpha angle has been most commonly used anatomic parameter to determine if the femoral head is spherical or not [12]. According to recent studies, the pathological value of alpha angle has been questioned [13]. There are further scientific reasons to consider its drawback as a pre-operative planning tool. It does not consistently correlate with clinical ROM and does not define the length and the shape of CAM deformity [14]. Radiologic parameters of pincer measured from a single or two arbitrary 2-D images with hip in neutral position have not been found in correlation with possible impingement which is the problem in hip flexion [15]. Radiologic acetabular morphology is strongly influenced by pelvic tilt. Pelvic posture in potential impingement positions of the hip depends on the individual adaptive pattern of the lumbar spine, the flexibility of periarticular and perilumbar soft tissue and muscle activity [15]. In symptomatic FAI patients, it is sometimes an expression of compensatory mechanisms developed in order to reduce pain and discomfort.

Radiologic parameters of hip dysplasia are fairly more reliable to determine pathomorphology although an isolated assessment of individual parameter is an oversimplistic approach that may jeopardize appropriate classification and may provide insufficient data to guide the treatment of hips with additional features of dysplasia and instability [16]. In praxis, radiographic assessment of acetabular coverage from X-ray images is most frequently limited to three parameters: the lateral centre edge angle (LCE), the acetabular index by Tönnis (ACI) measured on AP pelvic view and the anterior centre edge angle (ACE) measured on false profile. Acetabular dysplasia is associated with chronic increase of hip contact stress which is in correlation with certain radiographic parameters of dysplasia, i.e. the LCE and the geometry of the pelvis [17]. Assessment of hip contact stress provides information about severity of dysplasia and predicts fate of individual hip regarding osteoarthritis, but it does not have any added value in planning of correction [18].

Technical limitations of hip preservation surgery

There are several technical limitations of hip arthroscopy. With limited visualization and reduced manoeuvrability of the instruments, assessment of the surface geography is difficult. Intra-operative 2-D fluoroscopic imaging and dynamic testing of residual abutment of bony structures against the labrum during manipulation of the leg into impingement positions have been found unreliable intra-operative assessment tools during CAM resection in particular [19]. Listed limitations are responsible for a significantly high percentage of suboptimal corrections when done arthroscopically and probably the most important cause for a long learning curve in hip arthroscopy.

During PAO, acetabular bone fragment has to be fully released from the rest of the pelvis to enable its manipulation. The new position of the acetabulum should not only provide increased acetabular coverage and reduced contact stress over the cartilage surface but also prevent detrimental impingement effect of overcorrection [20]. Intra-operative 2-D fluoroscopy has been used to control position and direction of osteotomies and to assess position of the acetabular fragment during correction [21]. Imprecision may result in certain serious peri-operative complications, e.g. neurovascular or intra-articular injury [22]. In Bernese PAO, effort should be done to avoid the posterior column discontinuity that can lead to secondary fragment migration [21]. Osteonecrosis of the acetabular fragment that is too thin is another possible complication of Bernese and curved rotational PAO [21]. It is difficult to achieve optimal acetabular reorientation, especially if the fluoroscopic visualization of the pelvis is limited by its wide shape. Significant radiation exposure to the patient and the personnel in the operating room has been reported during PAO surgery [23]. Furthermore, intra-operative fluoroscopy does not provide sufficient feedback on accuracy of correction in terms of objective measurement of radiographic parameters of acetabular coverage. Evaluation of anterior and posterior coverage and acetabular version using false profile is particularly difficult. For this reason, Troelsen et al. introduced intra-operative assessment of angles during PAO using special measuring device visible during fluoroscopy [24]. Additionally, an effort has to be done to achieve best possible contact between the osteotomized bone and the rest of pelvis in order to provide good healing of the fragment in new position. The last is important to prevent formation of pseudoarthrosis, one of worrisome complications after PAO [25].

Computer assistance in hip preservation surgery—a new horizon

Recent advances in computer technology offer a wide range of innovative solutions in terms of planning and execution with a goal to improve accuracy and safety of hip preservation surgery.

Kinematic planning

Kinematic planning software is based on image segmentation methods, enabling decomposition of the 3-D image of the joint or bone parts into individual objects of interest. It is followed by simulation of joint motion or by virtual redirection of osteotomized bone. In FAI, by using collision algorithms, software detects the impingement zones and determines the volume of the bone resection based on impingement-free post-operative ROM rather than desirable alpha angle (Fig. 1). The same technology can be used for patients with hip dysplasia to fully assess geometric features of the pelvis and to design individualized treatment scheme [26]. Position and direction of all periacetabular osteotomies and new position of the osteotomized acetabular fragment can be planned on 3-D reconstruction model of the pelvis (Fig. 2).

There are several kinematic planning software available for clinical use. They utilize CT imaging in order to reconstruct 3-D skeletal anatomy. Supplementary, some provide platform for intra-operative assistance. For instance, virtual post-resection fluoroscopic images can be created and compared with intra-operative fluoroscopic images in order to verify adequate execution of correction plan. Furthermore, it is possible to incorporate selected 3-D images obtained by planning software into surgical navigation system to enable complete 3-D visual control of correction according to pre-operative plan. Finally, software support export of 3-D image in a file format compatible for 3-D printing of selected anatomy and patient specific guiding templates. Some technical advances of kinematic planning tools have been proposed before becoming widely accepted. First, the geometric centre of the hip rotation has to be defined further in details. Second, for non-concentric dysplastic and arthritic hips, kinematic analyses should take into account some translation of the joint during weight-bearing, motion and muscle activation. Third, planning from CT images takes into account neither the soft tissue tensioning, muscles and ligaments in particular nor the impact of impingement lesions on the preoperative plan. Finally, CT scanning has potential harmful effect on patient's health due to radiation exposure. In order to obtain 3-D surface geometry alone, low-dose CT has been suggested minimizing radiation exposure down to 10% of the dose received by conventional diagnostic CT [27]. To overcome above listed flaws of CT, 3-D reconstruction of skeletal anatomy from MR images has been suggested but protocols are still in the developing phase [28]. Despite a high cost, a need for additional technical support and a time-consuming nature of the method, kinematic planning is gaining popularity over anatomic planning of FAI corrective surgery.

Intra=operative navigation

Intra-operative navigation enables real-time tracking of surgical instruments and full 3-D visual feedback during execution of correction. The key to success is accurate registration of the anatomy of interest. Regarding registration of anatomy and tracking of instruments, navigation systems can be image-based [14] or imageless [29]. Image-based systems provide real-time 3-D image of the joint by matching anatomy using intra-operative imaging modalities, fluoroscopy or CT scanning. Miscellaneous fiducials (markers) have been suggested to improve accuracy of fluoroscopy-based systems [30]. Imageless systems transmit information about position of optical probes attached to anatomic landmarks on the bone. The main advantage of imageless systems is the absence of additional intra-operative radiation exposure. Optical systems demand absence of visual obstacles between the sensor and the

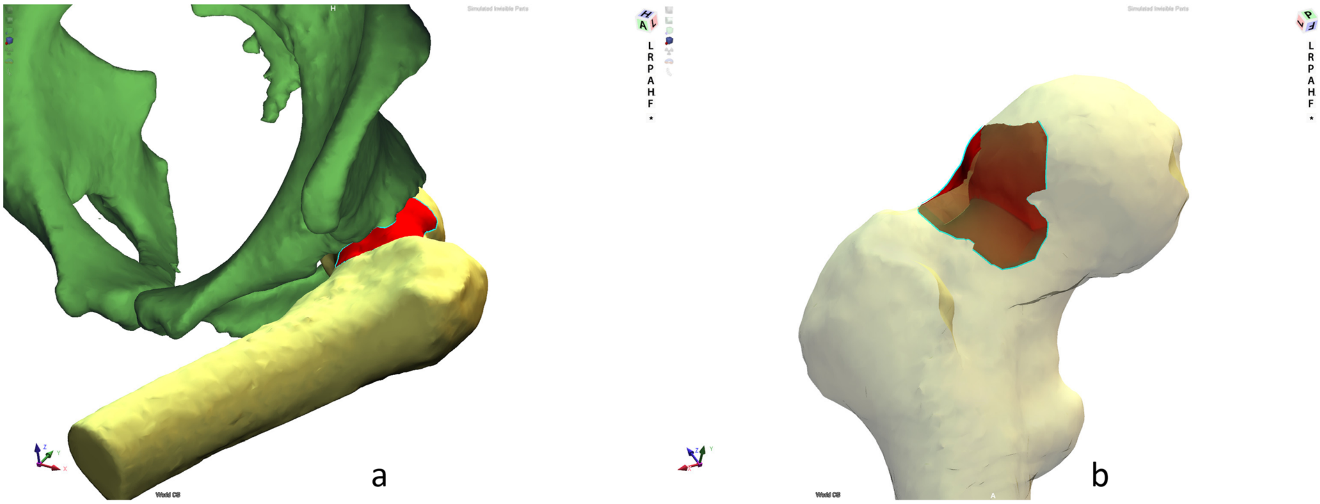

Fig. 1 Kinematic planning of femoral osteoplasty on CT-based 3-D model utilizing EBS software (Ekliptik, Slovenia). **a** After segmentation, the hip is placed into impingement position and the bone which comes into a conflict with the acetabular rim is identified (red). **b** Position, surface and volume of CAM impingement area can be studied pre-operatively from different perspectives; PA view

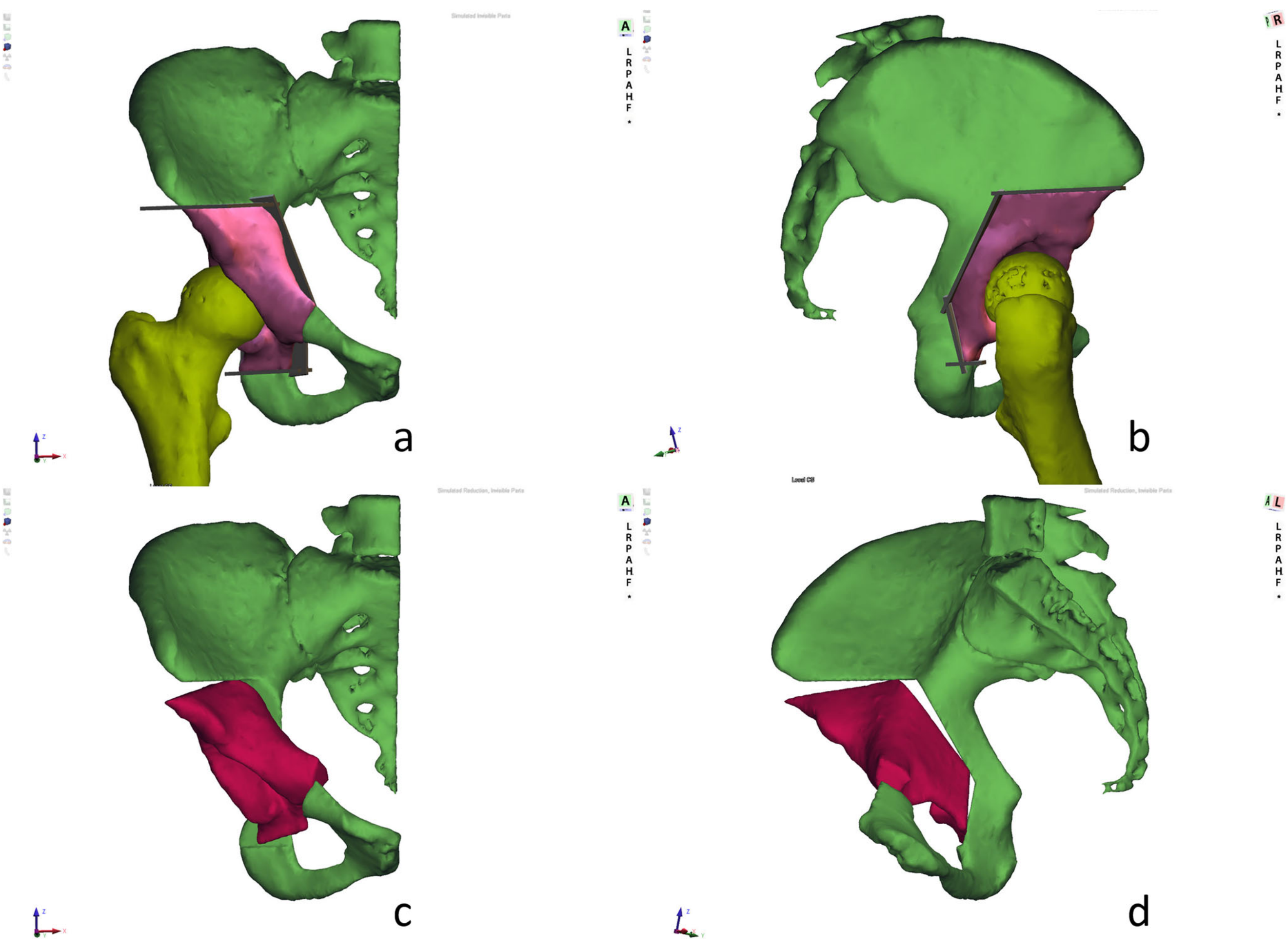

Fig. 2 Planning of periacetabular osteotomy on CT-based 3-D model utilizing EBS software (Ekliptik, Slovenia). Position and directions of osteotomies are optimized in AP view (**a**) and in outside-in false-profile view (**b**). New position of osteotomized acetabular fragment and its contact with the rest of the pelvis is fully visualized and controlled in all three dimensions: AP view (**c**), inside-out false-profile view (**d**)

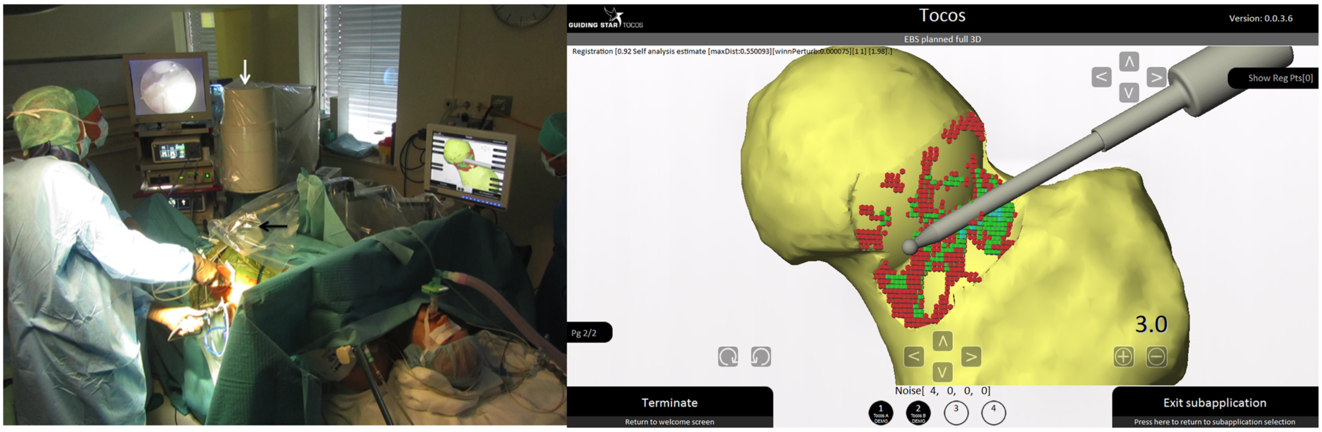

Fig. 3 Navigated arthroscopic femoral osteoplasty using Guiding Star surgical navigation system (Ekliptik, Slovenia). **a** Setting in the operating room–C-arm (white arrow) is moved at least 1 m away from electromagnetic transmitter (black arrow) to avoid interference from induced electromagnetic field. Real-time execution of arthroscopic femoral osteoplasty (left screen) is controlled on additional screen (right screen) showing the tip of arthroscopic bone cutter in relation to full 3-D anatomy of the proximal femur. **b** 3-D tracking of the instrument and full 3-D control of execution—the depth of femoral osteoplasty is controlled by showing progressive clearance of layers formed by 1-mm beads, each layer of beads in different colour. Osteoplasty is accomplished after all coloured beads are removed

camera. Alternatively, electromagnetic trackers can be attached to regular surgical instruments, which can then provide real-time information of the position and orientation of the instruments' alignment with respect to the anatomy of interest [31].

Navigation during hip arthroscopy

To date, few studies have approved positive impact of surgical navigation systems on accuracy of execution of arthroscopic CAM resection however with limited strength of evidence. In their cadaveric study, Kendoff et al. reported high precision of their image-based navigation systems with a mean deviation bellow 1 mm [32]. Audenaert et al. compared registration accuracy of image-based navigation system using intra-operative 3-D fluoroscopy with their imageless system and reported significant difference between systems, with mean registration error of 0.8 mm and 5.6 mm, respectively [33]. The imageless system used in their study did not defend its potential application in clinical praxis. Our navigation system Guiding Star based on electromagnetic tracking performed acceptable accuracy with mean error of 1 mm regarding the depth of bone resection and only 4% of bone volume mismatch (Fig. 3) [34]. In 2017, Van Houcke et al. reported results of the very first prospective randomized clinical trial comparing efficacy of navigated and non-navigated femoral osteoplasty on patients with CAM deformity [35]. Navigated group performed better regarding post-operative alpha angle and ROM.

Navigation during PAO

Navigation systems have been introduced in PAO surgery in order to provide safe osteotomies and to obtain reliable and accurate correction. Technology enables real-time tracking of

Fig. 4 Computer navigated PAO using Guiding Star surgical navigation system (Ekliptik, Slovenia)–real-time full 3-D assessment of correction. Osteomized acetabular fragment (red) is manipulated, and its position in relation to the rest of the pelvis is matched with planned position (yellow): AP view (left), outside-in false-profile view (right)

osteotomes in relation to 3-D anatomy of the pelvis. Further, after the osteomized acetabular fragment is fully released, correction can be performed by full 3-D feedback on the acetabular position in relation to the rest of the pelvis (Fig. 4).

Since 1997, when Langlotz et al. reported first twelve cases of computer-assisted Bernese PAO with encouraging clinical experience, several studies have shown its added value [36]. In 2006, Hsieh et al. reported results of their randomized control study of computer-assisted curved rotational PAO involving 36 patients [37]. The operation time was shorter when navigation was used and complications from technical errors attributable to a misplaced osteotomy were not encountered. The authors of this study considered a registration error value of 2 mm for their navigation system to be acceptable. Later, several validation studies of navigation system used for Bernese type of PAO with supplemental implementation of pre-operative plan were conducted by Liu et al. on four sawbone models and on cadaveric specimen [38, 39]. They reported on reasonable sub-degree accuracy of their system regarding execution of the pre-operative plan. According to results of a pilot study on ten patients with acetabular dysplasia recently reported by De Raedt at al., computer assistance can reliably be used with minimally invasive approaches to the pelvis and may become a valuable tool in the future for both experienced and less experienced surgeons performing PAO [40]. Just recently, Imai et al. reported clinical results after 98 PAOs with a minimum follow-up of three years [41]. Forty hips enrolled in their study underwent conventional PAO and 58 hips underwent computer navigated PAO. Authors concluded that computer navigation not only improved accuracy and safety of PAO but also prevented the progression into osteoarthritis.

Second-generation navigation named BGS (Biomechanical Guidance System) has been developed for surgical treatment of hip dysplasia based on real-time biomechanical feedback [42]. Dedicated software system provides measurement of contact surface angles in three dimensions and simultaneously estimates biomechanical loading pattern in means of joint pressure and weight bearing area during distinct activities of daily living.

Pre-operative 3-D image-based printed templates may be used as alternative modality of computer assistance to guide osteotomies and to keep the osteotomized acetabular fragment in the desired position prior fixation with screws [43].

Other possibilities for clinical application of computer assistance in hip preservation surgery

In addition to FAI and acetabular dysplasia, computer assistance has been proposed as a potential aiding tool for treatment of several other pathology of the hip. For instance, navigation of surgical instruments and image-based printed templates have been introduced in surgical treatment of hip tumours [44] and avascular necrosis of the femoral head [45]

Limb salvage with minimum risk of recurrence remains a predominant goal during treatment of aggressive tumours involving extremities. Thorough 3-D imaging studies are mandatory to plan multiplanar resection of such a lesion involving the hip joint. Planning may also include measuring of possible bone defect after removal of the lesion and helps to choose an appropriate reconstruction strategy, using either bone grafting or artificial implants. Evidences on usefulness of navigation during resection of hip tumours are scarce [46–48]. Just recently, Fujiwara et al. reported results on navigated surgical resection of periacetabular malignant tumours followed by hip prosthesis with acetabular cone construct implanted into the remaining ilium [48]. Lower incidence of incidental intralesional resection, lower local recurrence rate and more precise implant placement were demonstrated when resection of the tumour was performed with assistance of oncology-specific navigation system compared with resection without navigation. Furthermore, patients in navigation group reported better functional outcome. In spite of small number of patients included in the study and relatively short follow-up, reported results support the positive impact of surgical navigation during resection of tumours involving the hip joint. 3-D customized printed templates may also be used as guiding tools to perform bone cuts in accordance to the preoperative plan [49].

Certain pathology locally affect subchondral bone and require diagnostics and treatment by accurate targeting the lesion. Avascular necrosis of the femoral head is one of them. Core decompression by drilling in combination with cell therapy has been advocated to reduce intramedullary pressure and to promote vascular reperfusion into the affected subchondral bone in potentially reverse ARCO (Association Research Circulation Osseous) stages I and II [50]. Navigation systems may be used to display drill trajectory in three dimensions. Recently, authors have reported significantly improved first-pass accuracy when using navigation during core decompression [45]. Reduced operation time and decreased intraoperative irradiation exposure have also been demonstrated when navigation was compared with fluoroscopy-guided core decompression [51]. Similar technique may be used for collecting samples of pathologic intramedullary lesions during biopsy or during subchondroplasty of cystic bone lesions [52].

Different modalities of computer-assisted navigation have been also suggested to improve accuracy of proximal femoral osteotomies [53, 54].

Our computer assistance system: EBS planning software and Guiding Star surgical navigation system

EBS planning software (Ekliptik, Slovenia) and Guiding Star surgical navigation system (Ekliptik, Slovenia) have been used on our institution on patients undergoing hip arthroscopy, PAO and resection of malignant periacetabular tumours.

EBS is an advanced medical software application developed for 3-D pre-operative planning of various surgical procedures. Data is obtained from CT DICOM format and transferred to EBS, which automatically builds 3D model of the anatomy of interest. Software enables to study full skeletal anatomy and provides segmentation of bones or selected bone fractions from the main model, 3-D planning of osteotomies, planning of optimal spatial adjustment of the osteotomized fragments and kinematic planning of FAI surgery using motion analysis. Finally, preoperative plan can be adjusted by surgeon-based preferences and exported to a data file, ready to be transferred to the Guiding Star surgical navigation system. Furthermore, EBS enables the surgeon to design personalized guiding templates based on the patient anatomy and supports export of 3-D mesh models in STL file format for the latest 3-D printing technology.

Guiding Star is a surgical navigation system. It enables electromagnetic tracking of multiple sensors to produce precise measurements with six degrees of freedom in 3-D space of the magnetic transmitter. Each sensor can be firmly fixed to the bone or attached to the surgical instrument. Having two bone structures or the bone and the selected instrument with sensors firmly attached, it is possible to precisely calculate and observe the difference in distances and orientation between the selected bone sections or between the bone and the surgical instrument. Data from sensors is reported serially to a host computer via a USB or RS-232 interface. The first step during navigation surgery is registration of surface anatomy of interest which requires sufficient number of recognizable anatomical landmarks. Point to surface registration is completed by a restricted surface matching algorithm. By strictly following the predicted placement of sensors, the system can transform all the measurements into a form easily understood by the surgeon. CT-based 3-D pre-operative plan done by EBS software can be transferred into Guiding Star navigation system. This possibility enables precise real-time tracking of correction in all three dimensions and execution according to the pre-operative plan.

Conclusion and future directions

Full pre-operative spatial assessment of skeletal pathoanatomy and motion analysis of the hip on 3-D reconstruction model of the joint has significantly changed planning strategy in hip preservation surgery. Additionally, most of currently available planning software provide platform for intra-operative assistance. Surgical navigation systems enable real-time tracking of instruments and full 3-D intraoperative assessment during execution of surgical plan. Despite limited scientific evidence, advanced 3-D planning and intra-operative navigation seem to be sufficiently reliable and accurate for clinical application in hip preservation surgery. Most of studies have been focused on arthroscopic treatment of CAM impingement and treatment of hip dysplasia with PAO. Advanced tools, including navigation and 3-D printed templates, have been found valuable in contemporary limb salvage approach for surgical treatment of malignant tumours involving hip and pelvis.

Future generation of computer assistance in hip preservation surgery should enable recognition and treatment of combination of hip pathology. Impingement before and after PAO is surprisingly frequent [55, 56]. Additionally, proximal femoral version has a significant impact on hip biomechanics and should also be considered in correction plan [57]. Evolution of planning systems based on MR imaging and optimization of imageless navigation systems is expected to eliminate potential harmful effect of pre-operative and intra-operative radiation exposure on patient`s health. At the moment, 3-D planning and surgical navigation are time consuming, require supportive technical personnel and are relatively expensive. Before becoming widely accepted, automatization of certain steps, e.g. motion analysis and intra-operative registration, is necessary. Good-quality biomechanical studies and prospective randomized control trials on larger groups of patients should be encouraged to prove its added value for clinical use. Ultimate intention is to incorporate elements of robotic assistance into surgical navigation systems. In fact, robot-navigation-assisted core decompression has been already evaluated on patients with avascular necrosis of the femoral head [58]. Furthermore, feasibility of robotic hip arthroscopy has been proven on cadavers [59]. Robotic surgery may also enable surgeons to perform more complex and precise tasks in restricted spaces.

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Data availability All the illustrations presented in this article are author's own material.

Compliance with ethical standards

Conflict of interest The author declares that there is no conflict of interest.

Ethics approval Not applicable

Consent to participate Not applicable

Consent for publication Not applicable

Code availability Not applicable

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