Computer-assisted Simulation of Femoro-acetabular Impingement Surgery

Concept and Preliminary Clinical Results

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Introduction
In the past decade, sophisticated computer-assisted methods and simulations have been successfully introduced for various applications and questions in orthopedic surgery [1]. Computerized imaging and visualization tools guarantee more accurate measurements which lead to more profound knowledge and to a better understanding of orthopaedic pathologies. They allow more accurately performed surgical interventions and differentiated, standardized evaluation of postoperative surgical outcome [2]. Moreover, virtual preoperative simulations were proven to simplify surgical planning procedures of orthopaedic operations.
Within the same time frame, femoro-acetabular impingement (FAI) has been detected as a novel major precursor of idiopathic 'primary' osteoarthritis in hip joints affecting predominantly young and active adults [3, 4]. Due to the simple mechanical collision concept of rigid bodies and newly posed questions for this new pathological entity and its treatment, FAI offers an ideal platform for application of computer-assisted methods. We describe a possible application of computer aided simulation for different unsolved clinically relevant questions in assessment and surgical treatment of this new entity.

Femoroacetabular Impingement (FAI)

Pathomechanical Concept

Hip pain in young patients has been associated with abnormal hip morphologies for decades. As an example, hip dysplasia is well known as an underlying factor which leads (if untreated) to end stage osteoarthritis [5]. Recently, FAI was described as novel, purely mechanically based concept where subtle osseous prominences of the acetabulum and/or the femur can be another possible cause (Fig. 59.1). The main concept describes an early pathological contact of bony prominences of the acetabulum and/or the femur during activities of daily living. Two types are distinguished: the *Pincer* and the *Cam* type. *Pincer* impingement represents the acetabular cause where a partial or general overcoverage leads to a linear abutment of the femoral head neck-junction with the excessive acetabular rim. *Cam* impingement as the femoral cause is due to an increase of the femoral head radius mismatching with the radius of the acetabulum. In this case, the head is jammed into the acetabulum. As a result of FAI, labral tears occur and early chondral signs of osteoarthritis could be found [4]. The proposed treatment of FAI consists of surgical removal of the osseous prominences [6] through a surgical hip dislocation [7] or a reorientation of the acetabulum with a peri-acetabular osteotomy [8].

Surgical Challenges in Operative Treatment of FAI

The overall aim of surgical interventions in impinging hips is the improvement of the clearance for hip motion and the alleviation of femoral abutment against the acetabular rim. For the acetabular side, a resection arthroplasty of the excessive part of the acetabular rim is performed. For the femoral side, the aspherical portion of the head-neck junction is excised using an osteotome. Although the basic principles of surgical remodeling of hips with FAI have been well described, an accurate method for anatomically based assessment of the severity of impingement with a quantitative definition of the femoro-acetabular range of motion (ROM) as well as quantified planning of the amount of required corrective surgery is absent. To the author's knowledge, there is no interactive visualization tool for non-invasive preoperative assessment of hips with FAI.

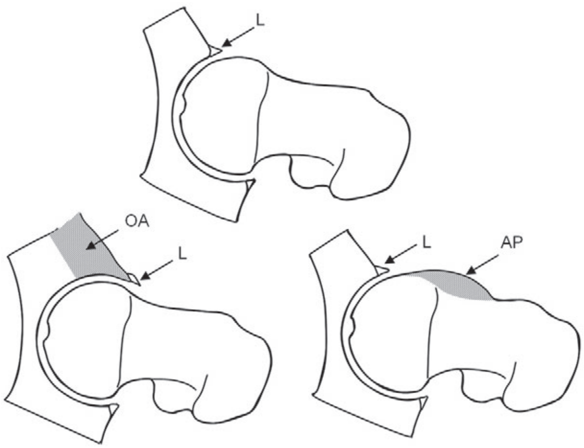


Fig. 59.1. *Top:* Normal hip with sufficient clearance for range of motion. *Bottom left*: *Pincer* impingement: The overcovering area of the acetabular rim (OA) leads to an early contact of the femoral head with the acetabulum. *Bottom right*: *Cam* impingement: The aspherical part (AP) of the femoral head is jammed into the acetabulum resulting in tears of the labrum (L) and considerable pre-arthrotic damage of the femoral and the acetabular cartilage. (Illustrations modified according to Lavigne et al. [6])

In this report, we describe our early experiences with a specifically developed software for femoro-acetabular impingement simulation including validation and the first clinical applications. Different aspects were addressed in detail including 1) the accuracy, reproducibility and reliability of the software; 2) the ROM pattern of hips with FAI in comparison to normal hips; 3) the specific impingement zone in hips with anterior FAI in comparison to previously reported intra-operative distribution of labral tears and chondral defects; 4) the effect of quantified surgical treatment for FAI on the resulting ROM.

System Description »HipMotion«

Software »HipMotion« was developed that is able to perform a computed-tomography (CT)-based three-dimensional (3D) kinematical analysis of any individual hip joint [9]. Computer hardware utilized was a SunBlade 100 workstation (Sun Microsystems, Volketswil, Switzerland). The CT scan of the patient's pelvis has to include approximately 10-cm of the proximal part of the femur and 4-cm of the distal femur covering both femoral epicondyles (Fig. 59.2). A slice thickness of 2 mm could be found to represent an acceptable compromise between data size and software accuracy. On the basis of the CT

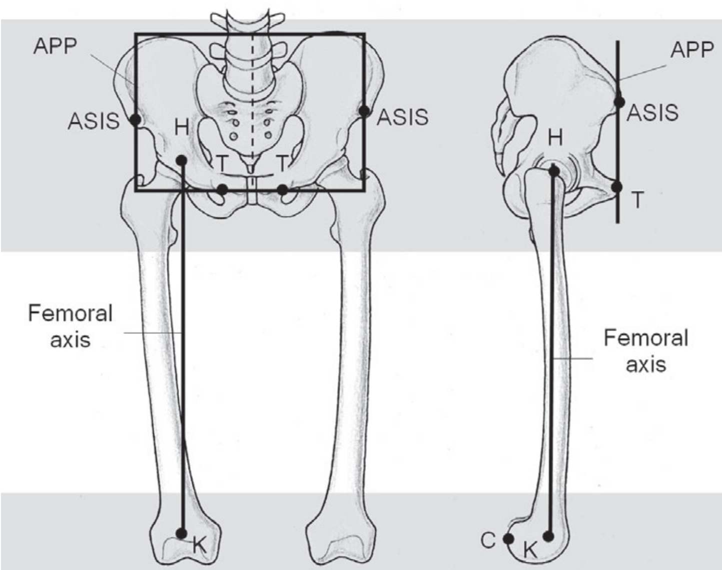


Fig. 59.2. Definition of the anatomical coordinate systems. The anterior pelvic plane (APP) as the pelvic reference is defined by both pubic tubercles (T) and the anterior superior iliac spines (ASIS). The femoral axis is constructed by the hip (H) and the knee (K) center. A neutral femoral rotation is defined with the intercondylar axis (C) being parallel to the APP. The hatched area represents the regions to be covered by computed tomography

data a virtual 3D model of the patient's hip joint is created semi-automatically. A pelvic reference coordinate system based on the previously described anterior pelvic plane concept [2, 10] is established using both anterior superior iliac spines and the two pubic tubercles (◘ Fig. 59.2). On the femoral side, in order to calculate the anatomic coordinate system the strict geometrical definition presented by Murphy et al. [11] is applied, for which the posterior aspects of the two femoral condyles, the femoral head and the knee center are digitized within the CT data.

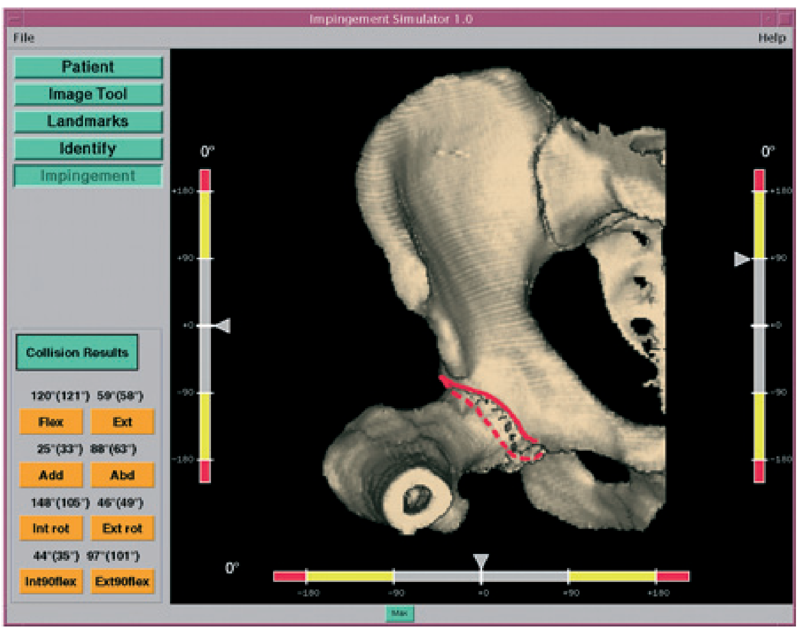
The acetabular contour is marked manually on the 3D model and is used to calculate the ROM within the individual virtual hip joint with a previously developed collision detection algorithm [12]. It enables fast and accurate calculation based on volumetric 3D models and can theoretically be used in any medical application to detect impingement between any anatomical structures and/or implant models. As a result, the individual ROM in terms of flexion/extension, abduction/adduction, internal/external rotation, and internal/external rotation in 90 degrees of flexion are displayed in a text field with the according normal mean values for comparison (◘ Fig. 59.3). The latter have been determined from the control group described later. Upon user request, any desired motion pattern can be displayed with visualization of the corresponding impingement point. The software also calculates and displays the location of all possible combinations of impingement points for a pre-defined range of motion, e.g. anterior or posterior FAI (◘ Fig. 59.4).

Quantified surgical maneuvers as trimming of the head/neck junction or the acetabular rim can be performed with HipMotion accordingly to the current standards of treatment for FAI [6]. For the acetabulum, accurate localization of the segment to be trimmed is achieved with a superimposed clockwise system and the width of the resected rim in millimeter (◘ Fig. 59.5a). For the femur, head-neck offset is created by mm-stepwise removing of the non-spherical femoral neck portion in the antero-superior aspect of the femoral head-neck offset (◘ Fig. 59.5b). At last, taking the new volumetric data into consideration, the automatic simulation of the revised ROM of the hip joint is repeated and results are related to preoperative values.

Results

System Validation

System validation was performed with both the help of sawbones and in a cadaver setup [13]. The actual ROM determined with a commercially available navi-



◘ **Fig. 59.3.** Interface of HipMotion. The actual range of motion of the individual hip joint is calculated and related to the mean values of normal hips (*brackets*). Upon user request, the hip can be rotated stepwise in any orientation with display of a possible femoro-acetabular impingement gation system (Image-free hip version 1.0, BrainLAB, Heimstetten, Germany) was compared to the predicted ROM with HipMotion (Fig. 59.6). A detailed study description and results were reported previously. Briefly, the same anatomical reference landmarks as determined on the virtual model were either digitized with a tracked pointer (all landmarks but hip joint center) or calculated kinematically (hip joint center). In summary, validation of the software with the sawbones revealed accuracy for the developed software of −0.7° ± 3.1° (range, −9°–6°) for all the 78 measured angles. Validation of the software with the cadaver hips revealed an accuracy of −5.0° ± 5.6° (range, −19°–7°). The accuracy of angle detection did not differ among the different motions neither for plastic bones (p=0.10) nor for cadaveric hips (p=0.28). The reproducibility and reliability was almost perfect for all motions except external rotation where only a moderate agreement could be found [14].

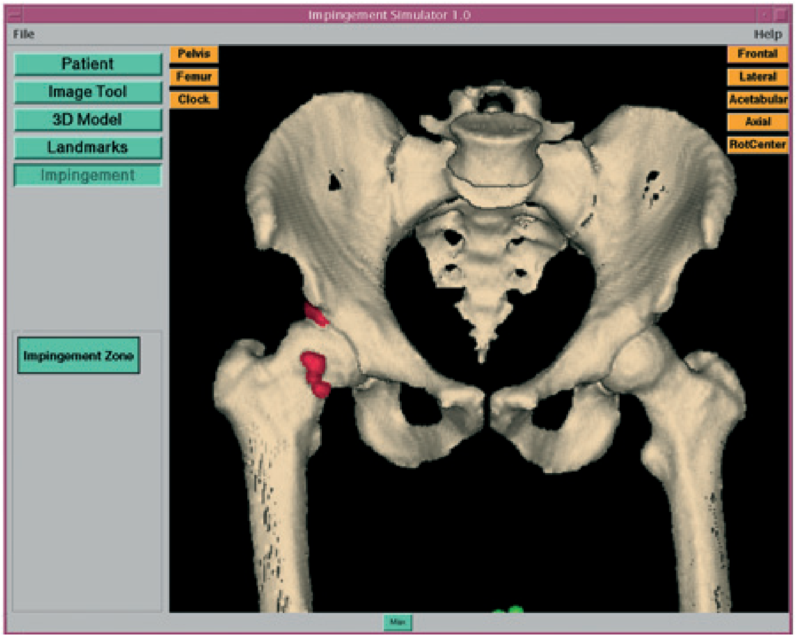


Fig. 59.4. Dependent on the individual anatomy, the impingement zones are detected both for the femur and the acetabulum with localization on the virtual three-dimensional model

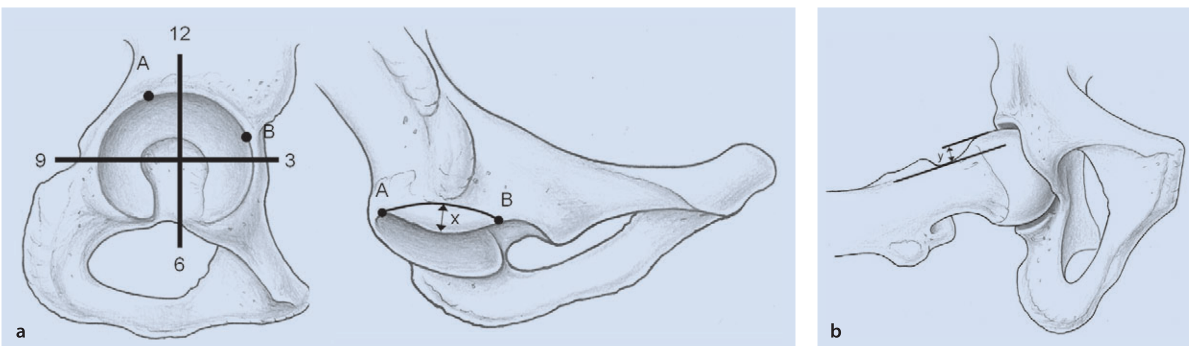


Fig. 59.5. a Quantification of the acetabular segment to be trimmed is achieved with a superimposed clockwise system and the width of the resected rim in mm (x). **b** For the femur, head-neck offset is created by mm-stepwise removing of the non-spherical femoral neck portion (y) in the antero-superior aspect of the femoral head-neck offset

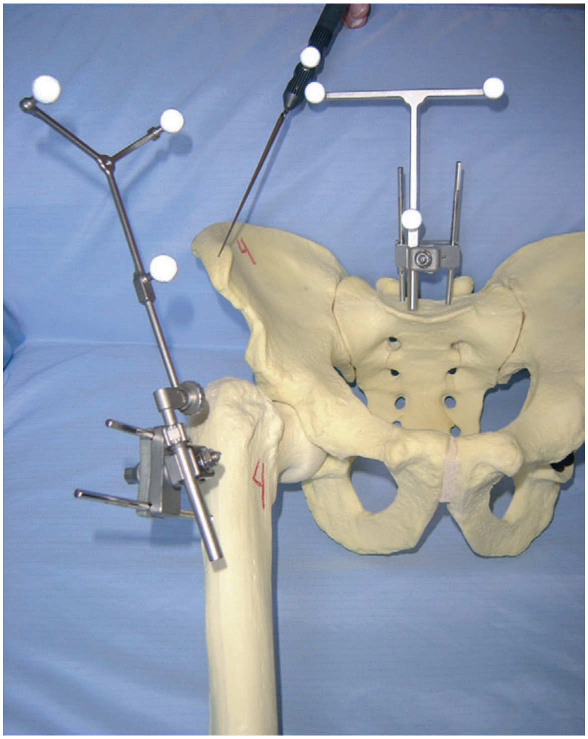


Fig. 59.6. Validation setup with the help of a navigation system. The anatomical references are digitized with a pointer. The resulting, effective ROM determined with a navigation system was compared to the predicted values with the software

Table 59.1. Exclusion criteria for the control group

Category	Specific criteria
Medical history	Total hip replacement
	Pain
	Previous hip surgery
Conventional radiographical criteria	Osteoarthritis grade > 0
	LCE < 25°
	Pistolgrip deformity
	Coxa profunda
	120° < neck shaft angle < 140°
	Acetabular retroversion
	Protrusio acetabuli
CT measurements	Alpha angle < 50°
	Femoral retrotorsion

Preliminary Clinical Results

Range of Motion of Normal and Impinging Hips

In a clinical pilot study, the ROM of normal (control group) and impingement patients (study group) were analyzed and compared with the help of the developed software. For the control group, the contra-lateral hip of 144 patients undergoing CT-based navigated total hip replacement was investigated retrospectively. All the painful hips, the hips with osteoarthritic changes and hips with radiographical signs of FAI were excluded from the control group (Table 59.1), leaving 36 patients for determination of the normal femoro-acetabular ROM. For the study group, 24 consecutive hips (16 patients) with anterior FAI were recruited prospectively from the outpatient clinic of one of the authors. The impingement group consisted of 11 cam, 6 pincer and 7 combined pathologies.

It could be shown that there was no difference of ROM for any motion between men and women. Patients with FAI had a limited flexion, internal rotation, internal rotation in 90 degrees of flexion and abduction in comparison to the control group ($p<0.001$). No difference could be found for extension, adduction and external rotation in 90 degrees of flexion (Fig. 59.7).

Among the study group, patients with cam impingement had a significantly increased internal rotation whereas patients with pincer impingement typically revealed a limited flexion.

Localization of the Impingement Zones

The distribution if impingement zones were automatically computed for all the possible combinations of flexion, internal rotation and adduction for the three impingement subgroups. The impingement zones were located antero-superiorly with various degrees of extension anteriorly or posteriorly. When comparing the frequency of these theoretical points of possible impingement with the distribution of labral lesions for anterior FAI reported in literature from other orthopaedic centers [8, 15], it was interesting to see that the theoretical impingement localization matches perfectly the location of intra-operatively observed labral and chondral lesions (Fig. 59.8).

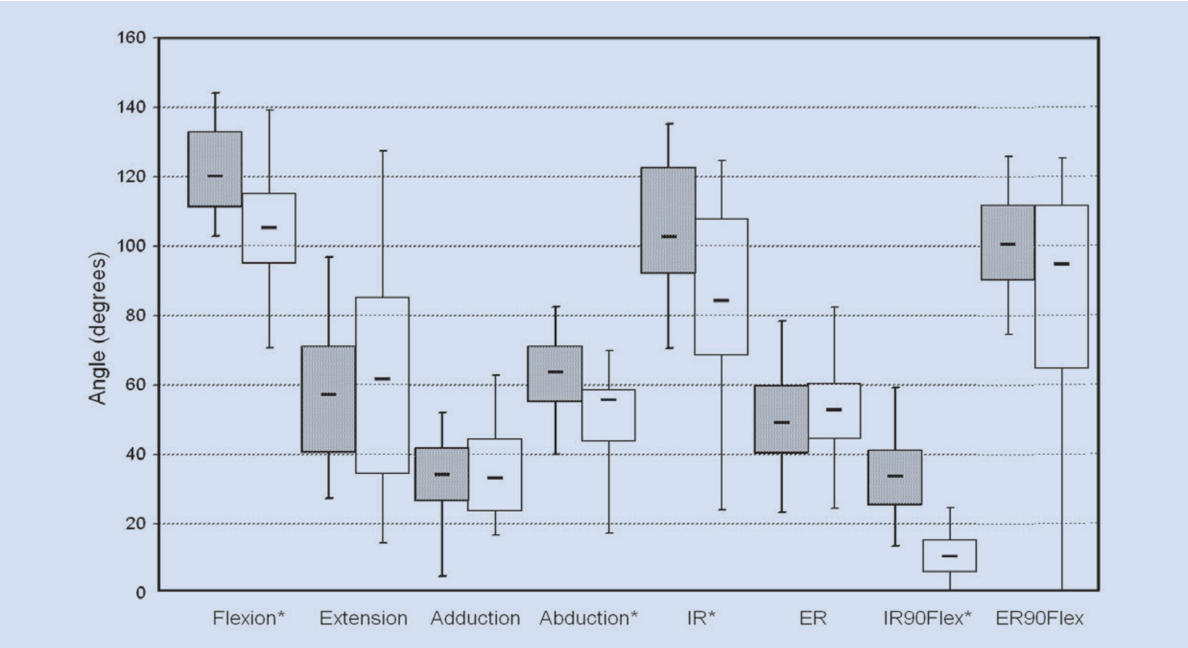


Fig. 59.7. Differences in range of motion for the control (*grey*) and the impingement (*white*) group. A statistically significant difference (*) was found for flexion, abduction, internal rotation (IR) and internal rotation in 90 degrees of flexion (IR90Flex). *ER* external rotation, *ER90Flex* external rotation in 90 degrees of flexion

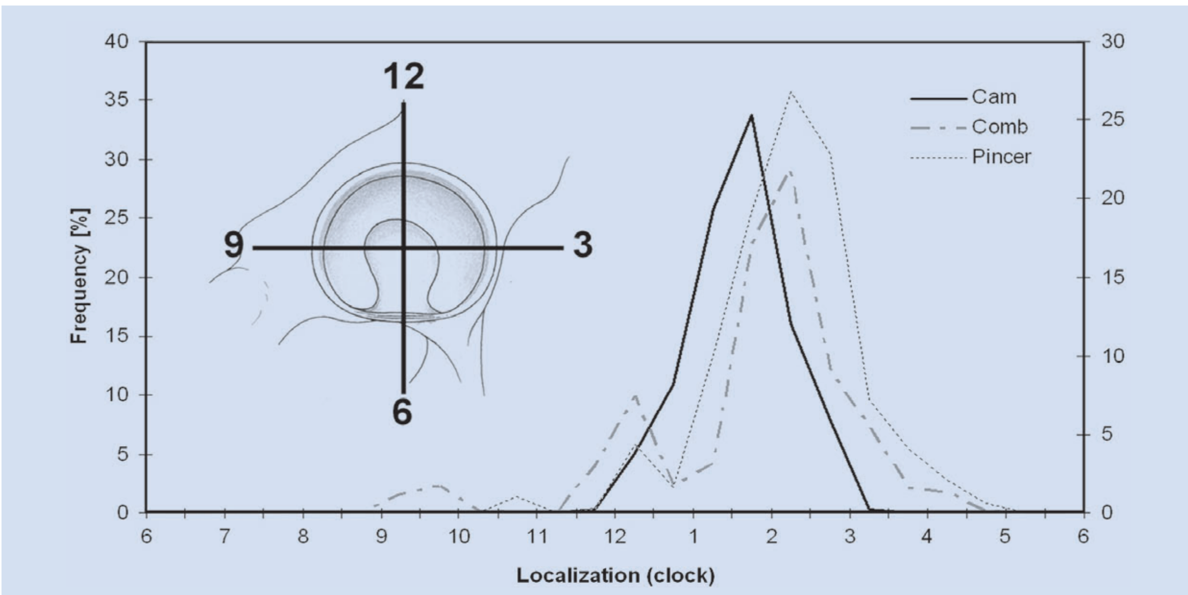


Fig. 59.8. Distribution of the sum of impingement points for the three different impingement subgroups described in the established clockwise manner. This theoretical distribution matches perfectly the intra-operative observation of labral and chondral lesions independently from the type of impingement [8, 15]

Effect of Surgical Intervention for FAI on the Resulting ROM

The effect of surgical treatment on the resulting ROM was determined for virtual acetabular rim trimming and femoral offset creation only and for a combined treatment. In order to have comparable values for all the patients, we trimmed consistently 3 mm of the acetabular rim of the individually displayed impingement zone independent from severity of impingement and individual preoperative ROM. Accordingly, the femoral head-neck offset was improved by 3 mm for each patient with a cam or combined pathology.

As a result, there was a statistically significant increase of ROM after virtual joint reshaping for internal rotation in 90 degrees of flexion and for pure flexion.

The mean improvement of internal rotation (in 90 degrees of flexion) after segmental rim trimming/femoral head neck offset creation was 5.6 degrees for pincer hips and 8.8 degrees for cam hips, respectively. For hips with a mixed impingement and a combined treatment, the mean ROM was increased by 14 degrees (8.1 degrees after acetabular rim trimming and 5.9 degrees after additional femoral head reshaping).

Discussion

Femoro-acetabular impingement is a common, often unrecognized cause of groin pain in young and active adults. Pre-operative assessment to identify the impingement source is critical to surgical management. So far, the established preoperative radiological diagnostic algorithm included a conventional antero-posterior pelvic radiograph, an axial „crosstable« view of the hip and a special two-dimensional MRI with intra-articular gadolinium contrast agent and a radial reformation technique. Recently, it could be shown that three-dimensional rendering techniques based on a CT-scan could greatly improve the visualization of the underlying dysmorphic hip pathology both for the surgeon and the patient [15]. However, this technique only included a static 3D interpretation without the option of interactive joint motion and dynamic surgical simulation.

We have developed and validated a computerized approach for three-dimensional CT-based FAI simulation. It could be shown that our software »HipMotion« represents an accurate and reliable tool for simulation of individual hip ROM, the location of the acetabular and/or femoral area of impingement and surgical simulation of the necessary osteoplasties. All measurements and surgical indicators are related to strict anatomical references, including a pelvic and a femoral coordinate system for angle calculation and a clockwise system of the acetabulum for intraoperative comparison and implementation of the planned osteoplasties. Our preliminary results of the pilot study show for the first time that – after elimination of individual tilt and rotation – hips with FAI have a significantly decreased flexion, abduction and internal rotation in 90 degrees of flexion when referred to anatomical landmarks. In addition, the benefit of isolated rim trimming, normal offset contour creation of the femoral head or a combined treatment on the resulting ROM was detected.

When comparing the location of impingement points detected in patients with FAI with HipMotion, a similar distribution to the previously reported and intra-operatively observed distribution of labral and chondral lesions was found. Therefore, the hypothesis that FAI creates joint damage at the specific location of impingement can be supported by our findings.

HipMotion is not applicable to all hips. Severely altered hips with advanced osteoarthritis cannot be analyzed reliably due to two reasons. First, a correct segmentation of the femoral head and the acetabulum is not possible since the loss of joint space hampers a reliable determination between the articular surfaces. Second, the eccentric position of the femoral head within the acetabular cup in degenerated hips does not allow a reproducible center of rotation. In these hips the hip motion does not only consist of a pure rotation but also of an additional translation which has not been implemented in our software. This phenomenon is also valid for severely dysplastic hips for which the software is not applicable either.

It would be desirable to use the proposed arthro-MRIs for three-dimensional simulation of impingement. Additional radiation exposure and costs for the patient could be reduced. In addition, important soft-tissue structures like labral and chondral lesions could be directly correlated with the location of impingement. In reality however, segmentation based on a MRI is difficult, has to be done manually and is more time-consuming in comparison to established semiautomatic segmentation techniques based on computed tomography. Another problem is the restricted field of view which is limited to the hip. Important anatomical landmarks (particularly the distal femoral or the contra-lateral reference points) cannot be digitized in this data volume.

In summary, this computer-assisted non-invasive method represents a novel approach to a pathoanatomical mechanical problem of the hip that has not been studied extensively so far with sophisticated computer programs. It will help the surgeon to quantify the severity of impingement and guide him in decision making of the appropriate treatment option. For the patient, a more logical visualization of their pathomorphology will improve the understanding resulting in a better compliance. HipMotion represents the basis for future steps where navigated instruments will allow to intra-operatively executing the previously planned osteoplasties. This could be combined with less invasive techniques such as hip arthoscopy or smaller incisions without full surgical dislocation of the hip.

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