The Digital Pre-Operative Planning of Total Hip Arthroplasty

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Abstract: Pre-operative planning is a very important part of hip arthroplasty (especially reimplantation of total hip and hip joint). Conventional pre-operative planning is realized with caliper, protractor, plastic transparent templates and x-ray images. This conventional templating technique is time consuming with many errors and impractical. This paper presents the current applications of computer technology in the field of surgery and pre-operative planning of total hip implantation. At the present time, orthopaedic surgeons use transparent template radiographs as part of pre-operative planning in order to gauge the suitability and correct size of an implant. The newly developed CoXaM software offers a simple solution to the problems by using digital x-ray images and handmade transparent plastic templates. The utilization of developed software has many advantages in the hospital unit (the elimination of storing large inventories of implants, the minimalization of errors from the magnification of templates and x-ray images, etc.). The proposed methodology provides the opportunity for comfortable, user-friendly and dimensionally accurate computer programming surgical operation. The technique is reliable, cost effective and acceptable to patients and radiographers.

Keywords: digital pre-operative planning; software; x-ray image; hip joint replacement; template

1 Introduction

Computer technology has many applications in different fields of industry, health care and medicine. This encompasses paper-based information processing as well as data processing machines (a Hospital information system or Clinical information system) and image digitalization of a large variety of medical diagnostic equipment (e.g. computer images of X-ray, MR, CT). Many of these applications allow the visualization and classification, respectively the identification and the assessment, of the diagnosed objects. The aim of the computer technology in medicine is to achieve the best possible support of patient care, pre-operative surgery planning and administration by electronic data processing.

Radiographs historically have not been standardized according to magnification. Depending upon the size of a patient, a film will either magnify a bone and joint (of large patients with more soft tissue) or minimize (in the case of thin patients). An orthopedic surgeon must estimate the degree of plus or minus magnification in order to select an implant that is the correct size. The surgeon may be helped by the incorporation of a marker that is of a known size. By calculating the difference between the size of the marker displayed on the film and the actual size of the marker, the orthopedic surgeon can identify the degree of magnification/minimization and compensate accordingly when selecting a prosthetic template. [1]

Accurate preoperative planning improves the procedure's precision [2, 3], shortens its duration [2, 4], and reduces the incidence of prosthesis loosening [5, 6] and loss of bone stock [5, 6, 7]. As well, it lowers the risk of periprosthetic fracture, helps restore femoral offset and leg length in hip arthroplasty, facilitates optimization of alignment and ensures the required implants are available while minimizing the costs [8] and complications (e.g., instability) [5, 9, 10, 11, 12, 13, 14, 15, 16, 17].

Kulkarni et. al. in 2008 devised a method whereby a planar disc placed on the radiographic cassette accounts for the expected magnification. Digital radiography is becoming widespread. Accurate pre-operative templating of digital images of the hip traditionally involves positioning a calibration object onto its centre. This can be difficult and cause embarrassment. [18]

Digital pre-operative planning enables the surgeon to select from a library of templates and electronically overlay them over the image. Therefore, the surgeon can perform the necessary measurements critical to the templating and pre-operative planning process in a digital environment. The pre-operative planning process is fast, precise, and cost-efficient, and it provides a permanent, archived record of the templating process. [19]

William Murzic et. al. in 2005 presented a study with the aim of evaluating the accuracy of a specific templating software (with an emphasis on femoral component fit) and comparing it to the traditional technique using standard radiographs. [20]

Incorrect preoperative templating of a THA might lead to inappropriate implant size and position [2, 3, 4, 5, 6, 7, 9, 10, 11, 12, 13, 14, 15, 16, 21, 22], and revision of the prosthesis might be needed. Preoperative analog [3, 9, 10, 12, 16, 23, 24, 25, 26, 27], and digital [4, 19, 21, 24, 26, 27, 28, 29, 30, 31, 32] templating methods have been studied. [17]

2   Anatomy and Morphology of a Hip Joint

The hip joint, scientifically referred to as the acetabulofemoral joint (art. coxae), is the joint between the femur and acetabulum of the pelvis, and its primary function is to support the weight of the body in both static (e.g. standing) and dynamic (e.g. walking or running) postures.

The hip joint (See Fig. 1) is a synovial joint formed by the articulation of the rounded head of the femur and the cup-like acetabulum of the pelvis. It is a special type of spheroidal, or ball and socket, joint where the roughly spherical femoral head is largely contained within the acetabulum and has an average radius of curvature of 2.5 cm. [4]
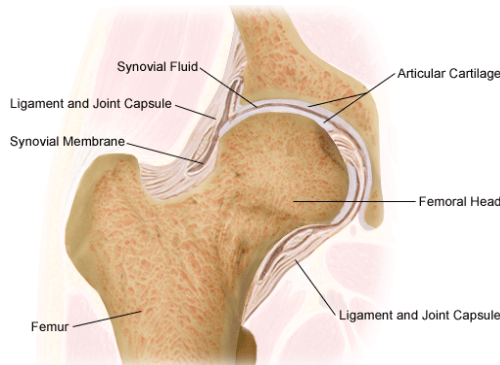

Figure 1
Right hip joint – cross-section view [42]

The hip muscles act on three mutually perpendicular main axes, all of which pass through the center of the femoral head, resulting in three degrees of freedom (See Fig. 2) and three pair of principal directions: Flexion and extension around a transverse axis (left-right); lateral rotation and medial rotation around a longitudinal axis (along the thigh); and abduction and adduction around a sagittal axis (forward-backward); and a combination of these movements (i.e. circumduction, a compound movement in which the leg describes the surface of an irregular cone) [34].
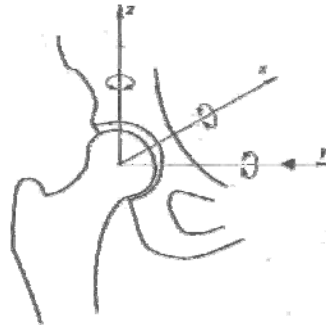
Figure 2
Three degrees of hip joint freedom

The most important morphological specifications (See Fig. 3) which can be measured on an anteroposterior pelvic radiograph are:

- the femoral neck angle (the caput-collum-diaphyseal angle, the CCD angle) – between the longitudinal axes of the femoral neck and shaft, which normally measures approximately 126° in adults,

- the acetabular inclination (the transverse angle of the acetabular inlet plane) – the angle between a line passing from the superior to the inferior acetabular rim and the horizontal plane, which normally measures 40° in adults. [33]
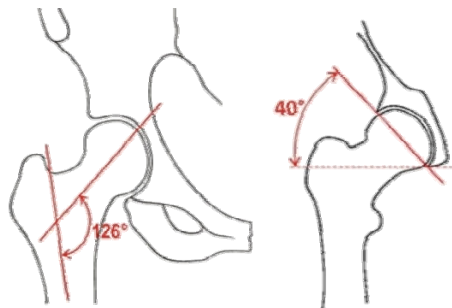

Figure 3
Femoral neck angle and acetabular inclination

The next important morphological specification is the femoral neck anteversion, which is practically unmeasured in AP projection and which can by measured well by CT or MR (3D measurement methods).

A perfect AP radiograph of the femur needs to account for the anteversion of the femoral neck. Patients are required to rotate the leg internally by a mean of 15°. Restricted rotation of the hip in osteoarthritis sometimes makes it difficult to

achieve this position. A study of the radiological dimensions of the femoral canal shows that the AP width of the medullary canal at the isthmus does not change significantly from 20° internal to 40° external rotation. At 20 mm below the lesser trochanter there is no significant change on internal rotation and an apparent increase of 1.1 mm with 20° external rotation. [35, 36]

3   Total Hip Prosthesis

Hip replacement (total hip replacement) is a surgical procedure in which the hip joint is replaced by a prosthetic implant. Replacing the hip joint consists of replacing both the acetabular and the femoral components (See Fig. 4).

Such joint replacement orthopaedic surgery generally is conducted in order to relieve arthritis pain or to fix severe physical joint damage as part of hip fracture treatment. Hip replacement is currently the most successful and reliable orthopaedic operation, with 97% of patients reporting improved outcome.
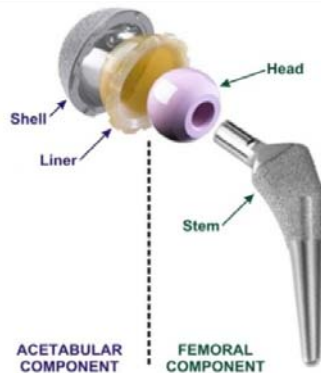

Figure 4
The modular structure of total hip prosthesis

The total hip prosthesis must be anchored securely within the skeleton for correct functioning. A loose sitting total hip prosthesis is painful, and such a loose total hip is also stiff.

There are two methods for securing the fixation of a total hip prosthesis to the skeleton [37]:

1   The cemented total hip – the surgeon uses bone cement for fixation of the prosthesis to the skeleton;

2   The cementless total hip – the surgeon impacts the total hip directly into the bed prepared in the skeleton;

The construction, form, and rehabilitation after the operation with these two types of prostheses are different.

    3   The hybrid total hip prosthesis – a cementless cup paired with cemented shaft.

With the increasing utilization of uncemented implants, templating has become more critical. With a higher risk of intra-operative fracture during insertion, it is re-assuring for the surgeon when the pre-operative prediction matches the intra-operative choice of implant. [38]

A tight interference fit is desirable when introducing the femoral component of an uncemented hip replacement. A stem which is too small may not be stable, and attempts to insert one which is too large increases the risk of intraoperative fracture. Such a complication has been reported in 3% to 24% of patients. [23, 35, 39]

Successful surgery requires the precise placement of implants in order that the function of the joint is optimized both biomechanically and biologically. Pre-operative planning is helpful in achieving a successful result in total joint replacement. Pre-operative templating in total hip replacement helps familiarize the surgeon with the bone anatomy prior to surgery, reducing surgical time as well as complications.

This activity takes time and also is subject to mathematical error. Digital pre-op planning allows for an image to be displayed electronically, and with the aid of a known sized marker, automatically calculates the magnification and recalibrates the image so that it is sized at 100% from the perspective of the user. [1]

Typically most reconstructive surgeons have used acetate overlays and radiographs to determine appropriate implant size. Pre-operative planning is realized with caliper, protractor, plastic templates and x-ray images. The measurement is time consuming and can involve multiple errors. Digital images replace radiographs, which can no longer be lost or misplaced in a completely filmless system. X-ray images are viewed on a diagnostic grade monitor, rendering prosthetic overlays useless. [19, 40, 41]

4   Digitalization of the Pre-Operative Planning by CoXaM Software

The "CoXaM" software was developed in Visual Studio 2005 (Microsoft) in the Visual C++ programming language at the Department of Biomedical Engineering, Automation and Measurement at the Faculty of Mechanical Engineering, Technical University of Košice.
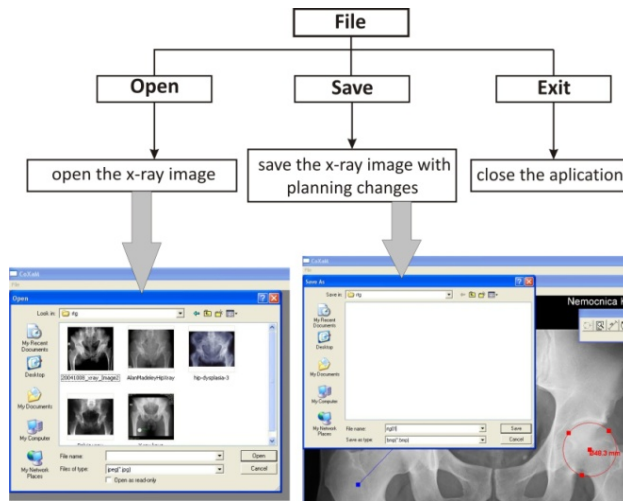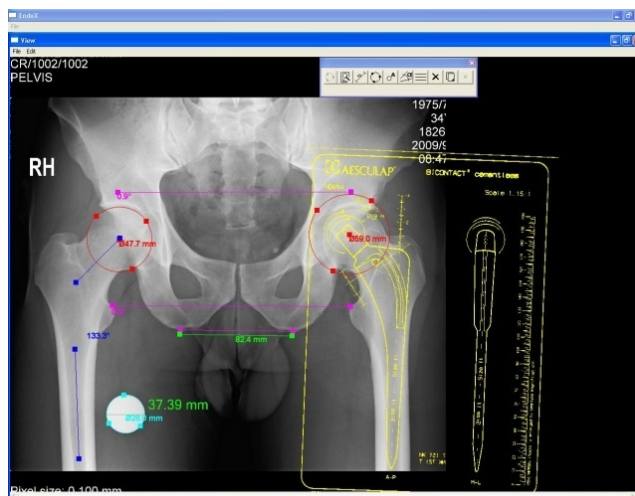
Figure 5
Overview of main menu

Figure 6
Example of using the "CoXaM" and control panel

The new, sophisticated software "CoXaM" (See Fig. 5) was designed for pre-operative planning and helps to determine on the X-ray image length dimensions, a center of rotation, and angle values (See Fig. 6). These parameters are considered in parallel with guidance lines. The software enables the digitalization of plastic templates from several producers, which will assess the suitability of the type of implant. By using digital templates, the surgeon can employ a sequential

method to determine which size of prosthesis to use and where to place the prosthesis within the bone to ensure optimum functioning of the joint following surgery. The incorporation of the various templates into the software in terms of the "magnification factor" is essential for accurate pre-operative templating and planning.
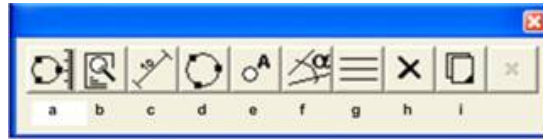
4.1   Possibilities of CoXaM Software

Figure 7

Control panel detail – a) calibration circle, b) center icon, c) measurement of dimension, d) circle, e) text, f) angle, g) examination of three line parallelism, h) removing the planning, i) templates

- Calibration circle (See Fig. 7a) – allows exact conversion of the marking dimensions for a given calibration feature on the X-ray. Determining the three-point plotted circle whose diameter in millimeters the real user enters – in this case 28 mm.

- Center icon (See Fig. 7b) – centers the x-ray image into viewport.

- Measurement of dimension (See Fig. 7c) – calculates the distance between two points. If the calibration is passed the result is in millimeters; otherwise it is displayed in pixels.

- Circle (See Fig. 7d) – from three points the software calculates the circle (center, diameter). If the calibration is passed the result is in millimeters; otherwise it is in pixels. The circles are used for finding the center of the hip joint and defining the dimensions of the femoral head and acetabular component diameter. With help of the circle you can determine the floatable center of rotation before and after surgery.

- Text (See Fig. 7e) – allows the user to enter text. The font used is Arial 12 pts.

- Angle (See Fig. 7f) – The angle between two lines (created from four points). It is not necessary that the two lines have an intersection point.

- Examination of a three-line parallelism (See Fig. 7g) – the L. Spotorno and S. Romagnoli method calculates the parallelism between three lines (created from six points) – the ischial tuberosities flowline (the base line), the superior acetabular rims flowline and the lesser trochanters flowline.

- Clearing the planning (See Fig. 7h) – removes all these tasks and clears the x-ray image.

- Templates (See Fig. 7i) – opens a digital template from the database of scanned templates from total hip prosthesis procedures. This allows calibrating of the templates and inserting it into the x-ray image. The size of the template is equal to the size of x-ray, and it is possible to rotate and move it.

At present, for preoperative planning software is used where it is necessary to define the magnification of a reference object on the x-ray image (See Fig. 8). This magnification will be determined of the real diameter and the diameter of the reference object measured on the x-ray image.

Using CoXaM software it is not necessary to know the x-ray image magnification. The user defines the value of the reference object diameter, thus eliminating the necessity of measurement (See Fig. 8).
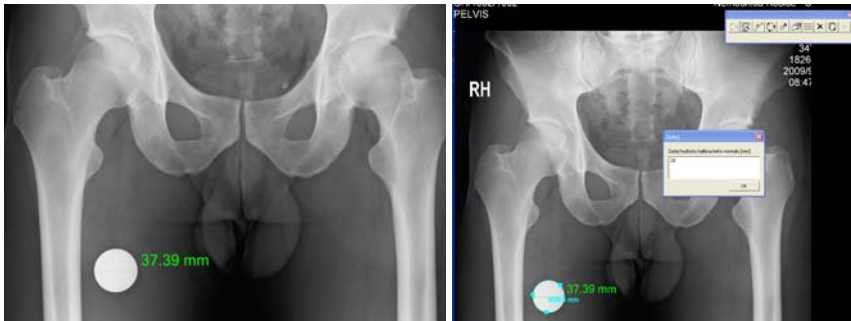

Figure 8

Software used at the present time (diameter evaluation – real diameter of the calibration component is 28.00 mm) and CoXaM software (determining of the reference object diameter)

Traditionally, an orthopedic surgeon places an acetate template enlarged to between 110% and 120% over an X-ray film magnified to between 110% and 130%. [1] An object (a disc or sphere is recommended) of a known size projected onto the film is necessary to determine the magnification.

Hendrikus J. A. Crooijmans MSc et. al. in 2009 designed a templating method using a new way of determining the hip magnification with a linear relationship between magnification of the hip and the reference object on top of the pubis symphysis; the relationship was determined on 50 radiographs. We then compared our method with two other templating methods: an analog method assuming an average hip magnification of 15% and a digital method determining the hip magnification with a one-to-one relationship between the reference object and the hip. [17]

In digital radiograph templating, the template and radiograph can be scaled to obtain identical magnifications. [17]

When properly placed, the magnification of the reference object represented the magnification of the hip (in a one-to-one relationship) and thereby enabled accurate pre-operative templating. The method required the reference object to be properly placed at the same distance from the detector as the center of rotation of the hip. Alternative methods for the correction of magnification, including using a line as a magnification reference [30], using coins placed at various positions [30, 43] as a magnification reference, using software to template digital radiographs [26, 28], or using software to template CT data have previously been described [17, 27].

For pre-operative planning for interventions of hip joint arthroplasty (implantation, reimplantation) plastic templates are commonly used. Each manufacturer offers its own plastic templates for the product of implants (types and sizes) (See Fig. 9).
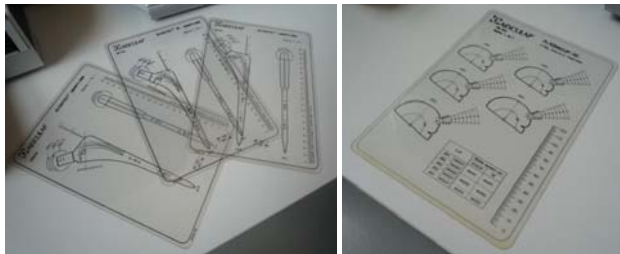

Figure 9
Plastic templates

CoXaM software works with electronic templates that are placed in a folder containing the scanned plastic templates. The user selects the required template from that folder (See Fig. 10).

In the event that the selected template was not calibrated, the next step is to do the calibration. That process is done in the calibration window, in which the abscissa is marked on the scale of the selected templates and the user inserts in the box (See Fig. 11 step 2) value. It is necessary that this value corresponds with the template scale (e.g. the scale of the template is 1,15:1, if the user marks 10 mm abscissa, then the inserted value in the box (See Fig. 11 step 2) is 11,5). After selecting the option "OK" calibration is confirmed. After that, the selected templates are drawn in yellow and applied to the x-ray image. The user can use the tool for template mirroring, in the event that the preoperative planning is for the counteractive hip joint.

It is possible to save the calibration before the confirmation; then for future reference calibration with that template is not necessary (for each template it is necessary to perform calibration when it is first used).
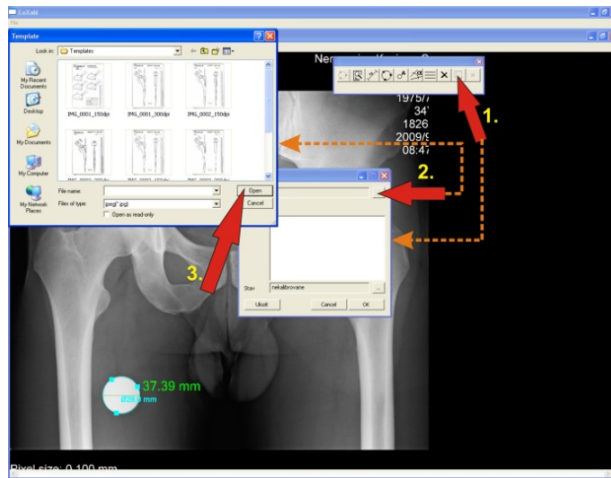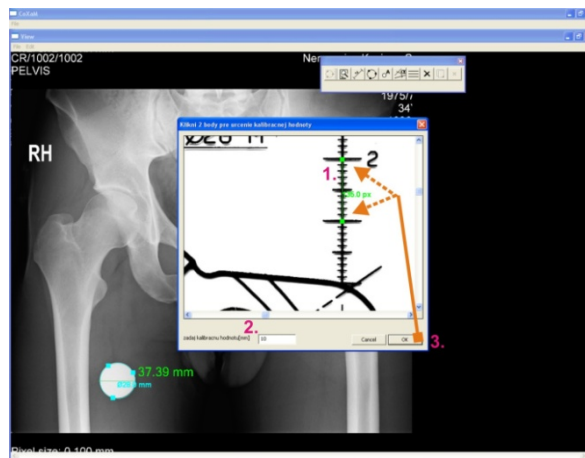
Figure 10
Selection of required template

Figure 11
Calibration process of template

The user can to move the template to the required location and rotate it around its center (See Fig. 12).

Selected orthopedic departments used a demonstration version of the CoXaM software. The respondents learnt a basic working knowledge of the software. Afterwards, the orthopedists filled in questionnaires in which they described their opinion of the CoXaM software. Learning how to use CoXaM software takes from 30 to 60 minutes, according to the results from the questionnaires. Preoperative planning for the skilled user takes from 10 to 15 minutes for each case.

Figure 12
Placement of the templates over x-ray image such that optimal fill of both

Conclusions

At present, computer and imaging technologies with electronic outputs are improving slowly but steadily in hospitals. The quality and user comfort of the software equipment often adds value during the hospital surgery planning process.

Hendrikus J. A. Crooijmans MSc et. al. in 2009 found a linear relationship between magnification of the reference object at the pubis symphysis and the hip. [17]

CoXaM offers a simple solution to the problem of using digital x-ray images and handmade plastic templates. The problem is solved by the digitalization of templates for use in software. The developed software combines digital x-ray images with digital templates for planning implantation and reimplatation interventions of hip joints.

The new proposed methodology provides the opportunity for comfortable, user-friendly and dimensionally accurate computer programming for surgical operations. The technique is reliable, cost effective and acceptable to patients and radiographers. It can easily be used in any radiography department after a few simple calculations and the manufacture of appropriately-sized discs.

The CoXaM software provides several advantages for orthopaedic surgery. X-ray film is no longer necessary. There are no radiographs to store, lose, or misplace. Over time this results in a cost savings as film and developing supplies are no longer needed. The disadvantages include the initial cost of outfitting the technology.

As digital technology improves and becomes more accessible to the health care industry, digital radiography will be used by an increasing number of hospitals and

orthopedic practices. More practices will become filmless and software programs will be necessary for successful reconstructive planning and templating. Significant clinical studies are planned to statistically confirm the qualitative value of the software and quantitative precision of the output parameters.

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