Integrated Digital Engineering Methodology for Virtual Orthopedics Surgery Planning

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Abstract— **The present work addresses the issue of Digital Engineering (DE) and Digital Information Services in general as applied to Orthopedics Surgery. In particular, the focus is on Total Hip Replacement (THR) with the use of Computer Aided Engineering (CAE) tools and practices.**

Initially, current THR practices and the reasons that novel processes are necessary are given. The problems and shortcomings of current methods and processes for THR are analyzed. A presentation of the proposed methodology follows, along with a description of the developed customized implant. The steps required are detailed in their natural order. Digital Imaging (DI) data are recovered from a Computer Tomography (CT) device. The 2D data acquired are processed with the use of custom developed software in order to become a fully 3D defined geometrical description of the patients hip bone structure. This geometry serves a dual purpose, since it is used for evaluation of the bone's stress conditions, as well as, for the planning of the surgery and training of medical stuff. Modern Computer Aided Engineering (CAE) methods, in particular the Finite Element Method (FEM), are used to asses the biomechanical behavior of the bone-implant system under various loading conditions. A Virtual Reality (VR) installation is proposed, to assist the surgery planning with Real Time (RT) simulation of the implant's positioning and the review of the calculation results. Finally, THR demographic data are presented, explaining the motivation for this work.

I. INTRODUCTION

Modern lifestyle and the overall aging of Europe's population have increased the number of people suffering from chronic musculoskeletal pains and motor impediments. Advances in biomechanical science, over the last decade, have assisted in understanding musculoskeletal diseases and in their early diagnosis and treatment. DE tools have had a significant effect on medical technology and surgery practices. The design and analysis of artificial implants is an excellent example of DE practices as applied to modern orthopedics.

THR is a widely applied operation aimed at restoring damaged hip joints with the use of artificial implants. These implants replace the patient's hip joint with a mechanical device that mimics the bone – hip connection [2] [figure 1]. Although THR has been used for many years, the operation's results are not always satisfactory. This is especially true, when the responsible disease (osteoporosis, arthritis…) is at an advanced stage and causes anatomical malformations.

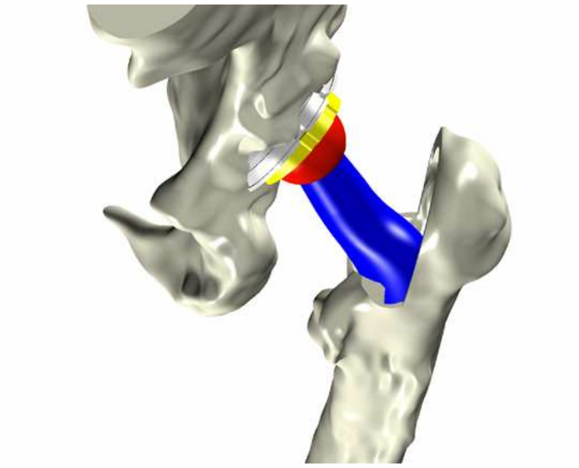

Fig. 1 Typical THR implant

Present THR has some limitations, leading to compromises in the operation procedure, as well as, post operation problems affecting the patient's life quality and the implant's lifespan. Such shortcomings can be the:

- insertion of the implant with minimum traumatic surgery,
- determination of the actual acetabulum and creating a new socket for the acetabular component,
- preparation of the femur canal for the insertion of the femoral component,
- selection of the proper type and size of the implant,
- proper anteversion of the femur and
- post operation balancing of the lower extremities.

Using an integrated DE methodology for THR alleviates a number of these problems [3]. Inserting the implant in the femur and determining the proper anteversion are easier. Calculating the proper implant geometry, with regard to the length and orientation of the femoral component, makes it easier to define the distance between the pelvis and femur. Finally, maximum contact surface is achieved between the implant and the femur, leading to optimized load distribution.

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II. METHODOLOGY

The proposed methodology comprises of several steps [figure 2]. Initially, the patient in need of THR is examined, with the use of a CT system and the images, acquired from hospital scanners, are collected. Processing of the images follows, to prepare the data for the construction of 2D curves corresponding to cross sections of the patient's bone structure. With a user driven, automated technique the images produce a detailed 2D geometrical representation of the bone, for each one of the input cross sections. Finally, a 3D reconstruction of the pelvis and femur is created by joining the 2D curve data.

The aforementioned 3D geometry is helpful for accurate surgery planning, fitting, as well as, choosing a suited standardized hip endoprosthesis or designing a customized one, if required. Furthermore, it is possible to simulate the bone-implant system under diverse operating conditions. With the use of FEM, the stress levels developed at the bones under specific loads are evaluated.

If the stress levels are within the proper limits, the endoprosthesis is accepted and in case of a customized implant can be forwarded for production with the use of a Rapid Prototyping (RP) system.

This process is supported with interactive VR applications [4] that provide the medical stuff with valuable insight and can also double as an excellent educational tool.

It should be noted that the described process is designed to work in several iterations, if necessary. In this way, problems encountered at any stage are corrected and the improvements are propagated back to the original design.

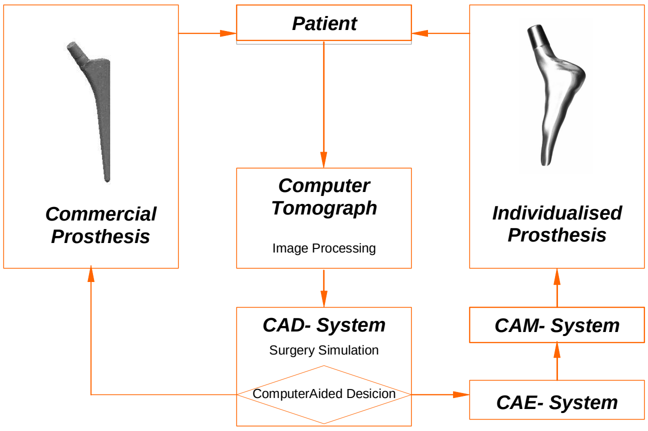

Fig. 2 Proposed Methodology [1]

III. DATA ACQUISITION, PREPROCESSING AND BONE RECONSTRUCTION

A. *Data acquisition from CT Scanners*

The data used comes from CT scanners, the standard format that CT scanners use to exchange data is Digital Imaging and Communications in Medicine (DICOM). Professional image toolkits are used to convert the data to an appropriate format for further manipulation in the software.

B. *Boundary extraction methodology*

Images from CT scanners are usually noisy or have reduced resolution. In order for the process of boundary extraction to be as successful as possible a further step must be taken, image enhancement/clearing. This step consists of image filtering, cropping and application of edge detection algorithms so that the data can then be used as an input for the boundary extraction algorithm [5].

For the boundary extraction, active contours models were used. Active contours models also known as snakes are energy minimizing curves that deform to fit image features. They are used extensively in computer vision and image processing applications, particularly to locate object boundaries. Snakes are curves defined within an image domain that can move under the influence of internal forces coming from within the curve itself and external forces computed from the image data (image force field). The internal and external forces are defined so that the snake will conform to an object boundary or other desired features within an image. In our particular application the feature of interest are the internal and external boundaries of the bones.

The process of boundary extraction is user driven as previously mentioned, the user must define an initial contour near the feature of interest and the algorithm will extract the nearest feature. The initial contour can be very simple e.g. a circle around the bone to extract the outer boundary.

There are two key difficulties with active contours models. First, the initial contour must, in general, be close to the true boundary or else it will likely converge to the wrong result. The second problem is that active contours have difficulties progressing into boundary concavities. Several methods have been proposed to address this problem. Gradient Vector Flow (GVF) image force field described in [6] and [7] was chosen for improving the initial image field so that the initial contour given manually by the user is not required to be too close to the target boundary. This method of computing the image force field also sufficiently addresses the problem of progressing into boundaries concavities.

Another consideration is the performance of the whole boundary extraction process, several known optimization techniques were applied (e.g. [8],[9]) for the fast converge of the active contours.

C. *3D Reconstruction*

Having all the points of each contour, the points are interpolated using cubic splines. A knot removal algorithm is then applied in order to reduce the necessary data and smooth the contours. The splines can be further modified through control point adjustment in the editor of the software. After the processing of the contours is completed, the selection of the contours which will be stacked together is done manually by the user. In that way all the individual branches of the object (bone) are created and then joined. For the final 3D surface reconstruction a skinning algorithm is used, the final skinned surface of the bone is a two parameter function (u,v), the u parameter is defined by the boundaries obtained and the v parameter is defined automatically by the skinning algorithm. Special care is taken in order the final surface does not have C1/G1 discontinuities. Later the final 3D parametric model is converted to a triangular mesh according to a desired resolution and then visualized using OpenGL graphic library.

D. Data exchange and integration

The parametric model created from the 3D reconstruction process can be extracted to standard 3D formats (polygonal or not) for use in other software for further processing like CATIA.

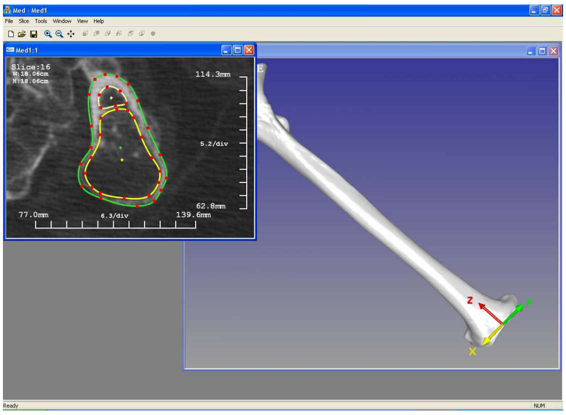

Fig. 3 3D reconstruction software

IV. ENDOPROSTHESIS SELECTION AND CUSTOMIZATION

The 3D reconstruction of the patient’s bone structure can be used for the selection of the implant. Using a library of 3D models for standard commercial implants, a fitting analysis can help determine the optimum model. The selection is based on contact surface, insertion path and geometrical conditions that are examined with the use of advanced CAD systems.

The choice of a commercial implant is not suitable for several patients, especially when highly irregular formations of the bone structure occur. In this case, given the 3D geometry of the femur and pelvis, a customized endoprosthesis can be designed. This kind of implant has the advantage that it can be tailored to specific requirements. The final design is then programmed for production by RP facilities.

V. BIOMECHANICAL ANALYSIS

Following the selection, or design, of the implant, a biomechanical analysis is applied, in order to determine the stress levels at the patient’s bone structure. This kind of analysis is based on standard engineering methods, used for decades in the manufacturing industry.

A. CAE, Geometrical Fitting, Packaging

The use of CAE applications facilitates the determination of an optimum implant in terms of fitting. In particular, the geometry of the implant can be positioned inside the femoral canal geometry, in order to determine the contact or overlap areas. Furthermore, the full assembly of the pelvis, implant and femur can be examined for the proper geometrical packaging.

B. CAE, FEM

A FEM analysis is performed for the femur under typical loading conditions for this kind of application. In more detail, initially the femur and implant 3D geometries are transferred to a CAE system. Material properties for the bone and the implant are assigned to their corresponding geometries, which are then discretized, meshed, into volume, tetrahedral, elements. The FEM modeling is completed by applying the proper boundary conditions and loading [9] that simulate a worst case scenario, considered as a benchmark [10] for evaluating hip implants [figure 4].

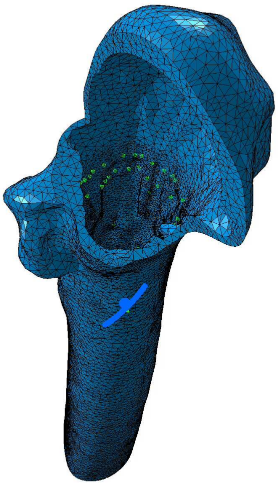

Fig. 4 Femur mesh

Once the modeling is complete, the solution phase follows. The FEM analysis results, mainly in the form of Von Mises Stress, are compared to the maximum allowed stress values for the femur material. This analysis can reveal sensitive areas where the strength of the femur is compromised. Furthermore, it serves as a pointer for improvements and optimization of the implants geometry [figure 5].

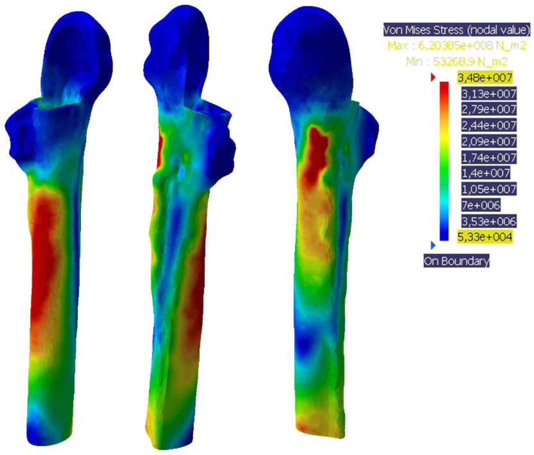

Fig. 5 Stress results on the femur

VI. SURGERY PLANNING

Surgical implications are often depended on the duration of an operation. Thus, it is imperative that the surgeon is as much prepared as possible before operating on the patient.

So far, it was possible to obtain knowledge of the patient’s anatomy only with the use of 2D scans. Using 3D data and VR tools, better insight is given and surgery planning is improved and it is possible to simulate the operation beforehand.

Finally, with respect to standard medical protocols, the information is stored for future use. Surgery report generation is automated to facilitate future revisions and follow ups of the patient’s medical condition [figure 6].

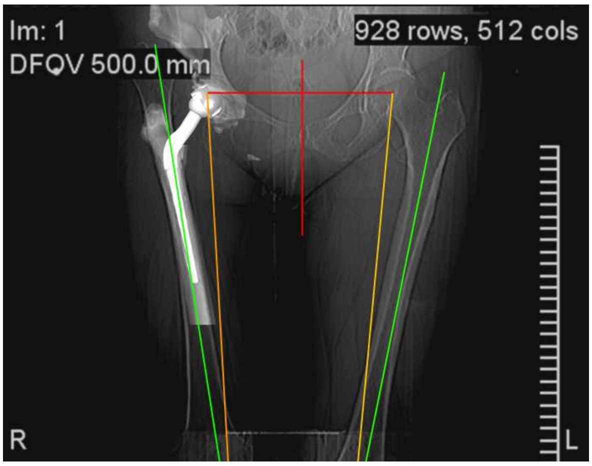

Fig. 6 Surgery Planning

VII. PRODUCTION PLANNING

In case a customized implant is dimmed necessary, the existence of the 3D geometry makes it easy to proceed to its production.

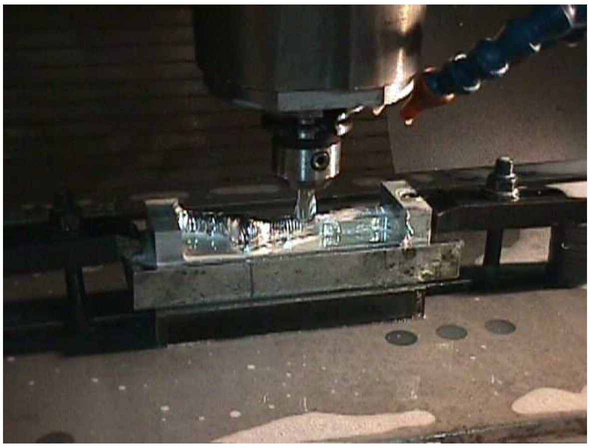

Fig. 7 Implant Production

This achieved by extracting the geometry to a format used by RP equipment, usually as a Stereo Lithography (STL) file, and further processing it. The final programming is then fed to the Numerical Controlled (NC) milling machines that manufacture the final product [figure 7].

VIII. DEMOGRAPHICS

The proposal to develop a fully integrated procedure for THR is further supported by demographic data. Future projections of the THR market predict an estimate of 885.7 million €. So far, in Greece hip implants are imported. A number of 6000 operations annually is estimated, costing roughly 20 million € to the National Health System for the imports. Lack of technical knowledge and versatile production facilities are responsible for the non existence of local production.

IX. CONCLUSIONS, FUTURE WORK

The use of DE tools is of enormous help to medical staff and surgeons in particular. Regarding the application of such methods to THR, it is possible to speed up operation and recovery of the patient with proper selection of the implant and surgery planning.

More detailed models, in terms of geometry, material and boundary/loading conditions, can be used in the future to increase the accuracy of the simulations. Furthermore, various types of CAE analysis, besides FEM, should be used for the same reason.

Finally, providing the whole process in a standalone package, with minimum user input, from CT images to final report, would be extremely beneficial. Especially for medical staff, that is not trained to use commercial CAE applications.

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