

METHOD OF EXTRACTING HIP JOINT BONES FROM C.T. IMAGES IN ORDER TO PERFORM STATIC F.E.A. STUDY

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Development of virtual simulation in biomechanical field attracts prostheses manufacturers because of the possibility of pre-testing the product at different loads or daily life situations, for the prosthesis itself and for better understanding of joints loads discharge. This method allowed specialists to predict the product mechanical behavior and to evaluate it, in order to decide if the implant can pass at the ex vivo experimental step or to design a customized prosthesis. This paper aims to develop a methodology of extracting hip joint bones from patients C.T. (Computed Tomography) scans in order to create C.A.D. (Computer Aided Design) files which will be used to perform static F.E.A. (Finite Element Analysis) study in dedicated software.

Keywords: virtual simulation, static study, hip prostheses, implant, hip, femur, automatization

1. Introduction

Nowadays, both virtual prototyping and virtual simulations of products which will be proposed for manufacturing are increasing in all industrial areas. Virtualization has begun to be seen with great interest in the biomechanical field, especially due to the low testing costs by the use of F.E.A. (Finite Element Analysis) that helps us to predict the behavior of implants in various situations or daily tasks to which the human body is subjected. Although this segment of virtualization for the biomechanical sector remains limited due to the complexity of the human body's shape and structure, prototyping and virtual testing successfully predicts the main failure scenarios of various implants and there are continuous improvements due to the constant upgrades of specialized software.

In case of total hip replacement, we can speak of a prototyping and a verification of the interaction between the patient's bone tissue and hip implant only in special situations, if we are talking about accidents from which results severe hip joint trauma or if we are dealing with rare malformations. Because of additive manufacturing technology, more and more researchers are developing custom hip implant models based on patients' C.T. (Computed Tomography).

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Researchers such as Jie Wu et al. or Simina Vasilache have developed methods of bone segmentation with the help of C.T. of patients who suffered accidents that produced pelvic fractures [1] [2].

Even if the results in the automatic 2D detection of osseous and soft tissues become more and more precise, if we look at the method used by Jeff Calder et al. [3] or the 3D bones segmentation procedures set forth by J. Zhang et al. [4] in the case of vertebrae, by using specialized bone segmentation software such as ScanIP from Simpleware that helps the engineer to build and test different implants, such as the hip prosthesis, still involves knowledge in medical trained personnel because of the fact that segmentation time lasts due to X-Ray frames constantly checking, operate software knowledge and also anatomical acquaintance in order to be able to separate tissues.

2. Medical image typology and processes used in bone segmentation

The X-Ray (2D electromagnetic radiation image) is one of most common type of medical image used by orthopedic surgeons in order to realize the preoperative planning of a T.H.A. (Total Hip Arthroplasty) or to understand the gravity of bone fracture. With the ongoing technological progress, this type of image files used in orthopedics are becoming a limitation because of the difficulty to convert it in a 3D images and in a C.A.D. (Computer Aided Design), files used in virtualization processes. Because of this, biomechanical engineers have found the solution to convert and store these type of images as D.I.C.O.M. (Digital Imaging and Communications in Medicine) files. D.I.C.O.M. files represent a codification way and transfer of medical and associated images obtained from special medical devices such as C.T., M.R.I. (Magnetic Resonance Imaging) or ultrasounds.

In this paper we used the C.T. images of a male patient, with a total of 1559 frames of the whole body, from which we extracted only the bone tissue from the left femur and the pelvis.

The quality of the final 3D file that we want to extract with the help of Simpleware ScanIP software is linked to the quality of the D.I.C.O.M.; in this category we can distinguish the gray level, the contrast, the edges, the number of frames and the distance between them (the quality increases with the number of frames and by diminishing the distance between them) [5] [6]. In most cases the images present noises because of the image acquisition, the conversion of optical signal in electrical signal or various fluctuations. To restore the image balance, we can eliminate the noises of the D.I.C.O.M. files by applying algorithms in order to filter the disturbing noises, such as: contrast balance, light balance, Gaussian filter, edge enhancement, intensity scale, adaptive smoothing, etc.

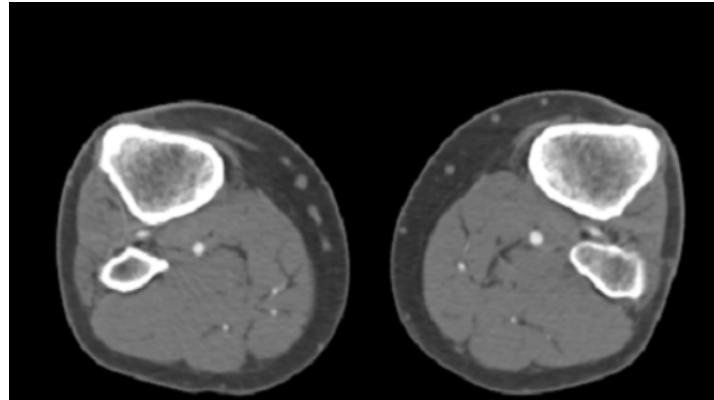


Fig. 1 Patient D.I.C.O.M. file used to perform bone segmentation

Bone segmentation is the particular operation with which we reconstruct the femur and pelvis by overlaying the pixels and separating the soft tissue of bone tissue in order to extract the bones' parts we are interested on. There are different type of algorithms used in specific cases to reach the final bone extraction: Otsu algorithm (by calculating the binary threshold) [7] [8], connected threshold [9] (evaluating the intensity in a particular interval), neighborhood connected [10] (it determines if a pixel from a close area belongs or not to the particular area in which this filter is applied), Watershed algorithm [11] (is a delimitation and separation of the grayscale level), isolated connected algorithm [12] (connecting the pixel with another by identifying if it belongs to the same area), level set segmentation algorithm [13] (is able to detect two different shapes and split them in two parts) and confidence connected algorithm [14] (relying on statistics from the selected area).

By using a combination of algorithms in order to proceed with the bone segmentation, we can extract a more accurate 3D model representation which is used to perform static studies in a hip joint traumatic accident situation.

3. Methodology of extracting bone tissue by using Simpleware ScanIP

Simpleware ScanIP is a software dedicated to process 3D medical image data by using a variety of algorithms and combined algorithms in order to achieve the desired result with the possibility of exporting in C.A.D files.

To start the images analysis, we import the D.I.C.O.M. images by selecting the D.I.C.O.M. directory and add all the frames: a crop and resample window will open and we can choose a pixel rescaling, a pixel skip and if we want to crop the files or not. After importing the data, a four windows view will appear and in this way we have the possibility to work in horizontal plane, vertical plane, side plan and verify our applied algorithms by refreshing the perspective

view. Since we want to create C.A.D. files and perform static study on the pelvis and femur separately, we need to extract one component at a time: the femur first, and then the pelvis; we need to proceed in this way because otherwise the software will recreate the mesh for the whole solid body and “acting” as one single piece.

In order to extract the femur, we chose to work in two views (in the horizontal plane and in the vertical plane / side plane) for better accuracy, starting by using the *Threshold* tool, choosing a lower and an upper value and selecting the option *Profile line* with which we can select two points along the entire hip and the software will automatically separate most of the soft tissue from the bone tissue (Fig.2). In order to isolate the femur, we used the *Crop* tool which can cut the 3D image by using reference planes: in this way we can focus on the specific area that we want to extract from the C.T. files.

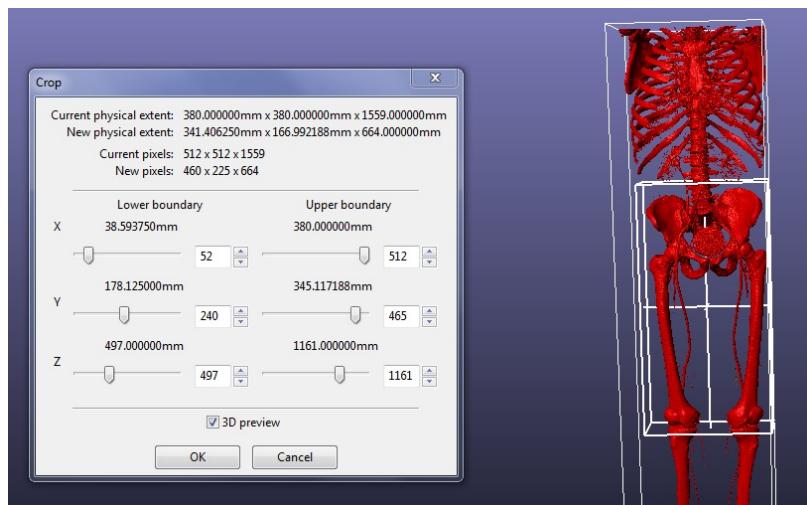


Fig. 2 Image processing with *Threshold*, in order to obtain the bone tissue in Simplware ScanIP

In most of cases, after the *Threshold* algorithm residues of other tissues that interfere with the profile line will appear, and this effect can be eliminated by using the *Island Removal* tool with a specific voxels size that we can choose depending on the situation; this algorithm helps us to “clean” the 3D image from the small residues.

Since in the previous image (Fig.2) we can notice that the algorithm applied selected also the femoral arteries, we proceeded through processing the image by using a *Region Growing* tool, and selecting the femur in a particular frame which offer us a better horizontal view, where we can distinguish well the femur. By using this tool in the active view area and creating a new mask overlapped on the initial mask, we can isolate and recreate the entire femur in all

the frames by applying it several times, until the bone is fully covered by the mask.

After checking the other frames, we observed that the new mask didn't cover all the bone tissue and there still were pixels in the initial mask that weren't covered by the new created mask: in order to fix this problem we can increase the multiplier and the *initial neighborhood (pixels)*, and select the areas where the second mask didn't cover the initial one.

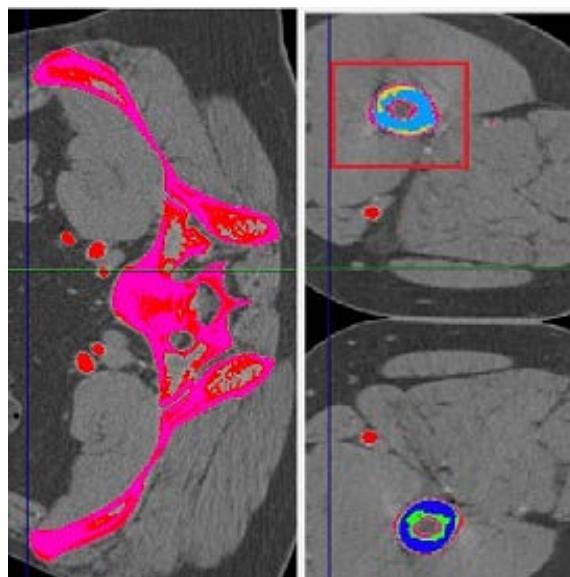


Fig. 3 *Region Growing* algorithm applied on D.I.C.O.M. in Simpleware ScanIP

Since we wanted the model to be as much accurate as possible, we chose to use a *Paint with Threshold* tool which helps us to select the pixel that we want, in order to cover all the bone tissue for every D.I.C.O.M. image frame.

For the image finishing we used a *Close* tool with cubic values for the active mask, in order to close all the small gaps between the pixels and to define better the final surface, and also a *Recursive Gaussian* with cubic values to provide more smoothness to the surface.

After arriving at the desired result we generated a model surface according to our masks, and then deleted the masks that we didn't need anymore; we could then export it as a binary S.T.L. (Stereolithography) file which can be used to perform the static study in a software with F.E.A. extension.

We proceeded in the same way to extract also the pelvis, with the mention that the best views to work in order to extract a more accurate model are the horizontal plane and the vertical plane.

In most cases after extracting the bone tissue in Simpleware ScanIP, we need to re-mesh the surface because of its complexity: additional simple software

can be used to reduce the mesh, or redefining the surface, otherwise the static study will be slow or the system could easily crash.

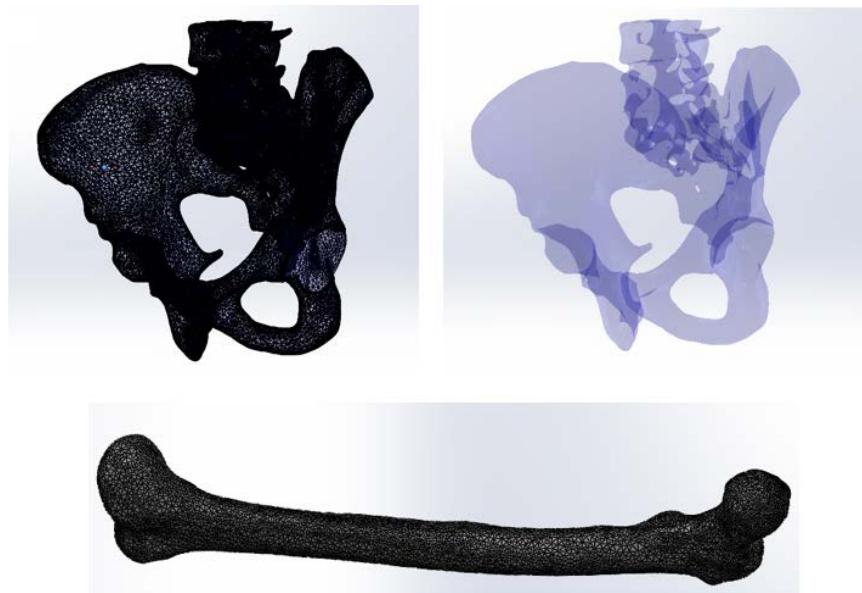


Fig. 4 C.A.D. models of pelvis and femur extracted with Simpleware ScanIP

6. Hip and femur Static F.E.A. Study

The F.E.A. studies are a convenient alternative to understand the mechanical behavior of bones at different loads or specific situations that can occur in the daily life activities. The bone tissue is a complex organic material that combines two types of tissues, cortical and spongy, with different mechanical properties.

The cortical bone (also called compact or lamellar bone because of its osteons distribution) is a tissue that offers excellent mechanical properties because of its strength [15], situated at the external part of the bone and being responsible of the most part of human body weight; it has a Young modulus of 17 000 MPa, a 0.3 Poisson ratio and a density of 1800 kg/m³.

The spongy bone (also called cancellous or trabecular bone) covers most of the internal part of the humans' bones (especially the bones which connects other limbs by forming an articulation like the head of the femur, which is fully covered by spongy tissue in the interior); it is a weaker tissue, less dense and also less stiff than the cortical bone [16], with a Young modulus of 600 MPa, a 0.2 Poisson ratio and a density of 1300 kg/m³.

For this particular static study we chose to use cortical bone for both hip and femur because of its better mechanical properties, considering the hip and the femur as if they were made by a homogeneous, linear elastic and isotropic material.

a. Hip F.E.A. Static Study

The imported hip that was extracted with ScanIP Simpleware was treated as a solid body with a standard solid mesh type that has 4 Jacobian points, ~9.98 mm element size and a tolerance of ~0.49 mm. In order to perform the study, the hip was fixed on the vertebral disk area and around the exterior part of the acetabulum. We applied a force of 2000 N in the acetabulum cup which is equivalent of a high shock in the hip that can occur in many accident situations.

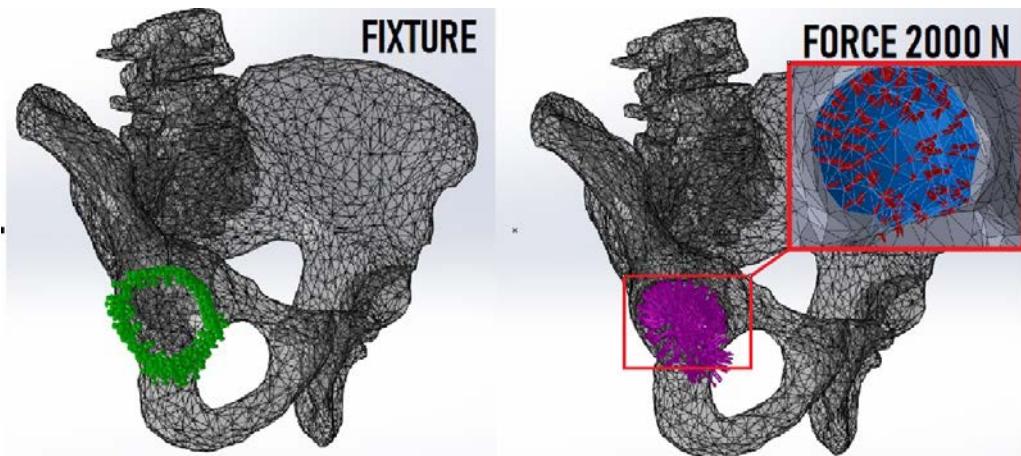


Fig. 5 Hip Fixture and force applied inside the acetabulum cup

The C.A.D. model contains a number of 82 089 nodes and 50 220 elements with a maximum aspect ratio of 84.5.

Table 1

Hip Static Study - Resultant forces

Selection set	Sum X [N]	Sum Y [N]	Sum Z [N]	Resultant
<i>Hip C.A.D. model</i>	649	724	754	1230

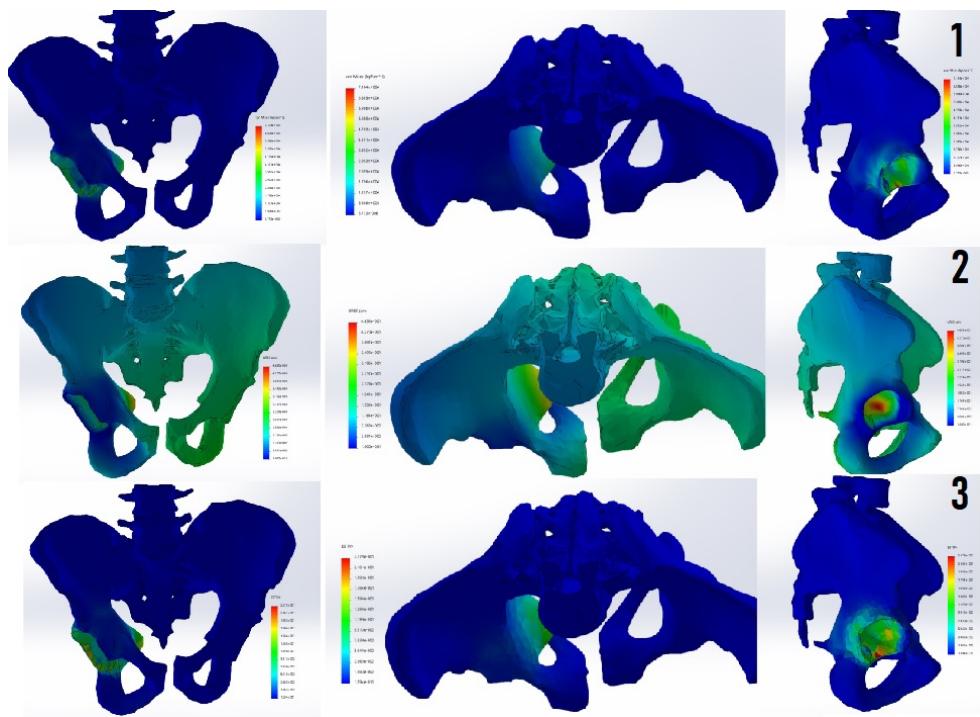


Fig. 6 Hip F.E.A. Static Study Results: 1. Stress Results; 2. Displacement Results; 3. Strain Results

The results have shown a minimum of 5×10^{-6} MPa in node 36 135 and a maximum of 4.4 MPa in node 706 for the stress, a minimum of 0 mm in node 12 and a maximum of 0.003 mm in node 79 851 for displacement and a minimum of 1.3×10^{-14} in element 35 021, a maximum of 1.4×10^{-4} in the element 17 618 ESTRN: Equivalent Strain.

b. Femur F.E.A. Static Study

The imported left femur that was extracted with ScanIP Simpleware was treated as a solid body with a standard solid mesh type that has 4 Jacobian points, ~ 8.48 mm element size and a tolerance of ~ 0.42 mm. In order to perform the static study, the femur was fixed on the inferior part where is forming the knee articulation, a force of 2000 N was applied on the femur head which is equivalent of a high shock in the hip articulation and also a pressure of 24 MPa was applied along all the femur, which is the equivalent to the muscular pressure on the bones according to scientific measurements [17] [18].

The C.A.D. model contains a number of 56 384 nodes and 37 245 elements with a maximum aspect ratio of 15.2.

Table 2

Femur Static Study - Resultant forces

Selection set	Sum X [N]	Sum Y [N]	Sum Z [N]	Resultant
<i>Femur C.A.D. model</i>	650	662	999	1364

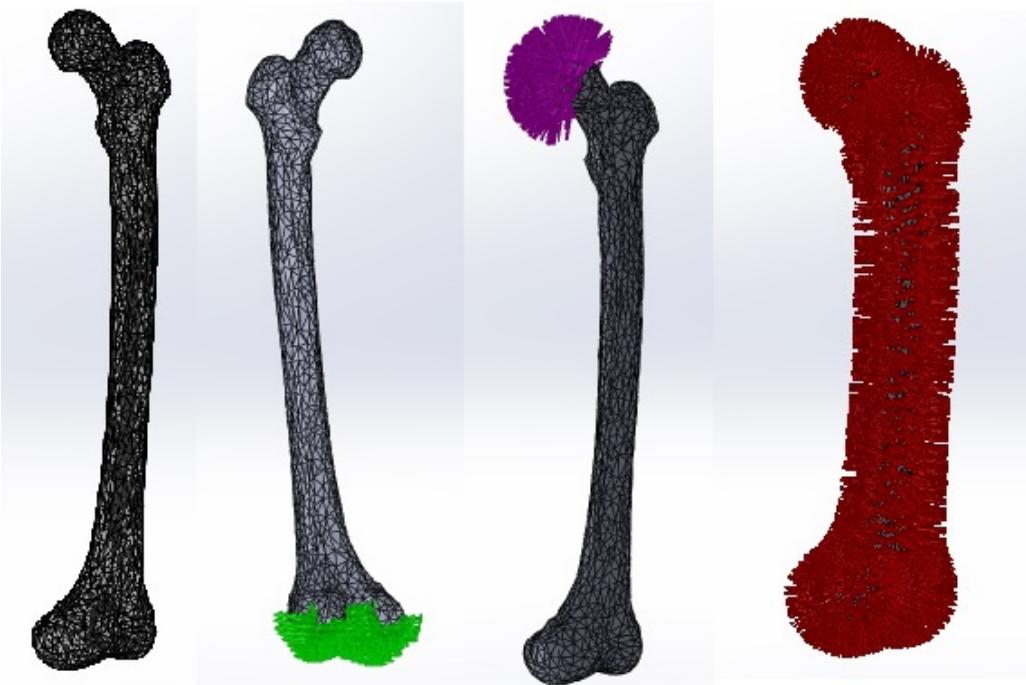


Fig. 7 Femur Fixture (green), 2000 N force (violet) and 24 MPa pressure (red)

The results have shown a minimum of 0.04 MPa in node 58 007 and a maximum of 98.36 MPa in node 45 494 for the stress which can cause a fracture in the middle of the femur due to the high force applied, a minimum of 0 mm in node 2797 and a maximum of 27.1 mm in node 74 for displacement and a minimum of 2.42×10^{-6} in element 19 783, a maximum of 5.29×10^{-3} in the element 19 128 ESTRN: Equivalent Strain.

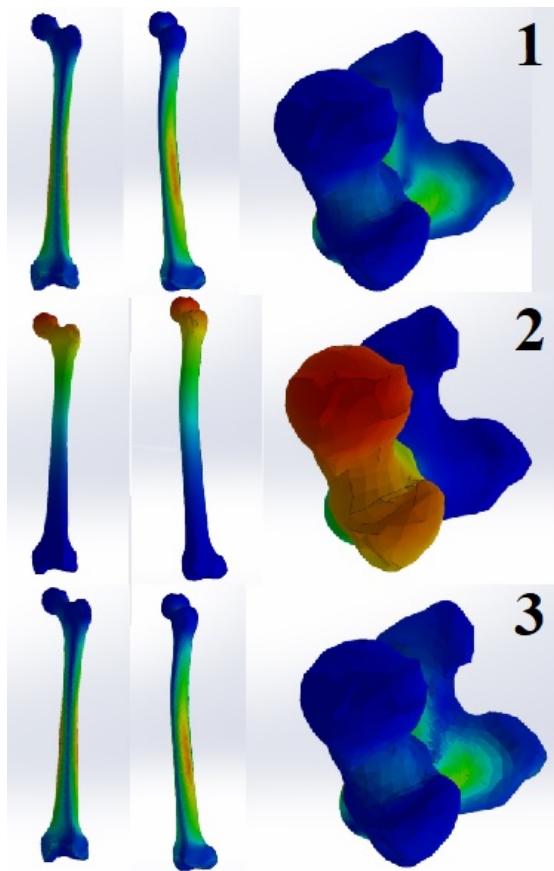


Fig. 8 Femur F.E.A. Static Study Results: 1. Stress Results; 2. Displacement Results; 3. Strain Results

7. Conclusions

Nowadays the virtual simulations such as the F.E.A studies are becoming one of the most used pre-manufacturing testing because of its low economic impact: in this way the companies don't need to spend consistent amount of money in order to verify the product. The prosthesis manufacturing companies started to use more and more this type of pre-verification in order to find the best geometrical shape before prototyping and to describe the final mechanical behavior of the implant. The bone segmentation procedures help engineers to extract bones geometry from different patient C.T. scans, to perform simulations directly on the virtual bone extracted, to study the force distribution and the mechanical behavior of the bone, but also to perform a bone-prosthesis mechanical contact simulation in order to study their interaction. Thanks to the bone segmentation, now we have the possibility to create custom hip prosthesis

that matches in the best way patients' anatomical parameters and responds more effectively to external loads and pressures, extending as a consequence the life cycle of the prosthesis.

The static F.E.A. study has highlighted the weakness points of both hip and femur. In the hip we can observe that the central part of the acetabular cup is the most stressed area, and this means that the acetabular prosthetic cup needs to be designed in a way that its central portion can discharge better the load. In the femur study we observed that the femoral head and neck are the most stressed parts, and the probability of fracture occurrence in that area is the highest: so for a T.H.A. we have to choose or design a prosthetic head and stem neck that can efficaciously discharge high loads without creating stress concentration and prosthetic fractures, which are common in the orthopedic field.

In conclusion, the bone segmentation methodology with the help of Simpleware Scanip represents a valid and effective technique that allows to extract different bones from various patients in order to make virtual simulation that predict possible failure scenario, offering us the possibility to optimize the prosthesis' design in order to reach an high geometrical compatibility with the anatomical morphology of the patient, and also to test in advance the mechanical interaction between bone and prosthesis studying also the effect in using different kind of materials for the prosthesis in order to optimize on the final results.

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