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CAD, CAE and Rapid Prototyping Methods Applied in Long Bones Orthopaedics

The paper presents some methods used to analyze human bone joints. First, there were defined the "hard" parts as the main bone components and "soft" parts as ligaments or menisci using CT images. These components are imported into a parameterized environment assembly module and a biomechanical model of human walking is being obtained, which is exported to a kinematic simulation environment and finite element analysis, where first the kinematic parameters are defined. With these defined parameters, the kinematic and dynamic simulation of the subsystems for classical, normal motion can be switched. Following the interpretation of the results, the initial parameters of the biomechanical subsystems may be modified. In the next phase, the components of the subsystems are divided successively and the finite element structure is obtained for the entire biomechanical system of the joints that participate in human locomotion.

Keywords: virtual prototyping, computer graphics, orthopaedics, virtual bones, rapid prototyping.

1. INTRODUCTION

The human locomotion apparatus, the specialized device that performs the locomotor function of the body, consists of a complex of organs with different structures and functions. In the 206 bone segments, over 430 striated muscles and over 310 joints, the nervous system (with its afferent and efferent pathways) and the vascular network that irrigates all these organs must be added. The discovery and refinement of the new investigative means have continuously changed the knowledge of the functional structure of the bone. Investigation of this organ by X-ray diffraction, electron microscopy, histochemical methods and in particular radioactive isotopes revealed new morphological and dynamic aspects.

Tibia fractures account for approximately 20% of all fractures; the superficial condition of the calf bone (the antero-medial surface and the anterior crest of the tibia being covered only by tegument and fatty tissue) makes them more vulnerable to direct impact trauma. They may occur isolated or in the context of polytraumas and are still an important public health problem with important socio-economic implications due to the disabling nature of the disease, on the one hand, the severe algic syndrome, and on the other hand, the immobilization or prolonged recovery period, as well as characteristic sequelae: joint abnormalities, muscular atrophy, persistent edema, osteoporosis of the metatarsiae (Sudek-Leri-che syndrome), algo-neuro-dystrophic syndrome, which in turn requires sustained, sometimes long-term treatment.

The treatment of diaphysis fractures of the calf is

complex, orthopedic (gypsum immobilisation) and / or surgical (osteosynthesis with blocked, non-lockable or elasticized centromedullary rods, screw plates, external fixator); in the choice of therapeutic methods, the morphopathological features of the fracture (number, head-quarters, fracture type, etc.), age, general condition of the trauma, presence of shock, especially if the fracture is part of a polytraumatism and last but not least service logistics and surgical team expertise, which directly affect the results. An important factor influencing the time of consolidation, evolution, prognosis, functional recovery and re-employment of patients with diaphysis fractures of the calf is the type of osteosynthesis materials and techniques. The classical intramedullary nails used in tibia fractures have important drawbacks such as complicated orientation, manipulation and positioning and, at the same time, difficult positioning of the distal bolts using the classic stem guide. Also, all these maneuvers can lead to errors or extra holes in the tibia, causing the bone resistance to decrease and, at the same time, to increase the duration of surgery with unpredictable effects on bone repair. Extending the duration of orthopedic surgery can also result in additional irradiation of medical and patient staff [1,2].

2. CAD METHODS USED FOR BONE VIRTUAL RECONSTRUCTION

In the last time we used the next methods to determine the virtual models of the human bones and prostheses:

- A method based on 3D scanning and Geomagic analysis programs. This method has the disadvantage that it does not allow to generate the internal bone geometry, such as the medullary canal. But, this method can be successfully applied for implants and prostheses.

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- A method based on planes reconstruction of the CT planes in a virtual environment. The CT images were inserted in these planes and were drawn the outer and inner contours of the bone. Finally, the bone was modelled using 3D shapes as Loft or Cut Loft for inner geometry.

- A method based on using software as InVesalius or Mimics which transforms the 2D CT images in 3D geometries. But, the results are files in .stl formats. To obtain a solid geometry of the bone, the software can transfer planar curves for inner and outer contours. In the final, these curves can be unified using Loft or Cut Loft shapes.

- Another method based on InVesalius or Mimics which can directly transfer the surfaces geometries of the bones. But, in the most cases, these geometries must be patched and after that, the outer and inner surfaces can be filled with solids.

- A method which combine all these methods. In many cases on specific areas of the virtual bone can be applied one of the method explained before.

These virtual bones can be finished using other CAD techniques based on different software [3-6].

2.1 First CAD method applied for the virtual reconstruction of a hip prosthesis with fixation pins (using 3D scanning operations and Geomagic software)

This hip prosthesis model is composed of the following elements (Figure 1):

- a femoral stem which has, on an important surface, hydroxyapatite coatings;
- a spherical metallic element;
- a high density polyethylene element;
- a metallic acetabular element with iliac bone fixation pins.

To determine the geometry of the hip prosthesis components, the 3D scanner and its scanning program have a common interface with the SolidWorks CAD software (Figure 2).



Figure 1. Hip prosthesis with fixation pins (assembly and components)

Obviously, the entire geometry of the cup with fixing pins can not be obtained using a single scan. The

Geomagic software allows the overlay of multiple scans and their automatic alignment. In Figure 3 are presented many scans automatic aligned.

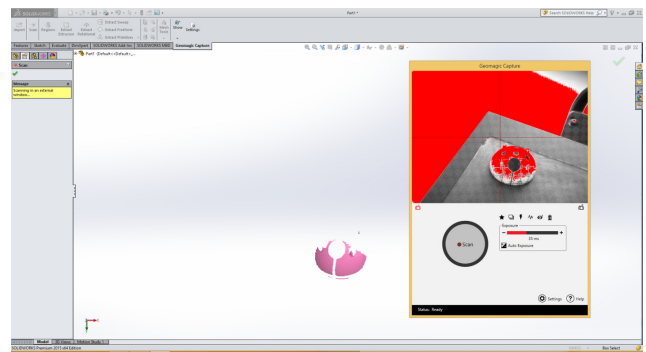


Figure 2. Geomagic's 3D scanning interface

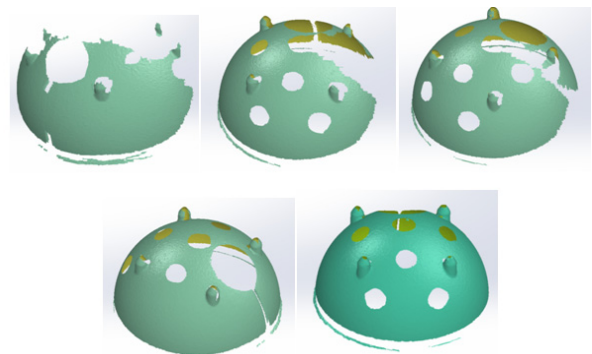


Figure 3. Automatic overlay of independent scans

An important property of the scanning program is to identify shapes and transform into solid elements or surfaces. Thus, Figure 4 shows the identification of a sphere and the transformation of the "cloud point" into a virtual solid.

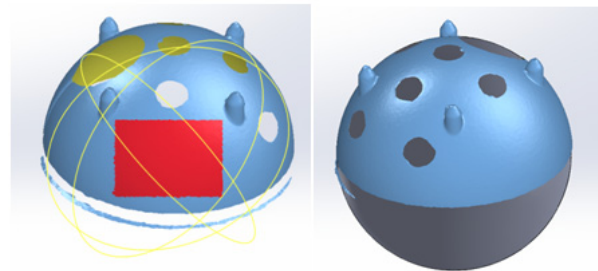


Figure 4. Identifying a solid sphere in the "cloud of points"

Using the software techniques, the other geometric elements of the cup with fixing pins were determined, using the internal scanning (Figure 5).

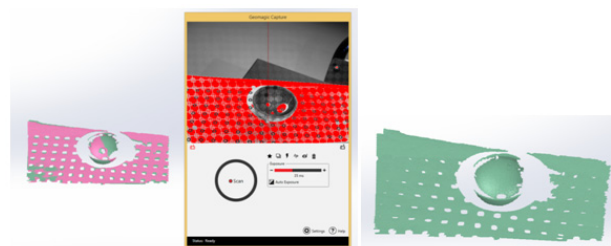


Figure 5. Inside scan of cup with fixing pins

For some components, the direct measurement technique was also used [4]. Finally, using the CAD tech-

niques, the parameterized virtual model of the pin with the fixing pins shown in Figure 6 was obtained.

For the stem of the prosthesis was used the same method. Finally, following the application of specific CAD procedures, the three-dimensional parametric model of the stem shown in Figure 7 was obtained.



Figure 6. The model of the cup with fixing pins



Figure 7. The final stem model (two views and one detail)

Using the same CAD and scanning techniques and methods, the polyethylene cup and spherical element model shown in Figure 8 were obtained.



Figure 8. Final models of the metal spherical element and the polyethylene cup (different views and rendering)

Finally, after loading these models into the SolidWorks Assembly Module and applying the appropriate motion constraints, the final model of the fixation pin prosthesis shown in Figure 9 was obtained [4].



Figure 9. The final model of the prosthesis with fixation pins (different views, details and rendering)

Using the same CAD and scanning techniques and methods, the polyethylene cup and spherical element model shown in Figure 10 were obtained.

Finally, after loading these models into the SolidWorks Assembly Module and applying the appropriate motion constraints, the final model of the fixation pin prosthesis shown in Figure 11 was obtained [4].



Figure 10. Final models of the metal spherical element and the polyethylene cup (different views and rendering)



Figure 11. The final model of the prosthesis with fixation pins (different views, details and rendering)

2.2 The second CAD method applied for the virtual reconstruction of a tibia bone

The images of a tibia bone made by the CT scanner in DicomWorks format were exported and converted to Windows Bitmap, and the resulting files were organized into separate folders, taking into account the areas highlighted in the scan schema.

These images that are compatible with most Windows files have been loaded into AutoCAD one by one. This computer-aided design program allows definition of non-parametrized two-dimensional models.

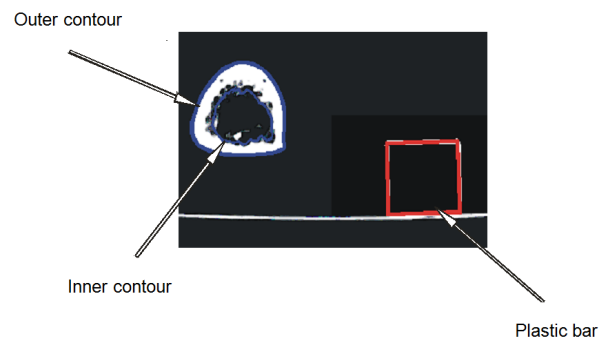


Figure 12. Drawing contours over a tomographic image

First, the images were loaded into this program to determine the scale at which they were made by the CT scanner. Because each tomographic image also contains the fixed mark (a plastic bar having a square section

with the side of 20 mm), by comparing the dimensions of the real size bar dimensions to the real plastic bar, the extent to which these images were loaded into AutoCAD so images appear on a 1:1 natural scale [7,8].

To begin with, the internal and external contours of the bone were drawn above the image loaded in AutoCAD and scaled accordingly to the natural size, and a square having the side 20 mm corresponding to the section of the bar used as a fixed mark (Figure 12).

In SolidWorks has defined a parallel plane with the Insert/Reference Geometry / Plane command placed at a distance of 3 mm similar to tomography distances. These contours defined in AutoCAD were transferred in SolidWorks one by one and this operation was repeated for each tomographic image. In Figure 13, three sections are transferred, for example, to planes located at 3 mm each.

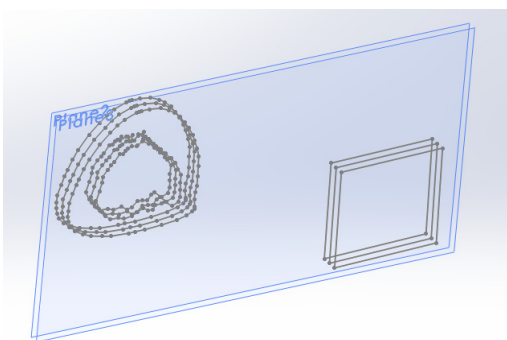


Figure 13. Three sections of the tibia successively transferred to SolidWorks

To obtain a parameterized solid, it "unifies" the outer contours into a LOFT type. To generate the inside of the virtual bone, the three inner sections were used to generate a CUT-LOFT type. The result of this operation is shown in Figure 14.

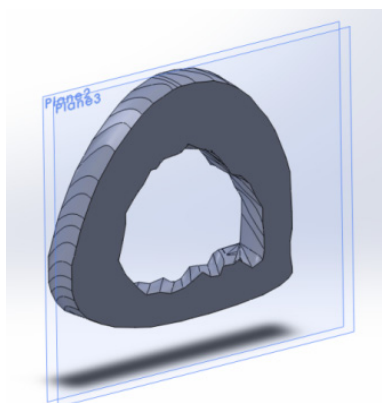


Figure 14. Virtual tibial segment

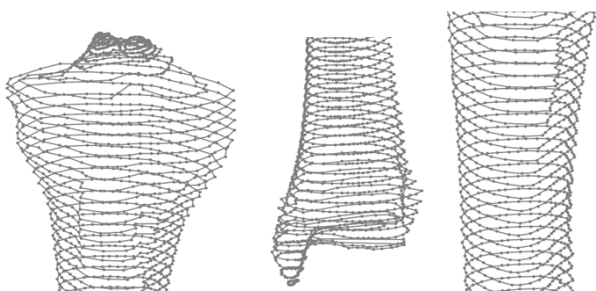


Figure 15. Tibia solid generation curves



Figure 16. The final model of the tibia (three views)

To achieve the final shape of the tibia, curves were generated in all defined planes. Figure 15 shows the curves obtained in several areas of the tibia.

For the modeling of the tibia, the LOFT form for the exterior and the CUT-LOFT form for the interior were used, and finally the three-dimensional tibial model shown in Figure 16.

2.3 The third CAD method applied for the virtual reconstruction of pelvis bones and femur

This method is based on software as InVesalius or Mimics, which transforms the 2D CT images in 3D geometries.

InVesalius is a free software built in collaboration with academic community. It generates 3D medical imaging reconstruction based on a sequence of 2D DICOM files acquired with CT or MRI equipments, providing several visualization tools.

In the Figure 17 was presented the user interface of InVesalius after loading DICOM CT files made on a living subject in the pelvis area. Also, the software define the images in axial, coronal and sagittal planes. Usual, the software can generate very easy 3D surfaces in .stl format.

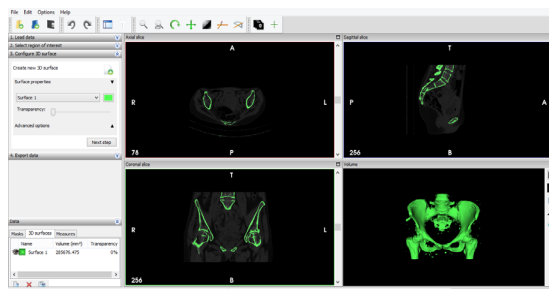


Figure 17. The user interface of InVesalius software

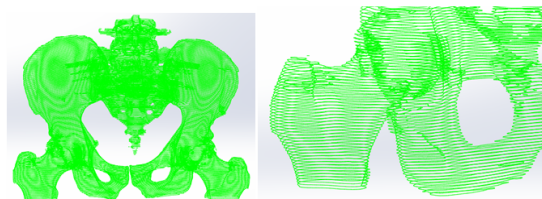


Figure 18. The main curves imported in SolidWorks

This type of model cannot be measured, modified, but can be 3D printed. To generate a valid geometry with solid shapes, from InVesalius or Mimics, we must to obtain the inner and outer contours in parallel planes.

This kind of model, made on pelvis area, can be loaded in SolidWorks (Figure 18).

These curves can be unified using Loft shape. In the Figure 19 was presented a part of the femur bone made by defining curves.

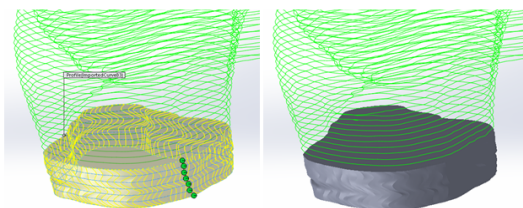


Figure 19. The Loft shape applied on curves for the femur bone

2.4 The fourth CAD method applied for the virtual reconstruction of pelvis bones

This method is based, also, on InVesalius or Mimics which can directly transfer the surface geometries of the bones to CAD software. Often, the surfaces are broken and it must be use a defining command as Fill Surface. In the Figure 20 was presented a broken surface before and after filling operation (added surfaces are in dark gray).

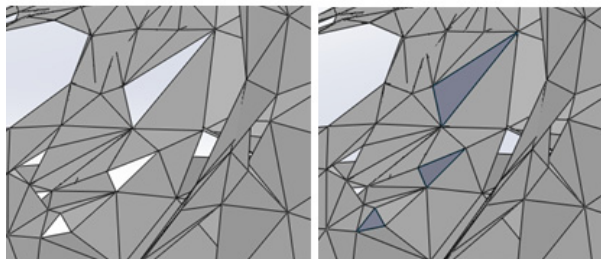


Figure 20. A broken surface before and after filling operation

After all the holes were filled the surfaces can be filled with solids. In Figure 21 was presented a geometry of pelvis after the solid filling operation.

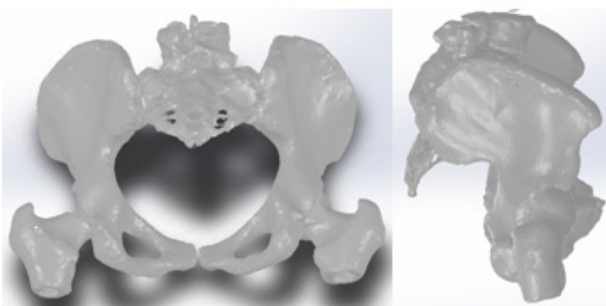


Figure 21. Virtual solid bones obtained by using fourth method (different views)

2.5 The fifth CAD method applied for the virtual reconstruction of pelvis bones

This method combine all the previous methods. In many cases on specific areas of the virtual bone can be applied one of the method explained before. Also, this method can use other software as Geomagic for SolidWorks. This software can works on .stl models using *Wrap*, *Remesh* and other specific operations which can transform entire mesh structure. Also, the software has powerful shape recognitions tools, almost of them can

transform .stl surfaces into primitive solids. As an example, in the Figure 22 was shown how the *Freeform* recognition tool works on a virtual pelvis surface.

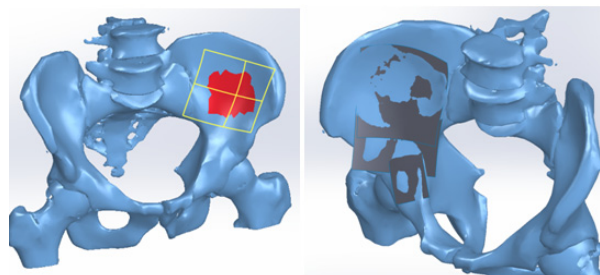


Figure 22. A Freeform recognition tool applied on a pelvis surface

3. RECONSTRUCTION OF HUMAN NORMAL WALKING IN THE MOTION ENVIRONMENT IN SOLIDWORKS

Using modeling operations similar to those described above, models for pelvis, fibula, rotula and foot bones were obtained (Figure 23).



Figure 23. The main bone components that participate in human walking

In the SolidWorks assembly module, all the previously-formed virtual bone components were loaded. Some of these were defined as mirrored objects. Using the Mate command and the anatomical angles in the medical specialty literature, all of these bone components were assembled by adding movement constraints (canceling degrees of freedom). In order to prepare the cinematic simulation of human walking, a "soil" component was also defined. All these components represent the biomechanical system of human walking (Figure 24).

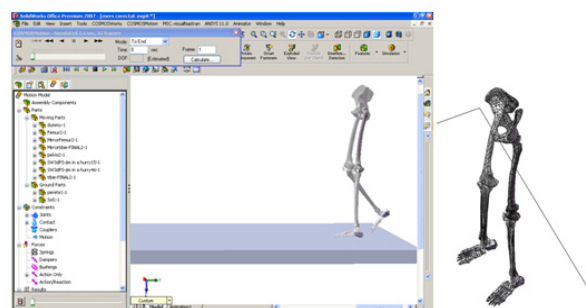


Figure 24. The bio-mechanical model of human walking

In this mechanical simulation program (based on the Adams algorithm) to obtain a complete simulation of human walking, the following initial parameters were considered:

- Acceleration value and direction ($9.81\text{m} / \text{s}^2$);

- Mechanical properties of material specific to bone components;
- The force produced of the body weight equivalent to about 85 kg (850 N);
- The angles and initial positions of joints of the biomechanical system studied extracted from the information obtained from the analysis of the film images;
- Mechanical properties of foot and ground contact;
- Initial angles of the joints extracted from the first image of the analyzed film;
- Other parameters required for kinematic simulation.

Virtual joints are considered active mechanical couples (motors) driven by motion laws obtained by the analysis of film images. Practically, data obtained in the joints have been transposed to control the mechanical couplings in the virtual environment [9,10].

The first result of the kinematic analysis for walking human biomechanism is the simulation film. In Figure 25 there are eleven main frames of this film.

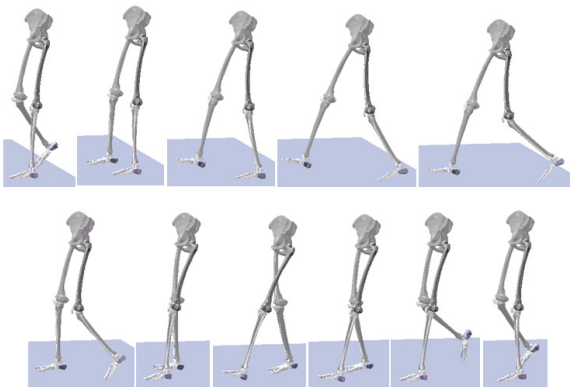


Figure 25. Eleven important images of the simulation movie

The simulation allows to obtain the entire kinematic behavior of each component of the biomechanical system analyzed. To determine the loads in the tibia important are the evolutions of the force (Figure 26) and the moment.

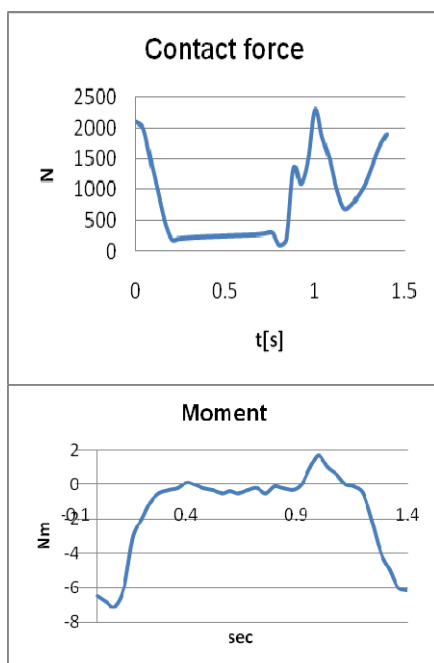


Figure 26. Evolutions of force and moment during walking

4. FINITE ELEMENTS ANALYSIS OF THE HIP JOINT WITH THE LOAD OF HUMAN NORMAL WALKING

It was intended to analyze the biomechanical model of the hip joint using normal walking load. For this, the model obtained in SolidWorks was exported to Ansys Workbench. Through this operation, the hip joint geometry is imported into Ansys. Initially, the SolidWorks and Ansys interfaces will show that in Figure 27.

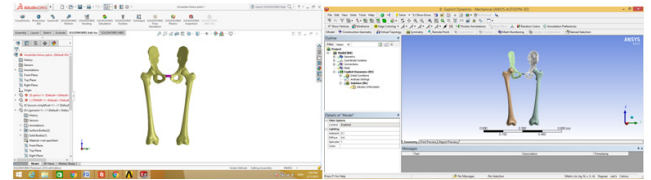


Figure 27. SolidWorks and Ansys user interfaces

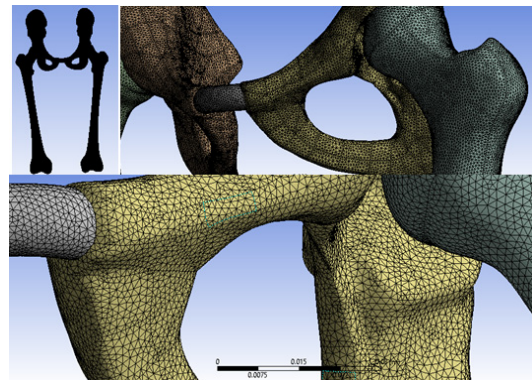


Figure 28. Structure of finite elements of the analyzed model

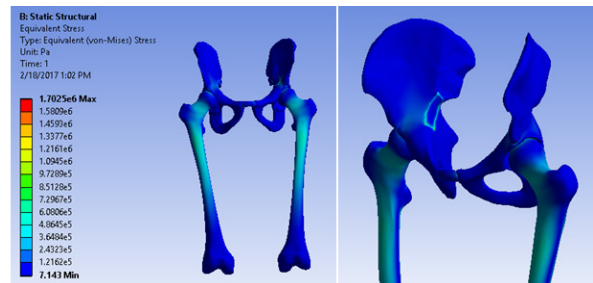


Figure 29. Stress map for the analyzed system

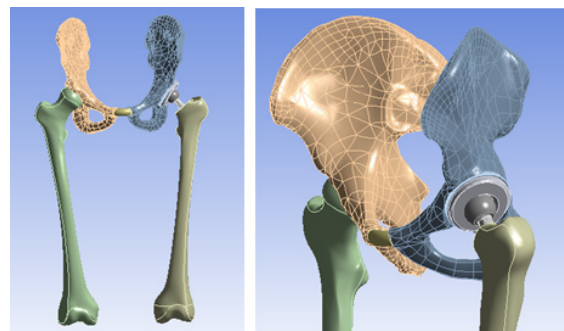


Figure 30. The biomechanical system of the prosthetic hip joint

In the Figure 31 was presented the finite elements structure for the prosthetic hip joint.

In Figure 28 was presented the entire finite elements structure of the analyzed bio-mechanical system.

In Figure 29 was presented the von Mises stress map of the human hip obtained for normal walking loads.

The prosthetic joint hip joint with acetabular polythene element was subjected to equivalent human walking loadings previously shown in the integral hip joint simulation (Figure 30). Appropriate materials were also used, and finite element division was performed under similar conditions (Figure 31) [11-13].

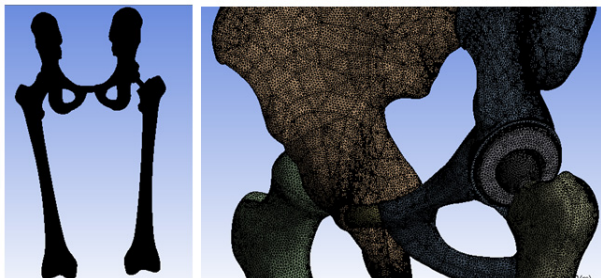


Figure 31. The finite elements structure for the prosthetic hip joint

Below are the diagrams with the maximum values for von Mises stress of the analyzed system (Figure 32).

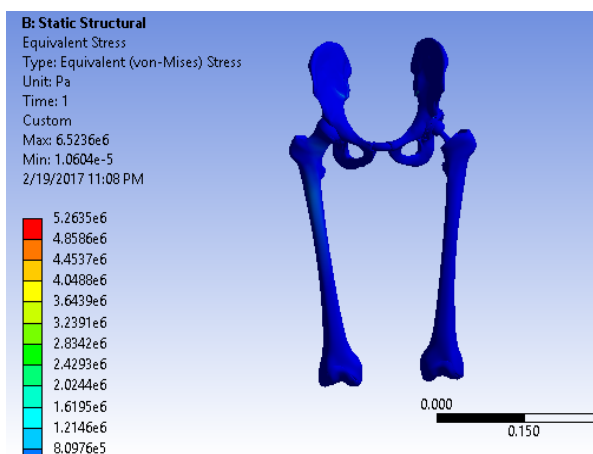


Figure 32. The stress map of the prosthetic hip joint

5. 3D PRINTING USED FOR ORTHOPAEDICS

In the last decade, a new concept called rapid prototyping, physical coating or without solid pre-form manufacturing, has become very popular. The process starts with a 3D CAD model involving CAM techniques and polymers. Using these techniques, our team fabricated physical polymers prototypes of bones, different implants and prosthetic elements for orthopaedic applications.

As a new concept, Rapid Prototyping is organically related to a range of innovative technologies that quickly enable the real model, functional prototypes, parts, subassemblies, or tools to make the product. These rapid prototyping methods use other techniques for materializing components or parts by adding the material rather than removing it. The technological methods that can be used for rapid prototyping, as an alternative to traditional manufacturing methods, are diversified. The techniques used and the conditions of use are very different, but their application is given by the proven effectiveness in the market impact in the direction of minimizing the launching time of a product.

In Figure 33 were presented a femur segment and a pelvis bone obtained with Prusa I3 3D printer [14].

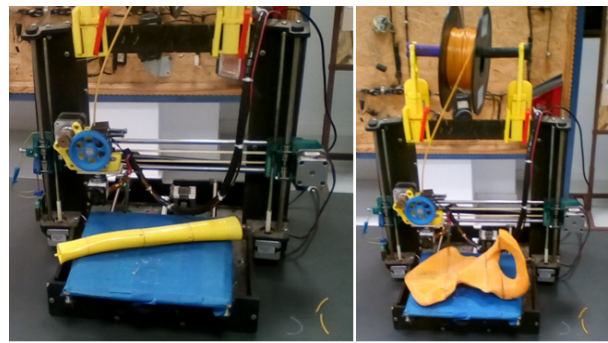


Figure 33. A femur segment and a pelvis bone obtained with 3D printer

6. CONCLUSION

From the analysis of the procedures, methods and techniques presented in this paper, the following conclusions and personal contributions were extracted and highlighted:

- The methods given by the new generation of assisted design and finite element analysis offer multiple possibilities to analyze complex biomechanical systems;
- New computer-aided devices, such as the 3D scanner and 3D printer, also offer their availability in the development of new software techniques for analyzing and improving the medical diagnosis;
- The emergence and integration of InVesalius or Mimics programs allow the development of new methods that connect more and more between the CT and the modeling of personalized pathological situations. It seems that the integration of these programs in the medical diagnosis will make the transition from classical tomography analysis to virtual reality diagnosis and, implicitly, to virtual surgery. It also opens the direct path to personalized prostheses;
- The Finite Element Analysis method allows for strain, strain and displacement maps, even in complicated situations such as those previously studied, even if the analyzed systems are complex, rigid or flexible or non-linear;
- In order to highlight critical situations or components of prostheses, comparative diagrams were made for each element or groups of prosthetic components;
- Subsequent analysis is required, both of the analyzed situations, but also of the surgical techniques or of the classical prosthesis deficiencies. These can lead to optimized hip prosthesis models that diminish the phenomenon of luxation, prosthesis failure, and improve the length of time until the first revision.

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САД, САЕ И МЕТОДЕ БРЗЕ ИЗРАДЕ ПРОТО-ТИПОВА ПРИМЕЊЕНЕ У ОРТОПЕДИЈИ ДУГИХ КОСТИЈУ

**Д.Л. Попа, Г. Бучиу, Д.К. Калин,
Б. Попконстантиновић**

У раду су приказане методе за анализу људских коштаних зглобова. Прво, употребом СТ слика, дефинисани су "чврсти" делови као главне компоненте кости и "меки" делови као што су лигаменти или менискуси.

Ове компоненте увозе се у модул за монтажу параметризованог окружења и добија се биомеханички модел људског хода, који се извози у кинематско симулационо окружење и користи за анализу коначним елементима, где се прво дефинишу кинематски параметри. Са овако дефинисаним параметрима може се извршити замена кинематских и динамичких симулација подсистема класичним, нормалним кретањем.

Након интерпретације резултата, могу се модификовати почетни параметри биомеханичких подсистема. У следећој фази, компоненте подсистема су подељене sukcesивно и добијена је структура коначних елемената за цео биомеханички систем спојева који учествују у људској локомоцији.