COMPUTER ASSISTED APPROACH TO THE AXIAL DEVIATIONS OF THE HUMAN LOWER LIMB

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ABSTRACT: The present paper aims to develop an informational flow regarding the pathology of the axial deviations of the human lower limb as well as the treatment strategies applied in order to correct them. This informational flow is very important and constitutes the premises for creating a high-utility IT product concerning the establishment of the optimal treatment strategy both in terms of the method and of the simulation of the results. Starting from the generated 3D models of the leg bones, the following steps will be taken: customizing the 3D models on radiographic bases, creating the generalized assembly, highlighting the pathological situation, performing the spatial modeling of the affected bone, modeling the surgical intervention, and finally, conducting a finite element analysis of the operated bone.

KEY WORDS: axial deviations, informational flow, 3D modeling, CAD, 3D generalized assembly.

1 INTRODUCTION

Computer-assisted modeling is particularly usefulness, perhaps more than in other areas, in the biomedical field. The modeling and simulation methods prove to be effective because it is most appropriate to study on models, since the objects under investigation are parts of the human body that cannot be dismantled and studied as real experimental objects [Cofaru, I. I., 2013].

In view of thorough modeling and simulation studies on the pathology and strategies of treating the lower limb disorders in general and the knee joint in particular, it is necessary to initially to conduct a CAD geometric modeling of the main bones that make up this articulation [Cofaru, I. I., Huzu, E.I., 2013].

The present paper aims to use three-dimensional models of human lower limb bones [Cofaru, I. I., 2013, McCormack, D., 2010] and assembling them in orthostatism for healthy subjects but especially for subjects affected by axial deviations of the leg. Starting from this 3D modeling, we suggest creating an informational flow that would be the logical structure for developing an IT product designed for dealing with the axial deviations of the lower limb. The paper is based on laborious modeling researches aimed at the bone system of the human lower limb and not only [Cofaru, I. I., 2013, Cofaru, I. I., Huzu, E.I., 2013, Andrew A., 2013]. Moreover, the 3D models of the femur, the tibia and the foot were created during these researches.

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2 GENERALIZED MODELING OF THE HUMAN LOWER LIMB ASSEMBLY

The achievement of a general assembly of the main bones of the human lower limb has the purpose of creating the premises of an assisted biomechanical system which will allow the study of a wide variety of axial deviations and the corresponding affections existing at this level.

For example, if only frontal foot deviations were considered (perfectly achievable by a generalized assembly), we can simulate, assess and verify only at the knee level the pathological situations such as: genu varum - (bow legs), genu valgus - (knock-knee), contortions (relative dislocations of the bone in the joints), osteoarthritis (cartilage wear), establishing responsibilities for the misalignment on the tibia, the femur or both on geometric criteria, establishing treatment strategies according to the value of the simulated angles, elements of great importance from both the pre-operative and the didactic points of view, possible checks of strains and stresses on a particular situation resulting in the customized assembly, being possible to determine from which geometric values should an intervention be made or developing certain predictions on the evolution of pathological conditions depending on the situation analyzed on the model.

Considering that for the knee joint there are two more planes (sagittal and transversal) with as many malformations and wear and that the way in which the assembly was made allows all these approaches for the other joints of the leg (the ankle and the hip), it results the complexity of such an assisted system and fully justifies the development of a generalized assembly.

Making such a generalized model can be considered to be an important original contribution.

In order to achieve a generalized assembly, it is important to use as reference the usual human body systems used in medicine. A primary reference system has been chosen, against which virtually all bone models will be reported. This reference system is tri-orthogonal and has its origin on the ground projection of the human body's center of gravity. The tibia, femur and foot models [Cofaru, I. I., 2013] were modeled relative to the system described above (Figure 1).

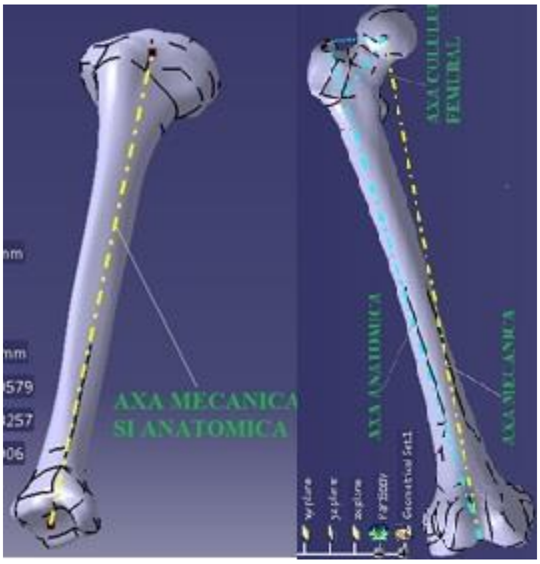

Figure 1. 3D models - tibia, femur, mechanical and anatomical axes

Some important points on these 3D models have been established, which will become origins for new local reference systems as well as points that will determine the axes of the lower limb. These axes are: the mechanical axis of the tibia coinciding with the anatomical one, which is also the axis of symmetry of this bone, the mechanical axis of the femur, its anatomical axis and the axis of the femoral neck (fig.1)

Introducing these axes on the model is very important because it highlights the geometric elements such as angles or reciprocal positions specific to a healthy or sick subject.

3 THE GENERALIZED ASSEMBLY. THE SKELETON SYSTEMS. CREATING LINKS WITH THE PATHOLOGICAL SITUATIONS OF THE LOWER LIMB

The assembling of the bones as previously modeled is done according to the classic methodology existing in the Catia V5R20.

For the accuracy of the assembly, we must keep in mind that the contact surfaces change depending on the subject under consideration, for example in the knee joint, the contact areas in the orthostatism will be different in the case of a healthy individual compared to one suffering from gonartrosis.

We suggest creating a system that allows the development of a generalized assembly by which we can study biomechanically both a healthy lower limb and one affected by various diseases.

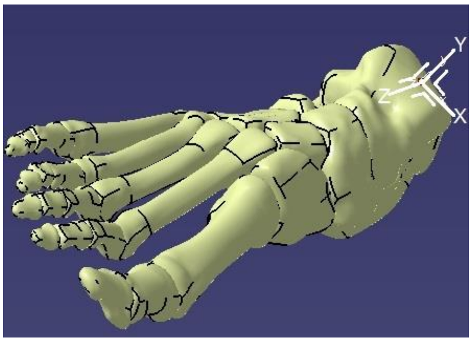

Figure 2. Foot Skeleton

In this regard, the Axis Systems function of Catia V5 was used and tri-orthogonal axis systems (Figures 2-4), which were called the Skeleton femur, the Skeleton tibia, and the Skeleton foot, were created in the points taken as origins in the above paragraph. The Skeletons are in fact reference systems that remain fixed, relative to which the eventual changes will be reported.

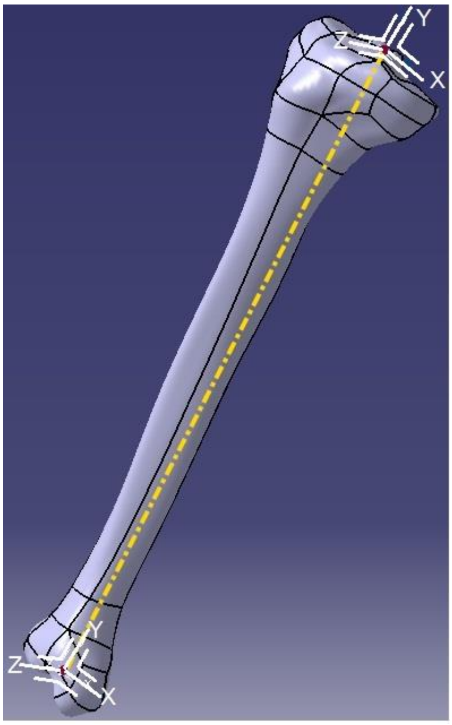

Figure 3. Tibia Skeleton

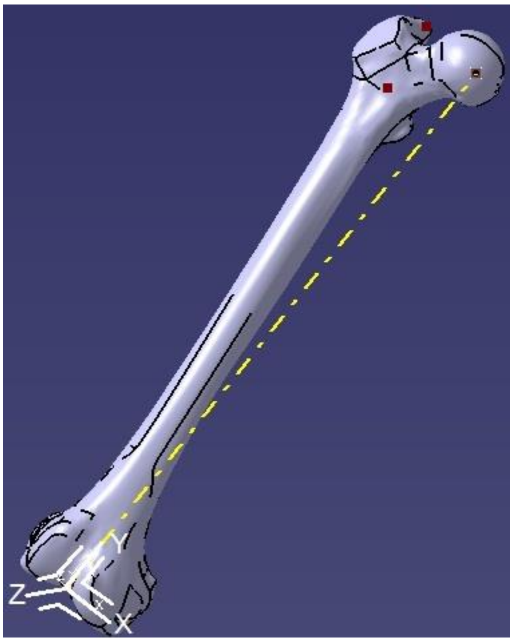

Figure 4. Femur Skeleton

This system of axes thus created take into account during the assembly of the normal anatomical contacts and, at the same time, the constraints applied to them, they can simulate various pathological situations.

Figure 5. Assembly of the Skeleton Systems

It is worth noting that the tri-orthogonal systems were chosen in Catia V5 as Euler systems, precisely to be able to perform relative rotations between their planes.

The geometrical elements that were taken into account for the assembly were (figures 2-4):

- the coincidence between the Y axis of the skeletons with the mechanical axes corresponding to each bone;

- the YOZ planes of the skeletons are parallel to the sagittal plane of the human body

- the XOZ planes are the horizontal planes corresponding to the contact areas in the knee and ankle joints.

- the XOY planes are parallel to the front plane of the body.

The constraints applied to the assembly were:

- the constraint of locking the Skeleton axis system;

- the coincidence between the mechanical axes and the Y-axis of the "Skeleton";

- the coincidence between the contact plan and the corresponding XOZ planes;

- the parallelism between the planes of the human body and the corresponding ones in “the Skeleton”.

Figure 5 shows the assembling of the lower limb bones in orthostatic position, including the Skeleton systems of the ankle and the knee joints.

All the triorthogonal axis systems have the

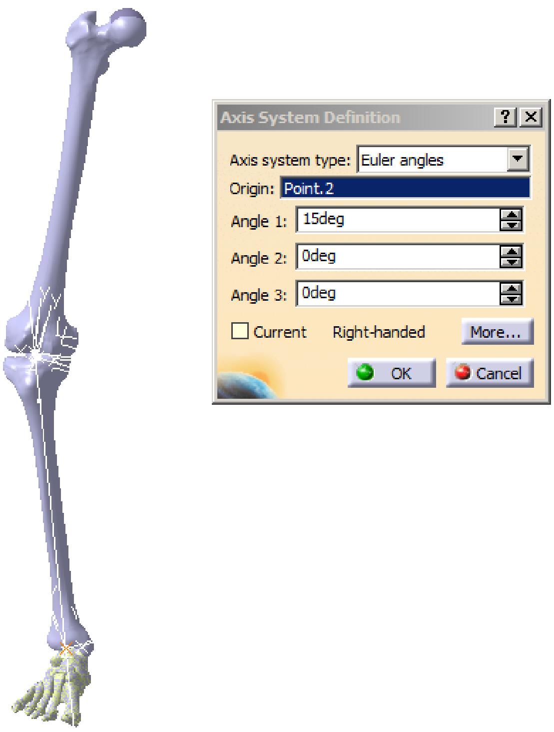

Figure 6. Genu Varum Deformation

ability to perform rotational and translational movements between the corresponding axes, resulting in relative positions that can characterize various pathological situations.

The flexibility of the generalized assembly model allows the generation of assembled models

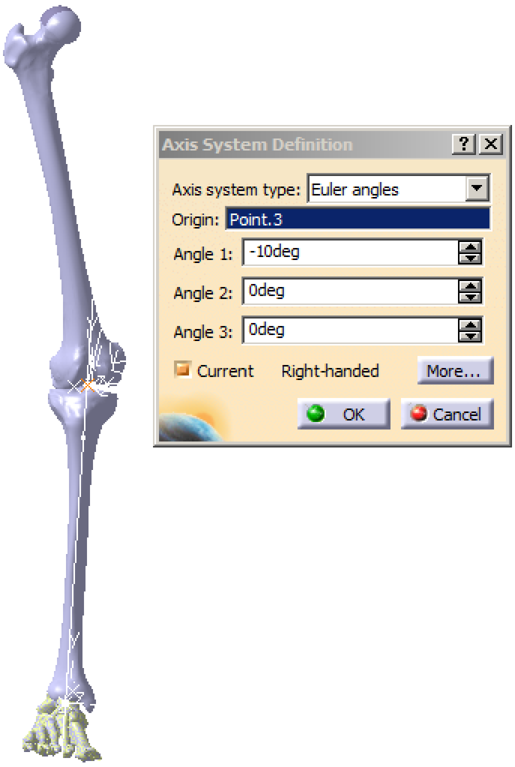

Figure 7. Genu Valgus Deformation

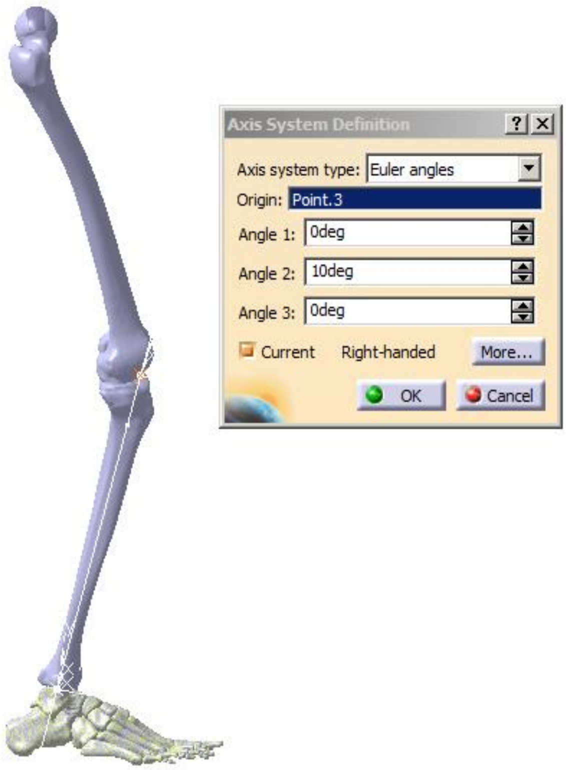

Figure 9. Genu Flexum Deformation

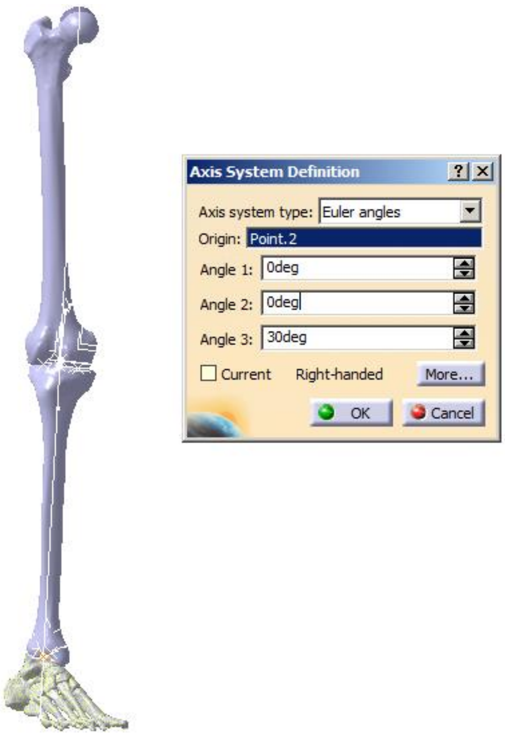

Figure 8. Varus Equinus Deformation

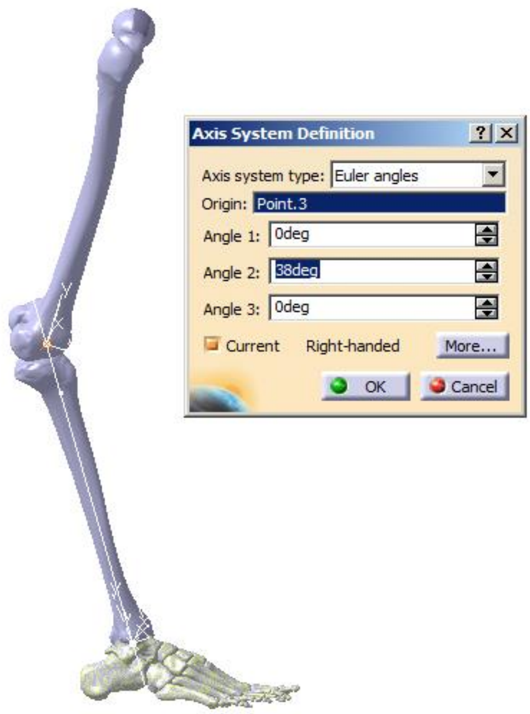

Figure 10. Genu Varum Deformation

simulating various pathological situations. Figures 6-11 show some of them:

1. displacement in the knee joint characterized by a rotation of the XOY plane around the Z axis with a 15^0 Euler angle (Figure 6) (in frontal plane - Genu Varum)
2. displacement in the knee joint characterized by a rotation of the XOY plane around the Z axis with a -10^0 Euler angle (in frontal plane - Genu Valgus) - Figure 7.

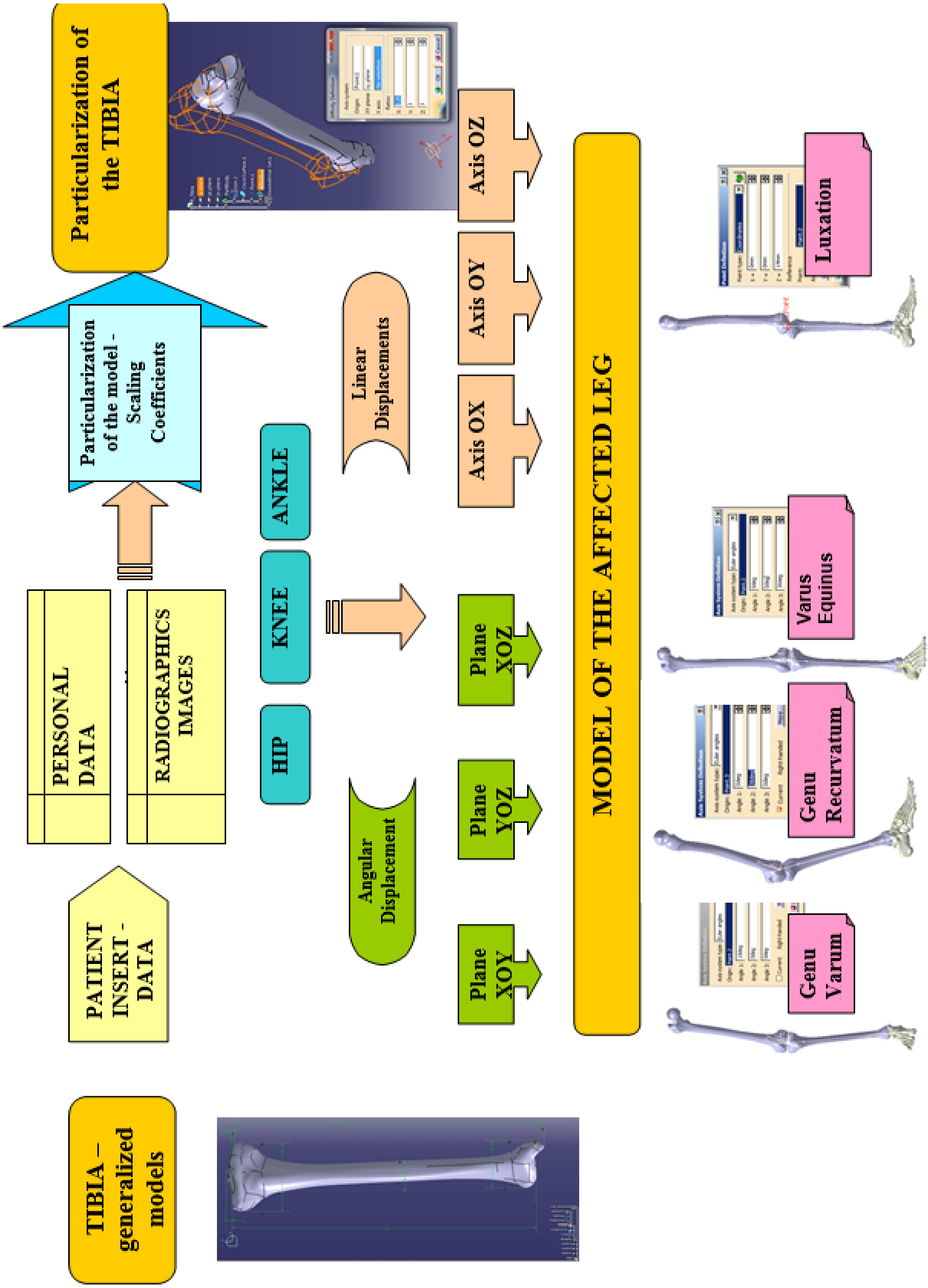

Figure 11. Informational flow – part I

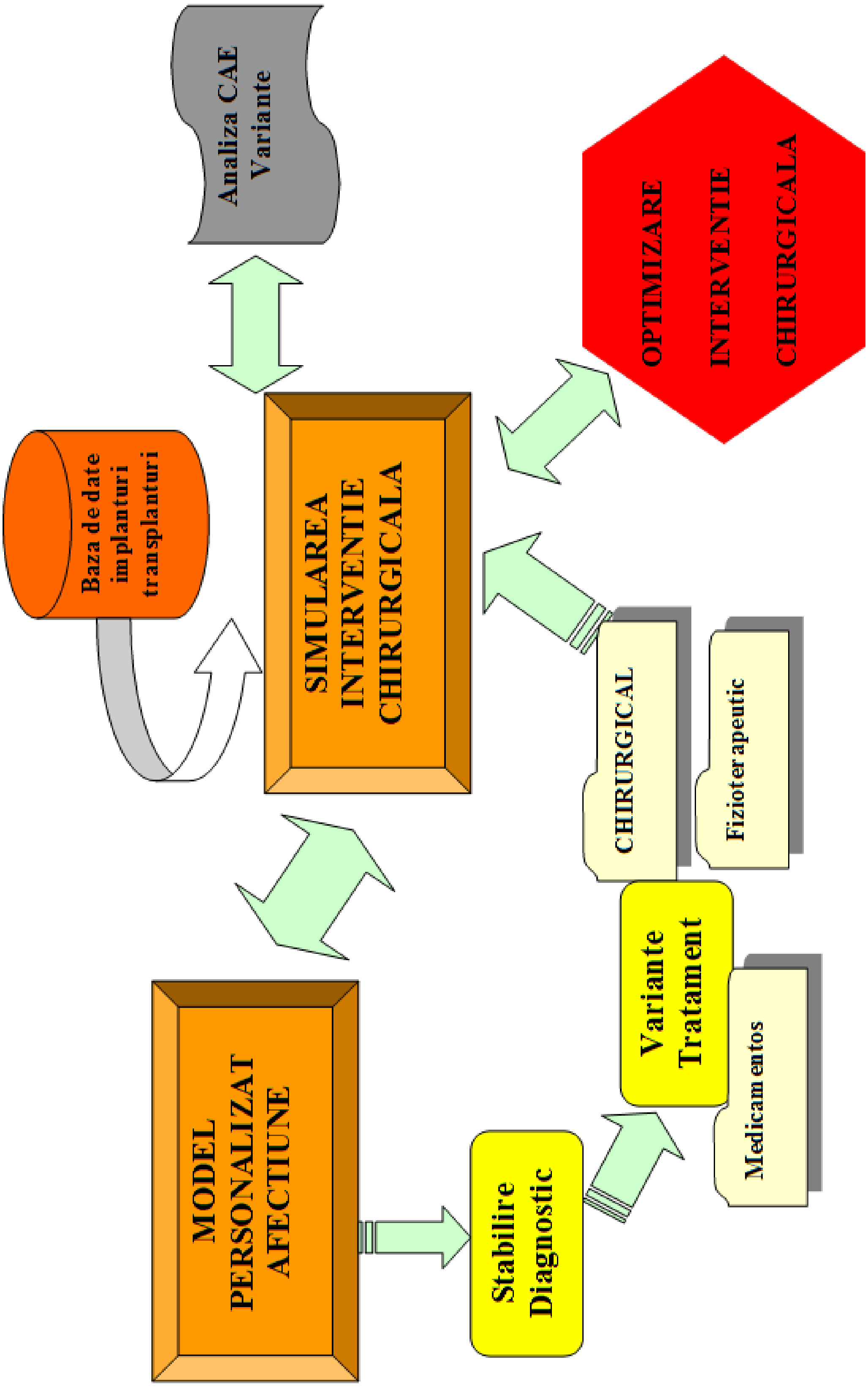

Figure 12. Informational flow – part II

3. displacement in the ankle joint characterized by a rotation in the XOZ horizontal plane around the Y axis resulting in an internal rotation of the foot by 30^0 - Figure 8.
4. displacement in the knee joint in the sagittal plane by the rotation of the YOZ plane around the X axis (Genu Flexum of 10^0, Figure 9).
5. displacement in the knee joint in the sagittal plane by the rotation of the YOZ plane around the X axis (Genu Recurvatum of 38^0, figure 10).

The bone models assembled in the presented situations can be studied in terms of strains and stresses by the finite element methods.

4 INFORMATIONAL FLOW FOR MANAGING THE AXIAL DEVIATIONS OF THE LOWER LIMB

The generalized assembly described above is useful in the modeling of pathological cases involving axial or positional deviation of the bones of the lower limb. Since there are a large number of pathological situations, which involve a multitude of medical strategies, for a rational exploitation of the modeled assembly, it is useful to design a computerized application intended for this purpose. An important step in the realization of this approach is the development and the systematization of an informational flow for managing the whole issue (Figures 11 and 12).

Figure 13. Particularization using the SCALING method

A first part of the information flow is dedicated to introducing the patient data into the system. These data can be personal general details, such as: Name, First Name, PIN, medical history, but also specific data directly related to the patient's affection. The radiographic investigations play an important part, resulting in the dimensional data and the shape aspects of the affected bones. This information gathered from 2D radiographies can contribute to the development of the customized 3D model of the studied bone. This can be done from the existing generalized 3D model (for example that of the tibia). Scaling coefficients will be applied to this three-dimensional model, which are obtained by reporting the standard dimensions from the generalized model to the dimensions resulting from the radiographies (Figure 11). Once these coefficients have been obtained, the customization can be done using parameterized CAD-specific tools as Catia V5R20. Such tools are the **Scaling** and **Affinity** functions.

From a functional point of view, both procedures make dimensional adjustments, the difference being them consisting in that while SCALING makes dimensional changes equally according to a set reference element such as the XOY plane (Figure 13), with AFFINITY the dimensions can be modified with different ratios on the three axes according to certain preset reference systems (Figure 11).

Basically, the reference can be input taking into account a convenient geometric criterion that agrees with the modeler.

An appropriate system of reference is given by the projection planes XOY, XOZ, YOZ. This choice is justified by the possibility of obtaining 2D geometric and dimensional information from the radiographic images taken of the bone in three perpendicular planes, the classical frontal, sagittal and transverse planes. The choice of using the SCALING or the AFFINITY function will be determined by the constancy or lack of constancy of the measured dimensional ratios.

Figure 13 shows the use of the SCALING function accessed from the Catia workbench where an increase by 1.35 of all dimensions in the XOY plane was performed. In the customized model of the tibia shown in Figure 11 (informational flow), the AFFINITY function is used to make a 1.35 increase of the X-axis dimensions of the generalized model.

After this first step, the informational flow aims at collecting data on the model of the deviation (Figure 11). Thus we choose one of the joints of the lower limb, namely: the ankle, the knee or the hip, and then the type of the geometric modification is highlighted relative to a healthy individual, which may be a rotation or a translation (Figure 11). In the case of the rotation, one can select the plane in which the angular rotation will take place, whereas for the translation, the axis along which the linear displacement will take place will be selected. The actual values for these changes also result from the 2D radiographies. These geometric data will be recorded in the data tables that will be exported to Microsoft Excel. The modeling parameters established for the generalized assembly in Catia V5R20 presented in the first part of the paper can be linked to this Excel file and thus the corresponding 3D model, a model that will reflect the created pathological situation, can be automatically generated.

Figure 12 shows the second part of the informational flow, related to the optimum way of solving the pathological situation. Starting from the customized model of the affection and, by using specific databases, personal or existing in the literature, together with the doctor's experience, the detailed diagnoses as well as the appropriate treatment strategies are established. For the situations when the treatment involves medication or physiotherapy, the way in which these strategies will be applied will be printed. For the surgical treatment, the IT product to be achieved will become very interesting through the possibilities of virtually performing the operation.

For example, in the case of a tibial affection such as varus gonarthrosis, a variety of surgical strategies such as high tibial osteotomy, total knee prosthesis or partial knee prosthesis can be studied on the 3D model of the tibia. The decision about the chosen variant can be made by virtually simulating the behavior of the tibia at different external loads, stresses, strains or displacements. After selecting a surgical strategy, this can actually be modeled on the computer by making the necessary incisions, assembling the implants or the transplants on the bone, and finally performing some CAE analyses of the behavior of the operated bone.

We believe that the suggested informational flow is very useful for achieving an efficient IT application for managing the axial deviations and optimizing the necessary treatment strategies.

5 CONCLUDING REMARKS

The present paper aimed at bringing contributions to the computer assisted study of the osteo-articular disorders of the knee joint in general and of the axial deviations of intra-articular origins at this level in particular. The application of the engineering research methods in this field can lead to higher solving solutions.

The motivation for such research lies in the need to develop deeper CAD_CAE studies due to the anatomical complexity of the system under consideration, as well as the particular social impact that such research may have, given the increasing occurrence of the axial deviations in the knee area in the case of the middle-aged or old individuals or of the professional athletes.

The 3D generalized assembly of the lower limb bones' models conducted in the paper gives the possibility to perform a biomechanical study of both a healthy lower limb and one affected by various diseases. Therefore the axial deviations of the foot (rotations, translations) have been especially emphasized, and the generalized assembly can be customized in many pathological situations (genu varus, genu varum, genu recurvatum, genu flexum, varus equinus, etc.).

Taking into consideration the complexity of the modeled system objectified by axial deviations - diagnosis - virtual preoperative analysis - virtual surgical intervention - virtual postoperative analysis, a very useful informational flow was created in order to develop a computing product that will be able to deal with this issue.

The development of this software application will be one of our future pursuits.

6 REFERENCES

► Andrew A., (2013) Amis Biomecanics of high tibial osteotomy, Knee Surg. Sports Traumatol Arthrose.

►Baumgarten, M., Meyers, N., Stephen, F. Wright, M. PhD &Thomas L. Wickiewicz, MD, (2007) the Coronal Plane High Tibial Osteotomy. Part II: A Comparison of Axial Rotation with the Opening Wedge High Tibial Osteotomy, HSSJ 3: 155–158.

►Cofaru, I. I. (2013) Researches regarding the biomechanics of the axial deviations of the human lower member and the development of the correspondent surgical devices, Sibiu, Doctoral Thesis.

►Cofaru, I. I., Huzu, E.I. (2013) Generalized Modeling of the human lower limb assembly", The 1st International Conference for Doctoral Students, SIBIU, IPC.

►McCormack, D. (2010) Mechanical Axis Deviation: Definitions, Measurements and Consequences, International Fellow in Pediatric Orthopedie Surgery, Georgia, U.S.A.