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ORIGINAL PAPER

The three-dimensional modeling of the complex virtual human elbow joint

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Abstract

The paper presents the algorithm to obtain a 3D virtual human elbow joint using CT images. For that purpose, we used CAD parametric software, which allows defining models with a high level of difficulty including complex 3D shapes. The virtual biomechanical system of the human elbow containing bones, ligaments and muscles is studied using the finite elements method and will be prepared for kinematical and dynamical simulations. The 3D virtual model will be useful for future studies concerning prosthesis optimization, improving the performances of endo-prosthetic and exo-prosthetic devices, different implants and prosthetic systems for normal and pathological situations, structures which are acted upon by SMA artificial muscles or which contain SMA elements.

Keywords: 3D virtual model, elbow joint, finite element method.

Introduction

That paper has the purpose of realizing a complex virtual model of the human elbow with the following requirements:

▪ To reproduce the bone, muscular and ligamentar three-dimensional geometry of the elbow joint as accurate is possible;

▪ To get the relative position and the position with respect to the fixed system of coordinate of these components to be as exact as possible, based on anatomical data and own experience;

▪ To have the material, mechanical and bio-mechanical properties of the virtual model to be almost identical to the real model;

▪ The virtual model must be a good research base (an initial model) for the future studies (kinematical and dynamical simulations, FEA analysis for different hypothesis a.s.o.);

▪ Finally, our team intends to develop a three-dimensional virtual model of elbow prosthetics by direct measurement method, which can be an important base for the study of the complex behavior of the elbow joint.

The elbow joint (articulation cubiti) is the intermediate joint of the upper limb, a mechanical joint between arm and forearm, which permits allows the closing of the arm to the body in the sagittal plane and the positioning by pronation–supination in the transversal plane.

The elbow is a complex joint with bone and ligamentar driving. Inside it are the following joints, which realize the specific movements:

▪ The flexion and extension movements are made in the humeroulnar joint as main joint and humeroradial joint as secondary joint;

▪ The pronation and supination movements are made in the proximal radioulnar joint (articulation radioulnaris proximalis) as the main joint and the humeroradial joint as the secondary joint. For that movement the articulate chain includes the distal radioulnar joint associated with radioulnar syndesmosis.

The present stage of the 3D modeling of the bone, tendons, muscular and ligamentar components

The human skeleton and muscular system contain the most complex joints whose behavior is not completely known and determined from the biomechanical point of view. For this reason, there have been many studies, which solve the problems only locally, not globally. Lacking generality, such studies do not create a solid base for the improvement of future research.

Thus, in [1] the authors propose a three-dimensional model for the elbow simulation using mechanisms with parallel topology with three DOF.

In [2] the authors present an artistically model of the muscles. The skeleton and muscles models were implemented using a procedural language. The muscles are automatically deformed following the position of the skeleton. An additional parameter creates the muscle tension.

In [3] the authors developed a three-dimensional model based on human thorax, upper limbs and muscles as a part of a complex project named Mechanical

Virtual Human of China (MVHC). Using that model, the authors made kinematical and dynamical determinations for different imposed situations.

In [4] the authors developed a three-dimensional model of the human upper limb as a base for the neuromuscular system. This system is a good virtual base for developing a control system for electrical stimulation.

In [5] the authors developed a model of the upper limb prepared for the FEM analysis (only skeleton) with the purpose of the developing of the muscle prosthesis for the recovery after surgical operations of the upper limb fractures.

Blemker S *et al.*, from Stanford University, developed a method for the muscles representation based on computer software for kinematical and dynamical simulations, which improve the speed of the simulations and used bone and muscle systems with accurate results [6].

Teran J *et al.*, from Stanford University, realized a complex model for the upper human limb, which was submitted to different applications. The developed model contains the most important groups of muscles modeled by 30 contact/collide elements. The resulting simulations had high resolution and the muscles are modeled by quasi-incompressible and isotropic crossing elements, which incorporate fields of active and passive muscle fibers [7]. Starting with 2001, at Technical University of Munich, such a model was developed which allows the user to study the knee properties and its components, to test the laxity and stiffness in six DOF [8].

The emerging field of computational biomechanics offers a new set of tools including the finite element method for studies, which can provide information that would otherwise be difficult or impossible to obtain from experiments. Finite Element Modeling based on continuum mechanics is a very powerful tool in predicting the behavior of ligaments. However, the construction and validation of models is very difficult because ligaments are nonlinear, anisotropic, viscoelastic, porous media and inhomogeneous [9]. Ligaments also undergo large deformations when loaded. Due to fiber orientation, ligaments are transversely isotropic with recorded tensile modulus in the directions of fibers ranging between 250 to over 1600 MPa [9]. Very few data are available for other material properties like transverse and shear moduli.

Although fibers are usually modeled as straight lines between the insertion sites of a ligament, on microscopic examination fibers appear not to be perfectly straight [10]. Several researchers have modeled ligaments using continuum mechanics.

At the University of Colorado, UC Denver School of Medicine, Centre for Human Simulation, Spitzer VM *et al.*, created a model which is considered to change the medical educational system by modeling an ideal cadaver re-usable and virtually dissecable [11]. Also, the simulation and modeling studies for virtual and bio-mechanical systems were developed in Romania [12–17].

Analyzing the current stage of research in this field, we extracted the following conclusions:

▪ Research of the functionality and of the determination of the mechanical parameters of the human skeleton is at the starting stage, the studies are partial, sometimes incomplete, because of the complexity of the analyzed system;

▪ An important part of the programs and simulations had a significant educational purpose and an obvious visual role, remarking the contributions for the Virtual Reality, Virtual Anatomy and Virtual Surgery; however, these studies had only a minor scientific character;

▪ The radiologically invisible components (muscles, tendons, cartilage, menisci) sometimes are not included in models or are *deduced*; thus, the models are affected and the biomechanical studies are incomplete;

▪ The studies of complex biomechanical systems can be realized also in Romania;

▪ The research is lacking combined studies (virtual model – experimental model) and thus has no possibility to verify the obtained results on virtual models; furthermore, some results are different from the results *in vivo*.

Material and Methods

The finite element model of the elbow joint consists of three bony structures (humerus, radius and cubitus) and their principal ligaments: annular and medial collateral and the muscles of the upper limb: the shoulder muscle (deltoid), the arm muscles (biceps and triceps), the forearm muscles (pronators and supinators of the forearm, flexors and extensors of the fingers) and the palm muscles (Figure 1). The bony structures (i.e., femur, tibia and patella) are represented by rigid bodies due to their much greater stiffness compared with joint soft tissues. Ligaments are each modeled by a number of uniaxial elements with different prestrain (or pretension).

The CT images of the bone components of the elbow joint

We studied the three bone components of the elbow joint: humerus, radius and cubitus (Figure 1).

Figure 1 – *Three studied bone components.*

To obtain the cross sections, we used a Philips Aura CT device installed in Emergency County Hospital in Craiova (Figure 2).

Figure 2 – *Philips Aura CT device.*

To obtain the tomographical images for the bone components we used two scanning schemes presented in Figure 3. First, we made a complete scanning operation at parallel planes disposed at 5 mm obtaining 147 images. For the ends of the three bones, and also in the joint area we used scanning planes at 1.25 mm, obtaining three groups of 196 images.

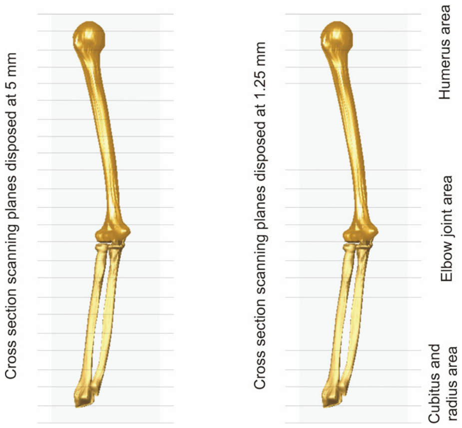


Figure 3 – ***Scanning schemes applied to the elbow bones.***

To have the possibility to report the next 3D model to a fixed coordinate system and to maintain a correct representation scale, the studied bones were scanned with a plastic bar having known dimensions (Figure 4).

Figure 4 – ***Scanning schema using a known dimensions bar.***

The CT device permits to obtain images in Dicom Works format well known medical imaging software. Figure 5 shows four images of the upper humerus.

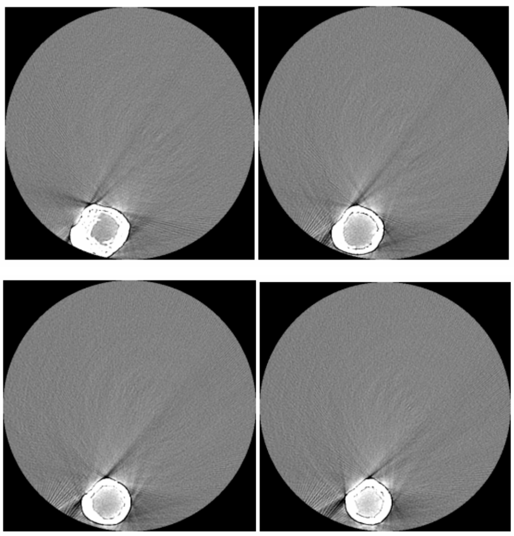


Figure 5 – ***Images of the upper humerus.***

Figure 6 presents four images of the lower cubitus and radius, which show the changes of the shapes of the bones.

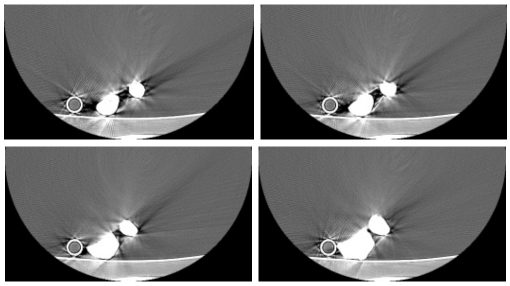


Figure 6 – ***Images of the lower cubitus and radius.***

Figure 7 presents four images of the bone components in the area of the elbow joint.

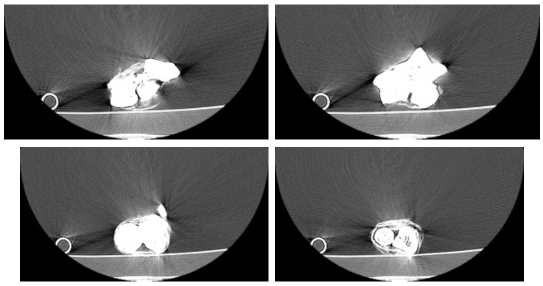


Figure 7 – ***Four images of the bone components in the area of the elbow joint.***

Figure 8 presents six important images obtained with the 5 mm scanning scheme which show the changes of the shapes of the three analyzed bones.

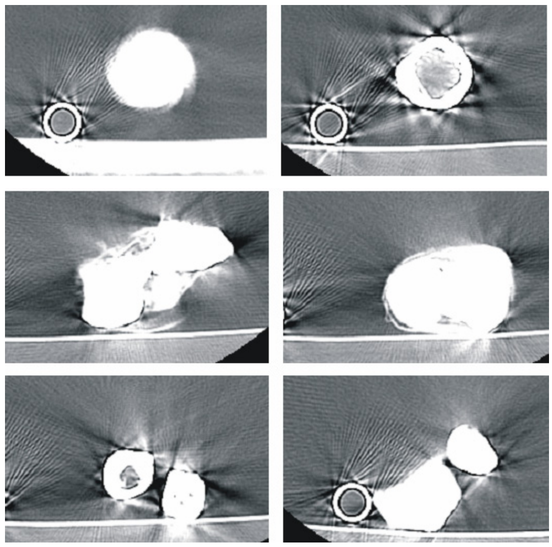


Figure 8 – ***Six significant images of the three bone components of the upper human limb.***

The three-dimensional virtual models of the elbow bones

Images were transformed from Dicom format to Windows Bitmap format and were imported, one by one in AutoCAD, CAD software that permits the generation of 2D and 3D unparametrized models. To define the virtual bone components we used the SolidWorks CAD software. This software allows us to obtain the parametrical three-dimensional models, which can be modified, edited and exported in kinematical, or FEA software.

Using SolidWorks we defined parallel planes disposed at 1.25 mm distance or 5 mm distance similar to the tomographical procedure. The sections were first defined in AutoCAD, and then imported one-by-one in Solid Works parallel sketches. These operations are repeated for each tomographical image, and for each bone. The definition scheme for the three bones is presented in Figure 9.

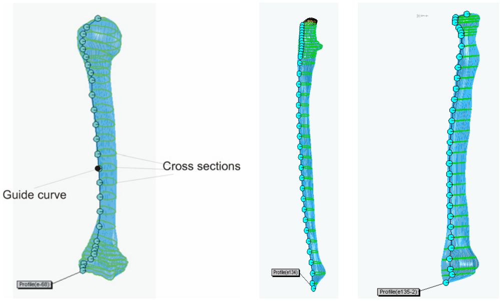


Figure 9 – ***The initial definition parameters for the humerus, cubitus and radius.***

Finally, we obtained the virtual models of the main bone component, which compose the human elbow joint: humerus, cubitus and radius (Figure 10) and the virtual biomechanical system of elbow joint (Figure 11).

Figure 10 – ***Views of the virtual models of the virtual humerus, cubitus and radius.***

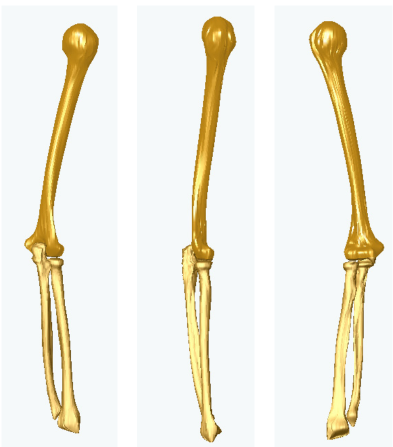
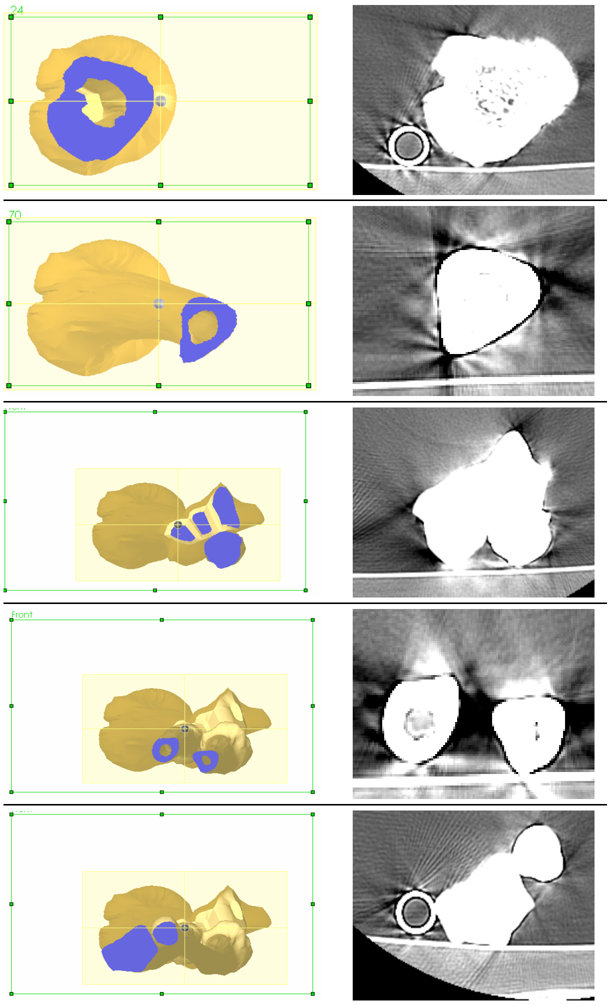


Figure 11 – ***The initial bio-mechanical system.***

The verifying operation of the virtual model of the elbow compared to tomographical images

To verify the geometrical shapes of the bones the virtual elbow was submitted to many section operations in planes similar to those of the tomographical procedure (Table 1).

Table 1 – ***Five main virtual sections and the correspondent CT sections for human elbow joint***



Finally, it is possible to make a comparison between the images of the human elbow joint – anatomical description (Figure 12, a) taken from [18] and the images of the virtual elbow joint obtained (Figure 12, b).

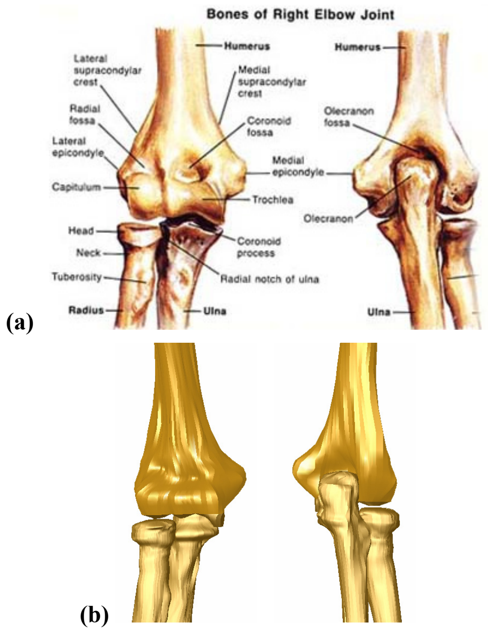


Figure 12 – ***Anterior and posterior views for the elbow bones.***

Main virtual models for the muscular and ligamentar components

Ligaments

Two ligaments are present in the elbow joint, the radial collateral ligament and the ulnar collateral ligament. These ligaments provide strength and support to the joint, as do the surrounding muscles.

The radial collateral ligament (the annular ligament) is located on the lateral side of the joint, starts from the anterior end of the radial incision, goes around the radial head and it extends to the lateral epicondyle of the humerus. This ligament prevents excessive adduction of the elbow joint.

The ulnar collateral ligament (the medial collateral ligament) is located on the medial side of the joint, extending from the proximal portion of the ulna to the medial epicondyle of the. This ligament prevents excessive abduction of the elbow joint. The ulnar collateral ligament and radial collateral ligament are very resistant. This explains why the detachment of the epycondyles is possible.

The radial collateral ligament

To obtain the 3D model for the radial collateral ligament, a 3D Spline curve made on the virtual model of the elbow bones was defined. On that trajectory, we defined five perpendicular planes on curve in five defined points. In these planes, we sketched ellipses controlled by dimension, position and angular orientation. These ellipses served to define the annular ligament using the general Loft (Figure 13).

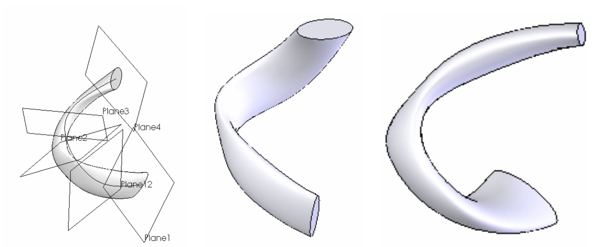


Figure 13 – ***The virtual model of the radial collateral ligament.***

That model was integrated in the virtual model of the elbow joint (Figure 14).

Figure 14 – ***The annular ligament in the elbow joint.***

The ulnar collateral ligament

Using a similar technique, but using only three planes we obtained the model for the ulnar collateral ligament (Figure 15).

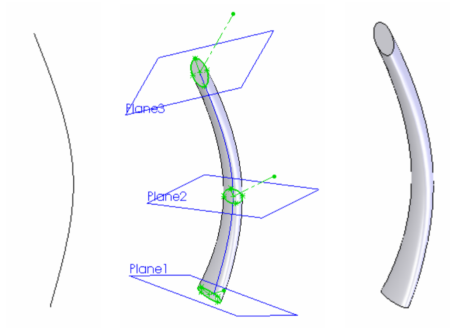


Figure 15 – ***The model of the ulnar collateral ligament.***

In Figure 16 is presented a comparison between the real positions [19] and virtual positions of the ligaments, which participate to the main movements of the elbow joint.

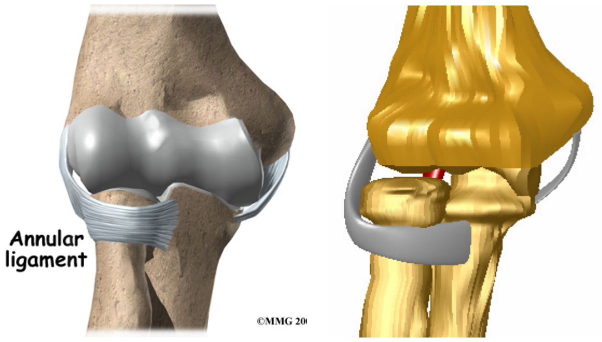


Figure 16 – ***The position of the ligaments (comparison between the real and virtual joint).***

The models of the main muscles groups which participate to the movements of the flexion–extension and pronation–supination

The muscles of the upper limb are: the shoulder muscle (deltoid), the arm muscles (biceps and triceps), the forearm muscles (pronators and supinators of the forearm, flexors and extensors of the fingers) and the palm muscles (Figure 17) [20].

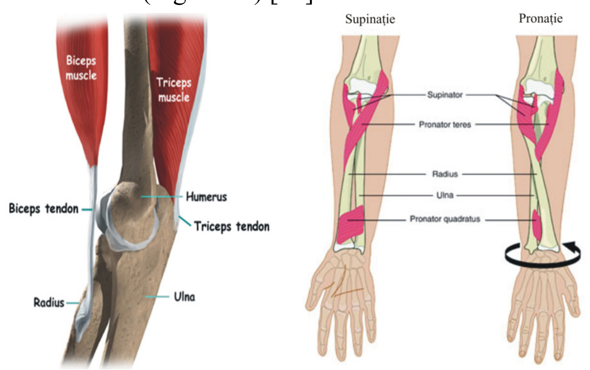


Figure 17 – ***The muscles controlling forearm rotation, attach at both sides of the elbow (biceps, triceps, supinator, pronator teres and pronator quadratus).***

The model of the biceps and triceps

Biceps and triceps muscles participate to the movement of flexion-extension of the human elbow joint.

Figure 18 shows three different views of the elbow model complete with biceps and triceps muscles.

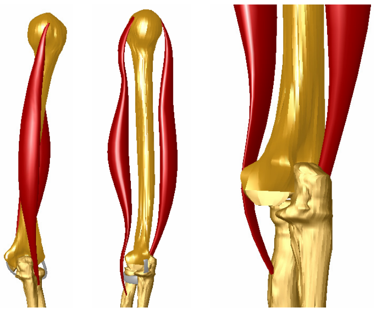


Figure 18 – ***The models of biceps and triceps integrated in the elbow joint.***

The models of the supinator, pronator teres and pronator quadratus

The main muscles group which participate to the movements of pronation – supination is made by: supinator, pronator teres and pronator quadratus.

To obtain the models for these muscles, we studied the positioning and the role for these important movements. Using the same method, we obtained the virtual models for the three muscles (Figures 19–21).

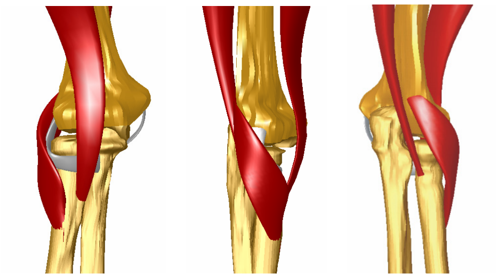


Figure 19 – ***The virtual model of supinator.***

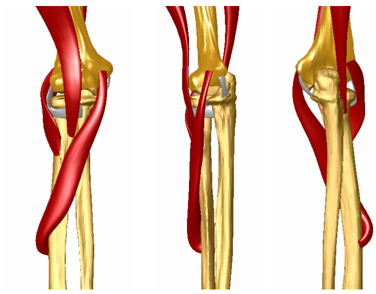


Figure 20 – ***The virtual model of pronator teres.***

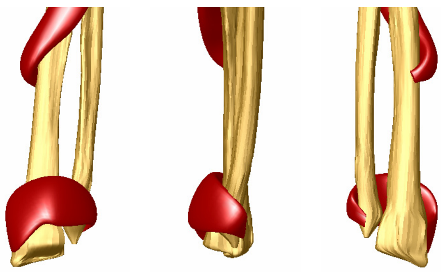


Figure 21 – ***The virtual model of pronator quadratus.***

MESH generation for the three-dimensional virtual models

For validation of the virtual model, but also for the future research work concerning the kinematical and dynamical analysis, numerical simulations, stress analysis, displacements analysis, prosthetics design, we realized the meshing of the solid models into finite elements. Thus, we defined the mesh structure for each virtual model component. In Table 2, for each component we present the main elements of the mesh generation; element size, noeuds number and elements number.

Table 2 – ***The main elements of the mesh generation for elbow joint components***

	Element size [mm]	Noeuds number	Elements number
Humerus	3	105853	65136
Cubitus	3	54406	32383
Radius	2	94856	5868
Biceps	10	2434	1024
Triceps	10	1351	594
Supinator	10	689	299
Pronator teres	10	408	141
Pronator quadratus	10	469	197
Colateral medial ligament	6	184	61
Annular ligament	5	471	180

The entire virtual structure of the human elbow joint model has 261 121 noeuds and 106 063 finite element, which ensure good precision and fidelity (Figures 22 and 23).

Figure 22 – ***The element finite structure for human upper limb.***

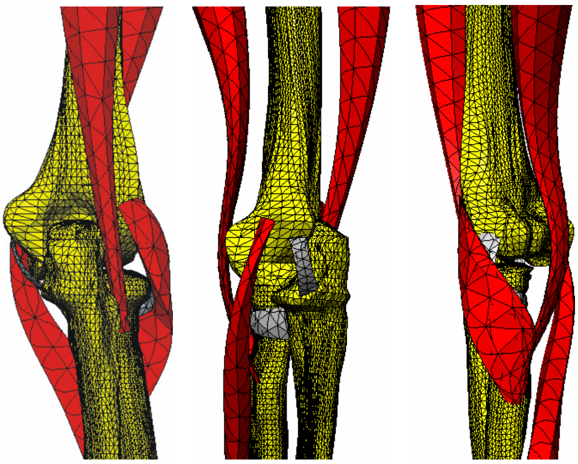


Figure 23 – ***The element finite structure for human upper limb (details).***

Conclusions

The virtual model of the human upper limb presented in this paper, patterned after human anatomy, can be a solid base for future research in the following directions:

▪ The kinematic and dynamic analysis of the elbow joint starting from different hypotheses (flexion–extension, pronation–supination, pathological situations, trauma);

▪ The elbow analysis using FEA method for different situations (normal movement, moving weights, different situations, accidents);

▪ Post-surgical kinematic and dynamic analysis of the elbow (different implants, prosthetics);

▪ Post-surgical situations analysis using FEA method;

▪ Studies of implants and prosthetics optimization function of dimensions, material, shapes, maximum stress, etc.

▪ Studies for improving the performances of endo- and exo-prosthetic devices, structures that are actuated by SMA artificial muscles or contains SMA elements. The big advantages of shape memory alloys are their incredibly small size, volume and weight, their high force to weight ratio, their low cost and human like behavior.

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