Stresses in Prosthetic Elbow Joint During Flexion-Extension Movement

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Abstract. The present paper aims to study the virtual behavior of a prosthetic elbow joint. The values and distribution of stresses in the prosthetic elbow joint by using FEA on the 3D virtual model during flexion-extension movement under the solicitation of a vertical external force are obtained. They are compared with those developed on the human healthy elbow joint. Solid Works software is used in order to obtain the virtual model and Visual Nastran to obtain the von Mises stress by finite element analysis. The maximum stresses values in metallic components of prosthetic elbow are about 4–5 times higher than those obtained in healthy elbow, for a flexion angle equal to 90 degrees.

Keywords: Virtual prosthetic elbow · von Mises stress · finite element analysis

1 Introduction

The finite element analysis (FEA) applied on virtual models is used more and more in the field of research in orthopedics or traumatology as a modern, efficient and accurate method for studying the behavior of human bones and joints [1–23]. FEA is often used to study the kinematic and dynamic behavior of the human musculoskeletal system, healthy bones, broken and implanted bones [1–4], as well as normal, osteoarthritic or prosthetic joints of lower limbs [5–11] and upper limbs [12–18]. FEA allows researchers to test virtual human bones, joints, bone-implants and joints-implants assemblies in order to study their biomechanical behavior or to design new implants and perform their optimization [2–4, 11, 15, 17]. FEA studies were developed in order to analyze and optimize bioinspired robotic structures, often used in rehabilitation [8, 9, 11, 19–24]. Virtual modeling of the healthy and prosthetic human elbow, simulations and FEA analyses of its biomechanical behavior, as well as the study of stresses occurred in the human elbow joint under various loads were addressed in several articles [12–15, 17, 18].

The aim of this research is to evaluate the values and distribution of stresses in the prosthetic elbow joint by using FEA on the 3D virtual model during flexion-extension movement under the solicitation of a vertical external force and compare them with those developed on the healthy elbow.

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2 FEA Analysis of the Virtual Model of the Prosthetic Elbow Joint

The Tornier-Latitude prosthesis system is a complex modular implant with great constructive flexibility, offering the possibility, depending on the situation found intraoperatively by surgeons, but also the residual instability, to move, intraoperatively, from an unconstrained prosthesis to one constrained by use of a piece that attaches to the ulnar component. The virtual model of the Tornier-Latitude total elbow prosthesis was developed based on the measurements and commercial prospectus of the product [16] and is presented in detail in the article [18], Fig. 1.

To determine the dynamic stress maps, the complex virtual model of the prosthesis elbow joint was exported to the finite element analysis software. The virtual simulation corresponds to the raising and lowering of a force of 100N, having a permanent vertical action and the application point located at the extremities of the ulna and radius, by the flexion and extension movement, having a total duration T = 1 s. In order to run the analysis with finite elements method, it is necessary to divide all the components of the Latitude prosthesis into finite elements. The main mechanical characteristics of each component of the prosthetic elbow will be provided, as input data.

Figure 2 shows the discretized virtual models for the humeral component and the ulnar component, while their mechanical characteristics are shown in Table 1.

Mesh structure of closing ulnar component, closing bushing, ulnar stem bushing, humeral ax, spherical coupling, radial stem are shown in Fig. 3, while the main mechanical characteristics are presented in Table 2 and Table 3. We noted HDPE – high density polyethylene.

The finite element structures of the radial head, the humeral stem screw, the spherical dome screw and the ulnar stem screw are shown in Fig. 4, and their mechanical characteristics are shown in Table 4.

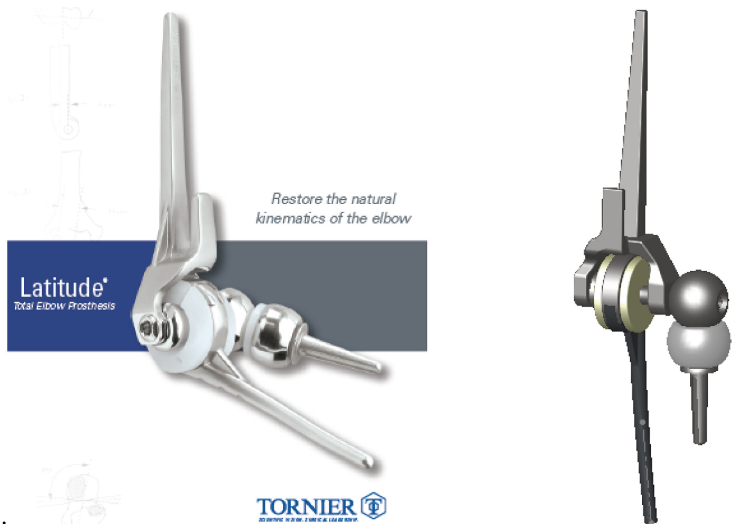
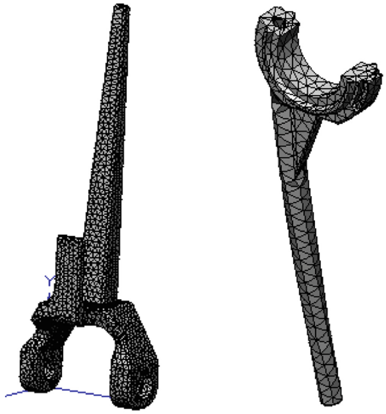


Fig. 1. Latitude total elbow prosthesis:a) Prosthesis prospectus [16]; b) the virtual model [18]

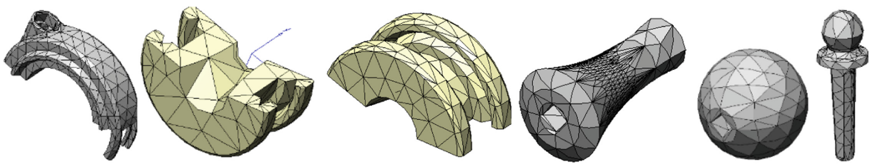


a) b)

Fig. 2. Mesh structure of: a) humeral component; b) ulnar component

Table 1. Main mechanical characteristics of humeral component and ulnar component

Component		
Properties	**Humeral component**	**Ulnar component**
Material	Titan	Titan
Density kg/mm^3	4.85e-6	4.85e-6
Masa, (kg)	0.0158 kg	0.00656 kg
Young's module (Pa)	1.02e + 11 Pa	1.02e + 11 Pa
Poisson's ratio	0.3	0.3
Nodes number	26199	5093
Elements number	15676	2783



a) b) c) d) e) f)

Fig. 3. Mesh structure of: a) closing ulnar component, b) closing bushing, c) ulnar stem bushing, d) humeral ax, e) spherical coupling, f) radial stem

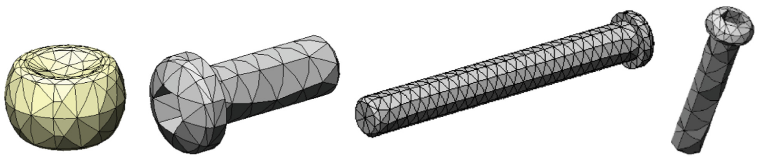
The three human bones: humerus, cubitus and radius, which are components in this assembly, were also divided into finite elements after they were prepared (cut) for virtual arthroplasty (Fig. 5), and their mechanical characteristics are shown in Table 5.

Table 2. Main mechanical characteristics of closing ulnar component, closing bushing, ulnar stem bushing

Component			
Properties	**Closing ulnar component**	**Closing bushing**	**Ulnar stem bushing**
Material	Titan	HDPE	HDPE
Density kg/mm^3	4.85e-6	9.52e-7	9.52e-7
Mass, (kg)	0.00267	0.000933	0.000746
Young's module (GPa)	1.02	1.07	1.07
Poisson's ratio	0.3	0.41	0.41
Nodes number	2974	1180	2338
Elements number	1644	550	1280

Table 3. Main mechanical characteristics of humeral ax, spherical coupling, radial stem

Component			
Properties	**Humeral ax**	**Spherical coupling**	**Radial stem**
Material	Titan	Titan	Titan
Density kg/mm^3	4.85e-6	4.85e-6	4.85e-6
Mass (kg)	23.6 e-4	92.5e-4	30.4e-4
Young's module (GPa)	114	114	114
Poisson's ratio	0.3	0.3	0.3
Nodes number	4223	1116	1034
Elements number	2404	615	508



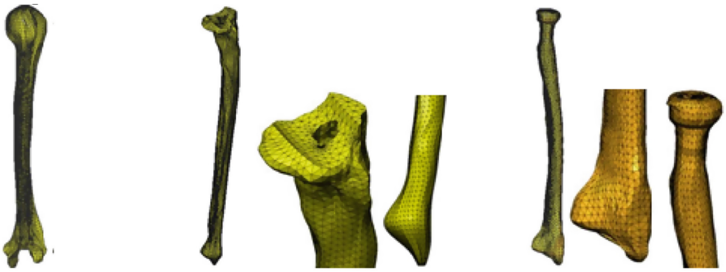
a. b. c. d.

Fig. 4. Finite elements structure of: a) radial head; b) screw of humeral stem; c) screw of spherical coupling; d) screw of ulnar stem

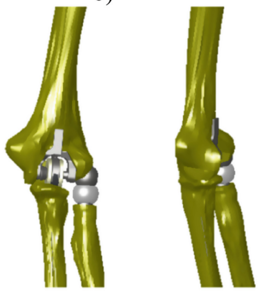
The complex virtual model of prosthetic elbow joint is composed of 118875 finite elements and 202704 nodes. The humerus was the fixed component, the other elements were considered mobile. In humero-ulnar and humero-radial rotation joints, a driving

Table 4. Main mechanical characteristics of radial head, screw of humeral stem, screw of spherical coupling and screw of ulnar stem

Component				
Properties	**Radial Head**	**Screw of humeral stem**	**Screw of spherical coupling**	**Screw of ulnar stem**
Material	HDPE	Titan	Titan	Titan
Density kg/mm^3	9.52e-7	4.85e-6	4.85e-6	4.85e-6
Mass (kg)	9.14e-4	3.8e-4	8.8 e-4	1.7 e-4
Young's module (GPa)	1.07	114	114	114
Poisson's ratio	0.41	0.3	0.3	0.3
Nodes number	1383	704	2799	631
Elements number	710	344	1512	300



a) b) c)



d)

Fig. 5. Mesh structure of: a) humerus, b) cubitus (ulna); c) radius; d) virtual model of prosthetic elbow joint

Table 5. Main mechanical characteristics of: humerus, cubitus and radius

Component			
Properties	**Humerus**	**Cubitus**	**Radius**
Material	Cortical bone	Cortical bone	Cortical bone
Density kg/mm^3	1.4e-5	1.4e-5	1.4e-5
Mass (kg)	2.19	0.431	0.595
Young's module (GPa)	21.4	21.4	21.4
Poisson's ratio	0.5	0.5	0.5
Nodes number	56313	48839	47878
Elements number	33562	28742	28245

movement was defined having an angular velocity x = -450 sin (2πt) deg/s. Figure 6 shows frames of the dynamic stress map for flexion-extension movements.

3 Discussions

Based on the stresses maps in Fig. 6, the diagram of the maximum von Mises stresses in the prosthetic elbow joint during flexion-extension movements for the analyzed period was drawn (Fig. 7), and compared to the diagram corresponding to the healthy (non-prosthetic) elbow, obtained and explained in detail in [15].

One conclusion is that the maximum stresses values are recorded in both cases for an angle of 90 degrees between the arm and forearm, when the bending moment is maximum, while minimum stresses are recorded in the maximum flexion position and the maximum extension position when the bending moment is very small, about 0. The maximum stresses values in prosthetic elbow are about 280 MPa, about 4–5 times higher than those obtained in healthy elbow, 75 MPa, but in first case, the maximum stresses are distributed on the prosthesis' components and they remain within admissible material strength values. Even the stresses present an important increase in the maximum tension states in the prosthetic elbow joint, they are developed on the prosthetic components, while the bones are solicited under normal demand. In the case of the prosthesis elbow, the maximum stresses are recorded in the contact area of the radial head prosthesis, which is a stress concentrator caused by the variation of the section.

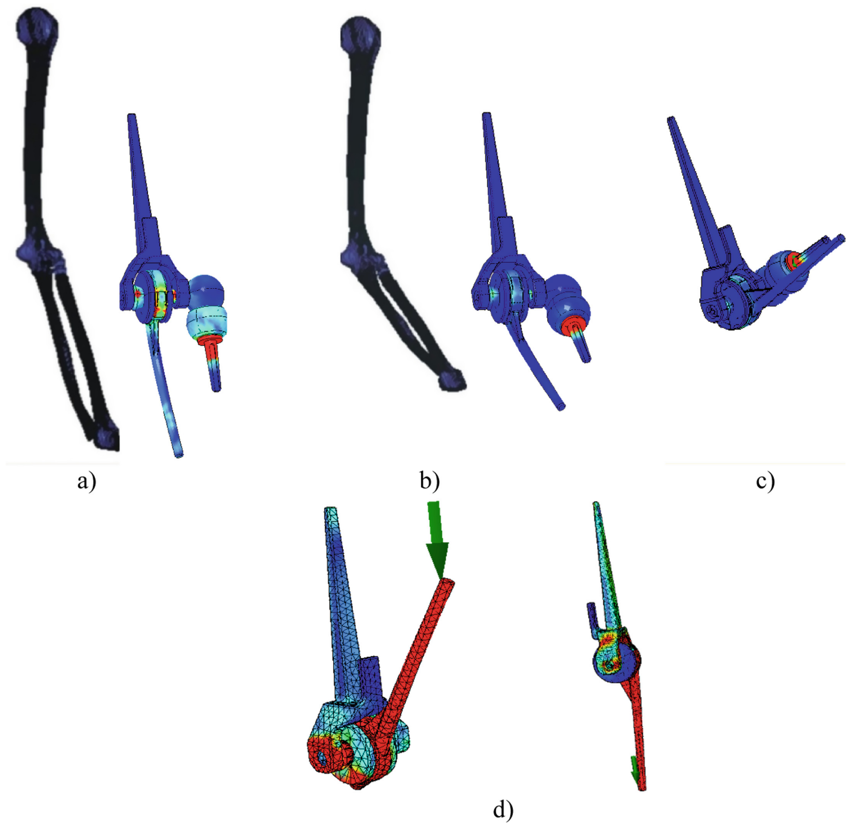


Fig. 6. Stress map for prosthetic elbow joint in flexion-extension movement for a) t = 0 s, b) t = 0.2 s, c) t = 0.8 s and d) prosthetic device in total flexion and total extension

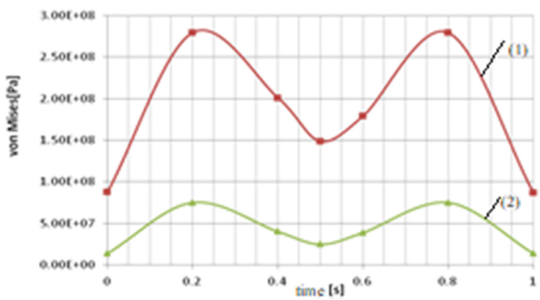


Fig. 7. Comparative von Mises stress variation for a cycle of flexion-extension movement of prosthetic elbow (1) and healthy elbow (2)

4 Conclusions

This paper presents the results of dynamic simulation of the flexion-extension movement of the Latitude prosthesis-joint assembly. The Latitude (Tornier, Stafford, TX) total elbow system, currently offers to surgeons the options of performing a hemiarthroplasty or a conversion from an unlinked to a linked total elbow arthroplasty, allowing that the later revision can be performed without the need to remove well-fixed stems. Using the Solidworks parameterized modelling environment, numerical simulations and FEM analyses were performed for flexion-extension of the assembly of elbow joint- prosthesis. Based on the developed stresses maps, the comparative diagrams of the maximum von Mises stresses developed during the flexion-extension movements of the healthy elbow and of the prosthetic elbow were drawn.

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