Contact stress simulation problem in case of the Mg alloys

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Abstract. This paper highlights the simulations of the contact stresses generated in the case of the load applied on biodegradable alloys based on Mg (Mg-0.5 Ca-xY), starting from previous studies done on these alloys and the homogeneity of the materials in different areas. Thus, it was tried to establish the parameters necessary for modeling, so that it would define as accurately the material studied. The main purpose of this paper was to identify the maximum values of the strain developed at the point of contact on the surface of the biodegradable alloys. This value was subsequently used to determine the limit values, for the practical use of these biodegradable alloys.

1. Introduction

Finite element analysis has evolved in recent years in biomedical engineering, helping to specify and validate feasible projects for different and more complex cases [1]. Biomechanics applies the laws of physics and mechanical principles in living organisms and with the help of biodegradable biomaterials, materials that could harm the human body are not introduced into the human body [2]. Software is a widely accepted for simulating structures that produce results in a faster and more efficient manner [3]. The femoral bone is a rather large bone, has an irregular geometry and a complex microstructure of biological tissue [17]. Bone tissue is part of the thick hard tissue of the body. The bones consist of inorganic strings from a collagen, protein and mineral matrix [4]. Normally, the bones retain body shape and help transmit force during movement. With the minimum available inputs, the finite element model defines the experimental motion [5]. When a broken bone enters the body, an operation is needed to clean the fractured area. In addition, when a fracture is exposed to the skin due to the risk of infection, there are several problems associated with healing [6]. As a method of improving the chances of performing normal human activities, the intramedullary rod is placed by the fixation method [7]. In the case of extreme fractures that occur in the human legs, the tibia bone is damaged causing failure to walk or perform normal human activities [8]. This method helps the man to walk, to climb steps, to move his legs or to run like a normal being, but with certain limits [9].

2. Research Methodology

In the first phase, the femoral bone was modeled and the rod assembly from Mg. Today the most used biomaterials are Ti alloys, Co-Cr alloys but also 316 stainless steel, however in the last years the biodegradable materials based on Mg have taken a pretty big advantage in the medical industry due to the high resistance against corrosion and high mechanical properties. In order to ensure adequate
resistance to corrosion, non-magnetic reaction and mechanical properties, the metallurgical requirements for these biomaterials are strict.

The plate is of the NCB Curved Femur Shaft Plate type with 10 holes, it has a length of 210 mm and a thickness of 5 mm and the holes are placed at a distance of 20 mm from each other, it was modeled according to the dimensions in the catalog [10].

Eight NCB Screws with a diameter of 5 mm and a length of 38 mm was used, they were modeled according to the shape and dimensions of the catalog [10] and the ISO 5835-1: 1985 standard [11].

Linear tetrahedron elements were used for the mesh. In the contact areas and stresses concentrators the local mesh densities has the following dimensions: local mesh size = 2 mm and sag = 0.5 mm. Otherwise, the global mesh densities has the following dimensions: global mesh size = 13 mm and sag = 1.5 mm. This resulted in a total of 21409 nodes and 87491 elements. To solve the static analysis with finite element, the mathematical fast Gauss method from CATIA V5 was used.

3. Results

Left thigh femur was extracted from a female skeleton [12] which was obtained by the segment method from the dicom top files downloaded from the human visual project [13].

The femur is a woman with a height of 1.63mm and 58 kg, which means that the length of the femur is \( L_f = 406 \) mm.

The femoral bone can be considered as an elastic anisotropic material resistant to yield strength of 120MPa. The femur was considered orthotropic with a density of 1850kg / m\(^3\) and with mechanical properties according to Table 1 [14].

| Young Modulus [MPa] | Poisson coefficient | Shear Modulus [MPa] |
|--------------------|---------------------|---------------------|
| Longitudinal \( E_1 = 1600 \) | xy plane \( \mu_{12} = 0.30 \) | \( G_{12} = 3200 \) |
| Transverse \( E_2 = 6880 \) | xz plane \( \mu_{23} = 0.45 \) | \( G_{23} = 3600 \) |
| Normal \( E_3 = 6300 \) | yz plane \( \mu_{13} = 0.30 \) | \( G_{13} = 3300 \) |

![Figure 1](image)

**Figure 1.** (a) Bone model and Mg plate, (b) The internal forces and moments of the human femur while walking at normal level have been estimated by various researchers [14-16].

The forces applied on the femur were calculated taking into account the forces and internal moments distributed due to body weight and contact forces at the hip and contact forces exerted by ligaments by all thigh muscles in a normal walking cycle of the patient. The walking cycle is between hitting the left foot and the next attack of the heel of the same foot [15].
At point O1 from figure 1(b), the internal forces and moments at the head of the femur were placed in the three directions, created by the contact force of the hip and the forces exerted by the muscles gluteus maximus, gluteus medius, gluteus minimus and tensor fascia latae. The O2 point is at a distance of 0.15Lf in the z direction, the forces resulting from the exercise on the three directions by the iliacus, piriformis, obturator, gemelli, popliteus, quadratus, pectineus and vastus lateralis muscles were placed. Point O3 is at a distance of 0.35Lf in the z direction, the force exerted on the y direction by the gluteus maximus muscles, adductor brevis and biceps femoris breve was placed. The O4 point is at a distance of 0.55Lf in the z direction, the force exerted on the z direction by the gluteus maximus muscles, adductor brevis and biceps femoris breve was placed.

The values of the modeled forces and moments are summarized in Table 2 according to the patient’s body weight (BW is the patient's body weight). A vertical load of 1.643∙BW characteristic for the patient walking as a normal person (without crutches) was used on the longitudinal direction of the femur. This case is a case of extreme load that should not happen in reality, but it is interesting to estimate whether or not the patient would suffer an injury.

### Table 2. Internal forces and moments exerted on femur.

| Force [N]/ Moment [Nm] | Relation | Value [N] / [Nm] |
|------------------------|----------|------------------|
| $F_{1x}$               | 0.786BW  | 445.86           |
| $F_{1y}$               | 0.835BW  | 473.66           |
| $F_{1z}$               | 1.643BW  | 932.00           |
| $M_{1x}$               | 0.130BW  | 73.74            |
| $M_{1y}$               | 0.0011BW | 0.624            |
| $M_{1z}$               | 0.0055BW | 3.120            |
| $F_{2x}$               | 0.926BW  | 525.28           |
| $F_{2y}$               | 0.497BW  | 281.92           |
| $F_{2z}$               | 0.572BW  | 324.472          |
| $F_{3y}$               | 0.1427BW | 80.947           |
| $F_{4z}$               | 0.3575BW | 202.795          |

![Figure 2](image.png)

**Figure 2.** (a) Mesh visualization with linear tetrahedral elements (b) How the femur was loaded.
Table 3. Mechanical properties of the Mg-0.5Ca-xY after simulation process.

| Mg-0.5Ca-xY | Sample 1 | Sample 2 | Sample 3 | Sample 4 | Sample 5 |
|-------------|----------|----------|----------|----------|----------|
|             | Mg-0.5Ca-0.5Y | Mg-0.5Ca-1Y | Mg-0.5Ca-1.5Y | Mg-0.5Ca-2Y | Mg-0.5Ca-3Y |
| Rigidity [N / μm] | 3.689 | 4.558 | 4.181 | 5.332 | 5.860 |
| Young Modulus [GPa] | 30.47 | 33.45 | 33.67 | 46.64 | 66.03 |
| Hardness [GPa] | 0.413 | 0.324 | 0.391 | 0.449 | 0.725 |
| Density [kg / m³] | 1798 | 1803 | 1808 | 1813 | 1818 |
| COF(coefficient of friction) | 0.555 | 0.593 | 0.676 | 0.504 | 0.346 |
| Von Misses stress in bone [MPa] | Maximum 65.5 | 66.2 | 67.6 | 67.4 | 67.8 |
| | Medium 26.2-39.3 | 19.9-39.7 | 20.3-40.6 | 20.2-40.4 | 20.4-40.7 |
| Von Misses stress in plate [MPa] | Maximum 266 | 265 | 265 | 296 | 361 |
| | Medium 80.8-160 | 80.4-159 | 80.6-160 | 92-179 | 113-219 |
| Von Misses stress in screws [MPa] | Maximum 395 | 403 | 405 | 442 | 455 |
| | Medium 118-237 | 121-242 | 121-243 | 133-265 | 137-273 |

Figure 3. Von Misses stress in the femur, (case for Mg-0.5Ca-3Y, Sample 5).
In the femur bone there are low stresses compared to the strength limit of the bone (which is around 120 MPa), the average values that are predominant are between 40.7 and 20.4 MPa. However, as we would have expected, some maximum values of 67.8 MPa can be observed in the area of stresses concentrators, namely near the holes according to the figure 3.

In figure 4 is presented the Von Misses stress in the Mg-0.5Ca-3Y alloy plate, maximum stresses of 361 MPa are observed in the area of stresses concentrators, even if these values exceed the resistance limit (the approximate value for magnesium is 278 MPa) it was expected as in areas with concentrator to appear points with maximum values above the resistance limit, and the static analysis was created for the most unfavorable situation, namely the load of 1.643BW (when the patient uses his foot like a normal person without using crutches), in reality the load is not static the load is variable and these maximum values are supported by the material for short periods of time. The predominant values are of average intensity between 113 and 219 MPa and are below of yield strength of the material.

Figure 4. Von Misses stress in the Mg-0.5Ca-3Y plate (Sample 5)

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Figure 5. Von Misses stress for Mg-0.5Ca-3Y case (Sample 5)
The average values are between 137 and 273 MPa values that are below of yield strength of the material. Figure 5(a) shows the stresses below of yield strength of the material. The highest stresses are present in the rod of the 455MPa screws near the geometric stress concentrator, namely the thread; it is known from the literature that among the geometric stress concentrators the thread is the one that creates the areas with the highest values for stresses.

In figure 5(b), you can see in red all areas that exceed the value of 67.8MPa (maximum value on the femur). This means that all the load, resulting from the forces and moments specific to a normal running cycle, is supported and taken over by the rod and the assembly screws. This is favorable for the recovery of the injury suffered by the patient's femur.

4. Conclusions
1. Additional strength and stability is obtained with the help of modified trapezoidal cross section in intramedullary rod.
2. Improved patient mobility post operation is obtained since the design is in accord with the anatomy of the femur bone reducing the chances of bone grafting during operation.
3. Active compression is achieved through a linear motion without rotation.
4. In the Mg-0.5Ca-3Y alloy the predominant values are of average intensity between 219 and 113 MPa and are below the yield strength of the material.
5. The highest stresses are present in the 455MPa screw near the geometric tension concentrator, namely the thread.

5. References
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