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Simulation of forces applied to the human femur: Analysis of finite elements

Simulación de fuerzas aplicadas al fémur humano: Análisis de elementos finitos

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Abstract

This document analyzes the efforts made to the human femur through a simulation of finite elements in Solidworks, in order to carry out the design of the femur in this study, the average height of the population of Malaysia were used, which is similar to that of the average Colombian population (Table 1.) and for the tests, a material with the same mechanical characteristics was simulated in the program of the human cortical bone, permitting a more approximate visualization of stresses and deformations to which the femur is exposed in the usual state and thus, identify the critical areas in which the probability of fracture or wear is greater, the results of this analysis do not apply For women in a state of pregnancy or people with osteoarthritic diseases. This analysis is important to identify which are the areas that present greater deterioration, considering that the bones lose their property of self-recovery over the years increasing the probability of presenting a fracture, having this information clear the prosthetic studies and medical treatments focused on the femur can be deepened. In this analysis, it can be identified that the male femur has greater resistance to tension and deformation than the female femur and how the femoral head is the most critical area of both the female and male fêmur.

Keywords: cortical bone, critical zones, deformation, effort, femur, tension.

Resumen

En este documento se analizan los de esfuerzos realizado al fémur humano, por medio de una simulación de elementos finitos en Solidworks; para realizar el diseño del fémur en este estudio se utilizaron las medidas promedio de la población de malasia que es similar a las medidas de la población promedio Colombiana (Tabla 1) y para las pruebas se simuló en el programa un material con las mismas características mecánicas del hueso cortical humano, permitiendo

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una visualización más aproximada de esfuerzos y deformaciones a los que se ve expuesto el fémur en estado habitual y así identificar las zonas críticas en las cuales la probabilidad de fractura o desgaste es mayor, los resultados de este análisis no aplican para mujeres en estado de embarazo ni personas con enfermedades osteo-artriticas, este análisis es importante para identificar cuáles son las zonas que pueden presentar mayor desgaste teniendo en cuenta que los huesos pierden su propiedad de auto-recuperación con el paso de los años aumentando la probabilidad de presentar fractura, teniendo clara esta información se puede hacer mayor profundización en estudios de prótesis y tratamientos médicos enfocados al fémur. En este análisis se puede identificar como el fémur masculino tiene mayor resistencia a la tensión y a la deformación que el fémur femenino y como la cabeza femoral es la zona más crítica del fémur tanto femenino como masculino.

Palabras clave: hueso cortical, zonas críticas, deformación, esfuerzos, fémur, tensión.

1. Introduction

The human bone is made up of an external and solid zone composed of calcium salts and collagen fibers [1] called cortical bone which supports most of the exerted loads and covers an internal area called trabecular bone or spongy composed of trabeculations that arise according to the different lines of forces to which the bone is exposed being this different internal zone not only for each individual depending on the functional demands and needs of each particular person but also for each bone, allowing a rigid and light morphology at the same time [2].

On the other hand, the collagen fibers that make up the cortical bone allow to have greater tensile strength and give it a heterogeneous structure allowing both cortical and trabecular bone to possess different mechanical properties that allow internal organs to be protected and provide rigid support to the locomotor system [3].

The bone material has particular features which are very different from those commonly treated by classical mechanics since having a heterogeneous structure presents an anisotropic behavior making it a complex material to analyze; This is how in some investigations mathematical models and different experimental techniques have been created in order to determine the anisotropy of the same and obtain values that allow bone fracture analysis to be taken as an isotropic material generating approximate values to the real ones [4].

The fact that bones are not anisotropic materials is not the only challenge posed by the study of the bones of the human body, it is also the behavior that it presents; according to its mechanical model, which corresponds to a viscoelastic - nonlinear material [5], but for biomechanical studies and identification of its mechanical characteristics, it is considered as an elastic - linear material, allowing to obtain acceptable values and very close to those actually obtained at the time of applying loads except in the case of loads of impact [4].

When a more detailed analysis of loads on the bones is performed and ruptures are generated, the mechanical properties of the cortical bone are worked, since on the one hand there are currently no records of isotropic parameters of the trabecular bone due to the variability of its structure and On the other hand, this is more flexible, but also more fragile than cortical bone, which is why fracturing the cortical bone causes the rupture of the trabecular bone [4].

Among all the bones that make up the bone system, the femur, in particular, is one of the most analyzed and studied by biomedical engineering research centers for its mechanical behavior in fractures, which has arisen a particular curiosity in some authors since having a direct connection with the hip is a fundamental part of the support and support system of the bone system; It has been shown that it receives direct loads especially in the proximal epiphysis and therefore obtains greater wear than that obtained by other bones, this in the long term generates fragmentation and lesions in the femur that prevent the mobility and displacement of the individual [5].

Additionally, the femur is one of the few bones for which its orthotropic or anisotropy mechanical properties are considered for its study since besides the age, height, weight and health status of the individual; its fracture probabilities increase or decrease depending on the state of the hip and the position in which it exerts pressure on the femoral head [5]. The bone is very resistant to the efforts of understanding, moderately resistant to those of traction, but it is fragile to those of shearing [1], these characteristics allow the femur to adequately fulfill its functions of providing stability to the body, but also makes it fragile under other conditions and therefore more susceptible to fractures and fragmentation.

In the trials and simulations referenced (CD Álvarez & Angulo, 2010 [1]; RSM Álvarez & Velutini, 2011 [2]; Cabrera et al., 2011[3]; Rincón et al., 2004 [4]; Romo, 2016 [6]), fractures or fragmentation are generated in the femur identifying their behavior against different loads generated, especially from the surgical neck to the head of the femur (Figure 1), that is the part in which a connection is generated and therefore a direct affectation between the hip and the femur, is a fundamental part of the skeletal stability of the individual.

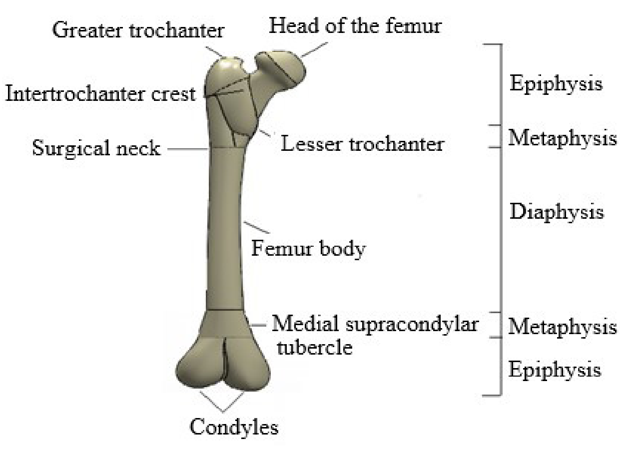

Figure 1. Parts of the femur. Solidworks male femur design.
Source: Own.

The characteristics of the fractures in the femur depend on the point at which the load is exerted, regardless of whether the same load is applied to the bone, it does not respond the same throughout its structure, since its morphology changes and its percentage of cortical bone, It varies depending on the area; in this article the areas of the femur are evaluated where the application of forces can create fractures more easily, identifying these areas as critical points and generating a comparison with what was found in tests applied directly to bones and simulations performed by other authors (Alexander, Cabrera, Manuel, & Botello, 2011[7]; CD Álvarez & Angulo, 2010 [1]; RSM Álvarez & Velutini, 2011 [2]; Cabrera et al., 2011 [3]; Rincón et al., 2004 [4]; Romo, 2016 [6]).

In order to determine or correlate the loads and inclinations of the forces necessary to produce fractures in the femur and determine which are the critical areas thereof, a simulation was carried out in Solidworks in which a male femur and a female one were created, literature with the mechanical characteristics of cortical bone under normal conditions found in some referenced articles that define these characteristics (Alexander et al., 2011 [7]; CD Álvarez & Angulo [1], 2010; RSM Álvarez & Velutini, 2011[2]; Cabrera et al., 2011 [3]; Rincón et al., 2004 [4]; Romo, 2016 [6]) and loads were applied in different zones, distinguishing by means of colors the stresses and deformations generated by the loads allows it to identify the areas that are most likely to vary their morphology and present rupture against the application of the different force vectors.

To define its morphology, it is considered that the anatomical variables are wide depending on the individual, therefore the measurements of the femur of individuals of stature, age and average weight of the population of Malaysia are taken, similar to the standard measures of Colombians (Children's Cardio Foundation and the Colombian Association of Pediatric Endocrinology with the support of the Karolinska Institute (Sweden) and financed by Colciencias) [8], but in the area of the femoral head, variables such as angles of inclination in relation to the epiphyseal line have been found, which varies from 56º to 90º, generating an impact on the behavior of the femur in front of the loads, that is to say that as long as the surface of the spherical area of the femoral head is greater, the load unit decreases and vice versa [2].

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Table 1. The average height of the Colombian population; [8].

	Man	Woman	Average
Average height (cm)	172	160	166
Range (cm)	156-186	148,5-171	152-178

In this article an approximation is made to the mechanical behavior of the femur; The analysis is applied considering the gender of the individual since they present percentages of asymmetry according to their anatomy.

2. Methodology

2.1 Geometry

For the design of the femur, the measurements of Malaysian individuals are taken as a reference, considering that the average height of this population is between 1.65 ± 9.63 meters and the average weight is 61.68 ± 13, 84 [9]; These measures are close to the average measures of Colombians (Children's Cardio Foundation and the Colombian Association of Pediatric Endocrinology with the support of the Karolinska Institute (Sweden) and financed by Colciencias see Table 1) [8].
In the study of which the measures were taken, the femur of 120 individuals between men and women were evaluated at an average age of 25 ± 5.18 years, excluding only women in pregnancy and individuals with osteoarthritic problems, considering that these two states generate drastic changes in the morphology and bone system of individuals [9].
According to the above mentioned, the measures defined for the femur design in Solidworks were (Table 2).
Considering that the bone is composed of cortical bone (external) and trabecular bone (internal), a thickness of 3 mm was given to the cortical bone and based on this the material was emptied, the above is because, once fractured the cortical bone, it is impossible not to generate any damage in the trabecular bone.

At the time of the design, it was initiated by a 2D model (Figure 2), in which the different parts of the femur were molded and adapted to the measurements of both the male femur and the female one, using as a guide a sketch of a Human femur, giving the two models a 3D format and generating detailed drawings in the femoral head, in the greater trochanter and the lesser trochanter.

Table 2. Dimensions used for the design of the Femur [9].

	Man	Woman
Length (mm)	436,86	436,86
Angle of femoral head tilt (degrees)	132,33°	129,87°
Diameter of femoral head (mm)	43,62	38,85
Diameter of femoral neck (mm)	28,88	25,95
Distance Femoral head to the sub-trochanteric area (mm)	91,08	81,78

To define the model, different planes were used considering that the emptying should be different in each of the zones (See Figure 3), depending on the thickness, since in some areas such as in the greater trochanter it conserves 3 mm of cortical bone, the amount of trabecular bone is minimal compared to the head of the femur.
Figures 4 and 5 show the finished designs of both the male femur and the female one respectively.

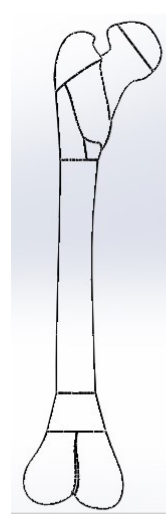

Figure 2. 2D sketch, male femur design in Solidworks.
Source: Own.

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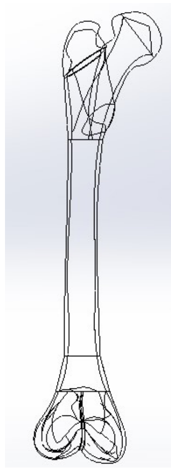

Figure 3. Emptying the femur. Female femur design in Solidworks.
Source: Own.

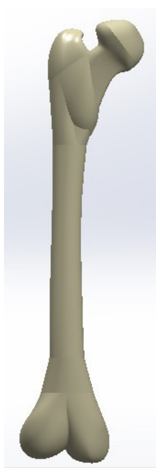

Figure 4. Male femur in Solidworks.
Source: Own.

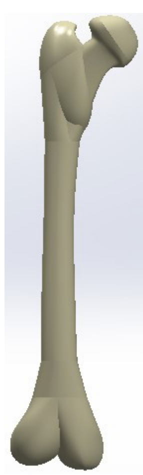

Figure 5. Female femur in Solidworks.
Source: Own.

2.2 Meshed

For the design of the man as well as that of the woman, it was sought to make a mesh that would allow obtaining the largest possible number of nodes, allowing the simulation to yield values as close as possible to reality, in the smaller areas a control of mesh was carried out to avoid errors at the time of application of loads. The total number of nodes obtained was 299,835 in the female model (Figure 6) and 132,263 in the male model (Figure 7) allowing to obtain values closer to those obtained in other studies such as that carried out by Cabrera, Estrada and Ramos, in which they obtained a model with 74,159 and another with 128,451 nodes [3]. The difference of nodes between the models is presented because they have different measures and the angle of inclination of the femoral head of the female model allowed a more detailed mesh in the upper area of the femur.

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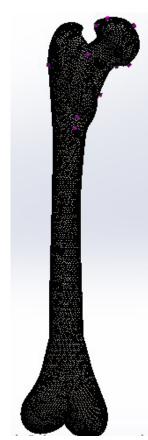

Figure 6. Female femur mesh. Solidworks design.
Source: Own.

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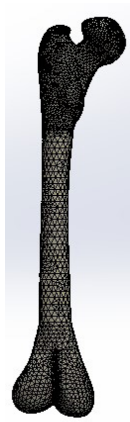

Figure 7. Mesh male femur. Solidworks design.
Source: Own.

2.3 Mechanical properties of the material

Solidworks allows to add materials to the system library, therefore, the cortical bone was added as new material, which was applied to the model so that its simulation behavior was as close as possible to the actual behavior of the bone and in this way be able to correctly identify the critical points.
In the analysis carried out by Bosh, Estrada and Ramos a Poisson coefficient from 0.2 to 0.366 in the 3 axes of the model is used, which has a density of 1900 kg / m3 for cortical bone analyzing the efforts generated by two mechanical fixators in the cortical bone in the human femur [7]. Rincon, Ros, Claramunt, and Arranz use in their study a Young Module of 18.8 GPA for the dry femur and a Poisson coefficient of 0.28 to 0.31 in the three axes, with this information they perform a mechanical characterization of the bone cortical in the femur [4]. Charles, Lacroix, Porubasta, and Planell to perform a finite element analysis of the efforts generated by intramedullary nails and osteosynthesis plates in the femur using a Poisson coefficient of 0.33 for cortical bone and a Young Module of 17 GP [10]. To perform a simulation and computational analysis of the medullary duct of the femur, Cerrolaza and Alfonso used a Young GP Module of 18 GP for cortical bone, a density of 1850 kg / m3 and a Poisson coefficient of 0.33 [5]. These values are similar to those presented by other authors and were used for this analysis.

To add the material to the system in this article, we evaluated the studies prepared by Bosh, Estrada, Ramos, Rincon, Ros, Claramunt, Arranz, Charles, among others, specifying the mechanical properties of the material to be used, in this case, the values supplied for cortical bone were: (Table 3).

Table 3. The values supplied for cortical bone [4].

PROPERTY	VALUE
Module of Young	18 GPA
Coeficient of Poisson	0,33
Density	1850 Kg/m3
Tensile strength	150 MPA
Compressive strength	280 MPA

2.4. Loads

To perform the finite element analysis, the Von Misses failure criterion is used, calculating the deformation and accumulated stresses in the bone from the application of loads, between the tests, compression loads were applied simulating those exerted by the surrounding muscles to the femur under normal conditions and on the other hand forces were applied (see Table 4) at different points to be able to observe the reaction of both the male and female femur against them.

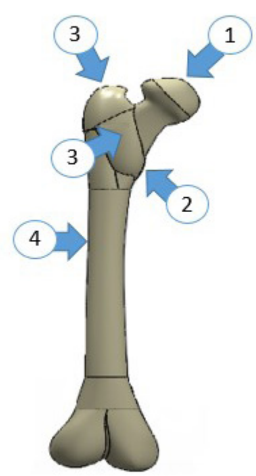

Figure 8. Areas in which the different loads were applied. Female femur design Solidworks.
Source: Own.

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The human femur receives the load on the femoral head generated by the weight of the upper area of the body, that is, from the hip to the head of the individual (Force 1 in Figure 8), on the other hand, the lesser trochanter receives the load generated by the abductor muscle that is in the crotch (Force 2 in Figure 8) while the greater trochanter and the inter-bronchial ridge support the iliac Iliopsoas (Force 3 in Figure 8) and the femoral body is surrounded by the sartorius muscle that connects with the iliac tibia (Force 4 in Figure 8).

Table 4. Compression loads applied [7].

LOAD	STRENGTH (N)
Load product to weight	2997
Abductor	1237
Iliac Tibia	1200
Iliopsoas iliac	771,5

Before performing the tests, a fixation is generated in the supracondylar tubers and in the condyles, areas which connect directly with the knee and are affected by other types of forces in which the knee and tibia are involved.

3. Outcomes

The results obtained in terms of deformation and tension show that the male femur withstands greater tensions, this is because the dimensions are greater in the head and femoral neck, and its distance from the head to the sub-truncated area is also greater, allowing to distribute the loads more comfortably.

Applying a force of 2997 N on the femoral head of both models, it can be observed that no tension is generated in that area, but if a deformation greater than that presented in the other affected areas, the tension in this area is 2,457e-01 N / m2 for the female femur (Figure 9) and 5,734e-01 N / m2 for the male femur (Figure 10), but the deformation observed in this area is greater than that observed in other areas obtaining the maximum value , that is, 3,924e-05 mm in the female femur (Figure 11) and 3,948e-05 mm in the case of the male femur (Figure 12).

A force equivalent to 1237 N is applied to the inter-border ridge and 771.5 N in the greater trochanter in the male and female femur, observing that the greater trochanter has a greater deformation in both cases despite receiving a lower load, This can occur, because the area of this is smaller than the area of the inter-bronchial ridge and the latter is supported by the surgical neck and distributes its load to the diaphysis or body of the femur.

On the other hand, it is possible to identify that the normal tensions that the femur receives affect or accumulate mainly in the diaphysis or body of the femur, especially near the distal epiphysis which is the thinnest area of the body of the femur and is the area in which the forces applied are crossed both by the upper part and by the lower part of the human body. Figure 9 represents the resulting tensions in the female femur after applying the loads, observing in the yellow and green areas where there is a greater accumulation of tensions, therefore, this part of the body of the femur will be classified as a critical area.

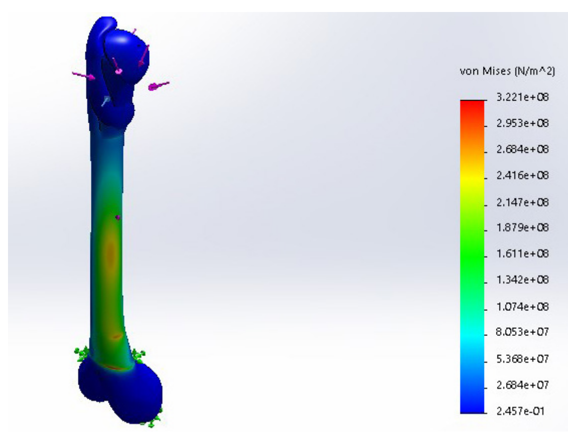

Figure 9. Resulting stresses of the female femur. Simulation in SolidWorks.
Source: Own.

On the other hand, Figure 10 shows a lower accumulation of tensions, since, in the area where the female femur takes a yellow and green color, the male femur only gets a lighter blue tone, which represents a greater Tensile strength.

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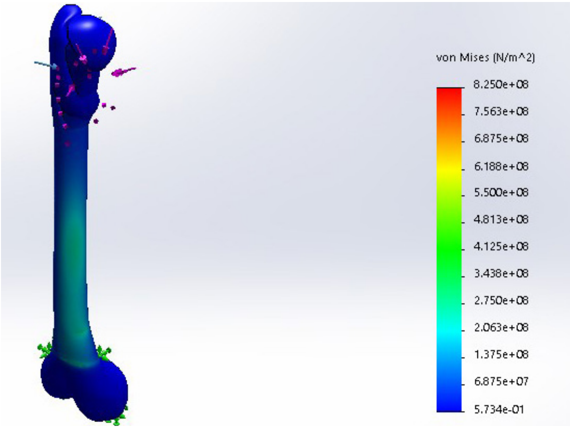

Figure 10. Resulting stresses male femur. Simulation in SolidWorks.
Source: Own.

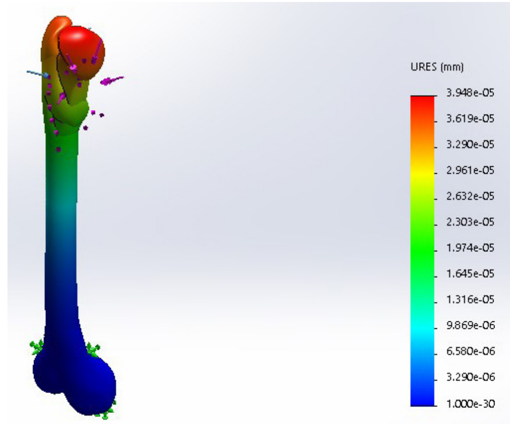

Figure 12. Deformations resulting in the male femur. Simulation in SolidWorks.
Source: Own.

The deformation is mainly reflected from the surgical neck to the femoral head, which coincides with that found in other simulations, such as those performed by Charles-Harris, Proubasta and Planell (Authors of the article "Intramedullary nails vs. osteosynthesis plates for femur fractures: finite element analysis")

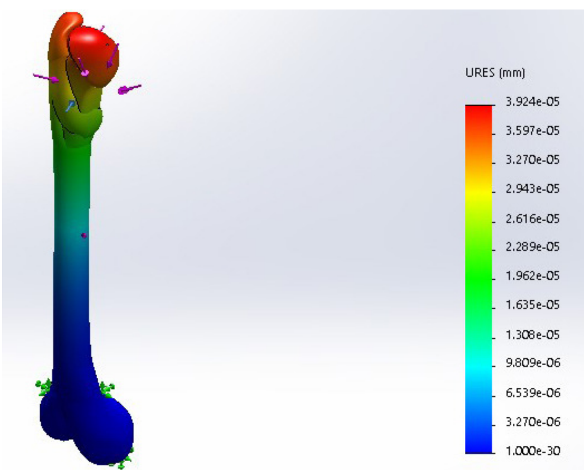

Figure 11. Resulting deformations in the female femur. Simulation in SolidWorks.
Source: Own.

As in Figures 9 and 10 where the tensions generated can be evidenced, in Figure 12 can be shown that the male femur is more resistant to deformation than the female femur, the femoral head becomes red, but in values older than those supported by the female femur.

In some studies, and analyzes can be shown that the areas with the greatest rupture are the femoral head and the neck of the femoral head, this is because they are the areas that are most deformed with the normal loads applied to the body, therefore when applying Extra strength are more likely to exceed their elastic limit and create a break [11]. The monitoring of the standards indicated allow your work stand out not only for its content but that is also visually appealing. Send the item without header logo of the journal and indicate only the date of shipment.

4. Conclusions

In the simulation the real values of the mechanical properties of the cortical bone were used; the information provided by the referenced articles and the characteristic of the program used, allowed to add the properties of this material to the system literature, obtaining an analysis with real approximation. The analysis was performed only considering the properties of the cortical bone because after a fracture which is generated in the cortical bone, it is impossible not to generate any damage to the trabecular bone or its structure since it is less resistant than the cortical bone.
It is important to keep in mind that in the analysis of finite elements a mesh was made with the largest possible number of nodes, allowing the program to

evaluate the design in detail and thus allow to obtain approximate values to the real one.

Despite having the same material with the same mechanical properties, the male femur is more resistant to tension and deformation than the female femur, because the measurements of the male femur are more extensive and an inclination angle of the femoral head is greater.

As identified in the tests performed, the critical areas in both the female and male femur are the lower part of the femoral body for tension and the surgical neck to the femoral head for deformation, especially the femoral head, the femoral neck and the trochanter higher.

Critical areas are classified as those that have the greatest impact on the tests carried out since, when deforming or accumulating greater tension at the time of applying normal loads of the human body, they are more likely to reach more in the moment of an impact or compression early to their elastic limit and create a rupture before any other area of the femur. The wider the loading area of the femur area, the closer the stress center is to the center of rotation of the femoral head and the variations in this sector may represent greater or less wear on the articular surfaces and the osteoarthritis.

References

[1] C. D. Álvarez & M. T. C. Angulo, "Clinical biomechanics of bone", *Reduca,* vol. 2, no. 3, pp. 32–48, 2010

[2] R. S. M. Álvarez, & J. A. K. Velutini, "Anatomy of the Human Femoral Head: Considerations in Orthopedics, Part II". *Biomechanics and Microscopic Morphology*, vol. 29, no. 2, pp. 371–376, 2011

[3] J. B. Cabrera, R. E. Cinqualbres & Y. R. Botello, "Original Article Comparative Numerical Analysis of fixatives for the treatment of proximal fractures of the femur Introduction", *Mechanical Engineering*, vol. 14, no. 3, pp. 199-208, 2011.

[4] E. R. Rincón, A. R. Felip & R. C. Alonso, "Mechanical characterization of bone material", *Technology and development,* vol 2, 2004.

[5] M. Cerrolaza & M. A. G. Alfonso, (2013). "Simulation and computational analysis of the medular duct of the femur in the presence of a hip prosthesis*", Rev. Engineering Faculty*. Vol 28, no. 4, 25–34.

[6] E. R. Romo. Thesis: "Final Degree Project Degree in Industrial Technology Engineering Numerical modal analysis of the femur. Influence of boundary conditions on natural frequencies", *Sevilla University*, Degree in Industrial Technology Engineering*,* 2016.

[7] J. B. Cabrera, R. E. Cinqualbres & Y. R. Botello. "Comparative numerical analysis of fixatives for the treatment of proximal fractures of the femur Mechanical Engineering", *Mechanical Engineering*, vol. 14, no. 3, pp. 13–14, 2011.

[8] El tiempo, "The average height of the Colombian population according to research carried out by the Children's Cardio Foundation and the Colombian Association of Pediatric Endocrinology with the support of the Karolinska Institute (Sweden) and funded by Colciencias" Available at: https://www.eltiempo.com/archivo/documento/CMS-13128617

[9] M. Y. Baharuddin, M. R. A. Kadir, A. H. Zulkifly, A. Saat, A. A. Aziz & M. H. Lee, "Morphology Study of the Proximal Femur in Malaysian Population". *Int. J. Morphol*, vol. 29, no. 4, pp. 1321-1325, 2011. https://doi.org/10.4067/s0717-95022011000400042

[10] D. Lacroix, I. Proubasta & J. A. Planell. "Intramedullary nails vs. Osteosynthesis plates for femur fractures: A finite element analysis", *Biomechanics*, vol. 12, no. 1, 64–70, 2004.

[11] A. M. Reyes, F. A. Verásteguí, J. A. Collazos, "Prototype development of a fingerprint biometric information system", *Rev. vínculos*, vol. 15, no. 2, 2018.