ANALYSIS OF TEMPORAL PARAMETER FOR STANFORD ISOTROPIC BONE REMODELING MODEL FOR IMPROVEMENT OF DATA PROCESSING

Bárbara Belisa Soffiatti

José Eduardo Gubaua

Gabriela Wessling Oening Dicati

Jucélio Tomás Pereira

bah.soffiatti@gmail.com

jose.gubaua@yahoo.com.br

gabyoening@hotmail.com

Prof_Jucelio_tomas@hotmail.com

Federal University of Paraná

Av. Cel. Francisco H. dos Santos, 210, Jardim das Américas, 81.531-970, Paraná, Curitiba, Brazil.

Abstract. *Bone is a living tissue, whose main function is to support the human body. It contains cells responsible for the formation and removal of the tissue depending on the stimulus to which it is submitted. They act in a process called Bone Remodeling. According to the activity that an individual makes, it generates stress and strain fields, which enable the remodeling process and the change of bone local density. The aim of this paper is to analyze the behavior of a human femur for different bone remodeling frequencies, since the updating of local density depends on the time interval in which remodeling will be executed. The density field is determined by application of loadings, which simulates a person's daily gait. This is made through an analysis of finite element methods (FEM) coupled with the isotropic model of Stanford bone remodeling. The mass variance in function of loading days shows similar behavioral curves for distinct bone remodeling frequencies; however, it has considerable differences as their time stabilization and their values of mass variance. The matter is to reduce simulation time of bone remodeling process in order to make a greater quantity of trials based on, for example, individual characteristics of people.*

Keywords: *Finite Element Method, Biomechanics, Bone Remodeling, Abaqus, Parameters Change.*

INTRODUCTION

Bone Remodeling (B.R.) is the process that characterizes how the bone structure changes according to biomechanical stimulus that it is subjected to, by the adaptation of bone cells. Osteoclasts, osteoblasts and osteocytes are cells that work together on the formation and resorption of bone. Many factors lead to bone remodeling as hormones and mechanical stimulus, for example (Robling et al, 2006). Different movements and activities stimulate diverse parts of human body and, as a consequence, various types of bones. One example is when a person walks; the gait movement generates a series of loadings on femur, which in turn creates stress and strain fields that work as a mechanical stimulus for bone remodeling. This process occurs in three main phases. Initially the old bone tissue is resorbed by osteoclasts action. Then osteoblasts start to form the new bone. The third phase is the finalization of the process, where bone tissue reaches its usual final properties. After completing their function, osteoblasts turn into osteocytes, which control cellular activity between bone and blood circulation (Roesler, 2006).

The advance of technology allows multidisciplinary studies, thus engineering can help to solve medical and biological problems, using computational and mathematical tools. A good method to analyze the behavior of a structure subjected to loads is finite element method (FEM). Bone remodeling can be simulated in FEM analysis, considering the mechanical stimulus and material properties. To characterize bone behavior, many scientists created bone remodeling models that account different aspects of the human body and external environment to change bone morphology. The big issue on this kind of simulation is the time of data processing, knowing that a bone takes more than 3 months to remodel properly in an adult individual (Roesler, 2006).

This paper provides a computational analysis of a human femur subjected to daily loadings that simulate a gait. For the simulation, we use for FEM analysis the software Abaqus coupled with a subroutine in Fortran language, which contains the isotropic model of Stanford bone remodeling. This model is better discussed on section 1.1, bringing all the formulation and parameters that the remodeling is dependent on, moreover it explains how bone density updates. For this model, the frequency in which bone remodeling occurs, Δt, can impact on the time of simulation and data processing due to the updating of bone density is described as

$$\rho_{n+1} = \rho_n + \dot{\rho}\Delta t, \tag{1}$$

where ρ_{n+1} and ρ_n are the new and old densities, respectively, and $\dot{\rho}$ is the change rate of density. In general, scientists use a daily frequency, which means that bone is remodeling every day. However, for a long period of evaluation (days), the use of a daily Δt becomes very time-consuming. Furthermore, some studies depend on trials of different parameters for many individuals, which mean a great number of simulations. The aim of this paper is to analyze several values of B.R. frequency for the same femur model and see if the results will have a similar behavior to the daily updating. That way, when we use a Δt of 5 days, for example, it means that the updating of density, will remodels just once but considering five days of loading.

1 METHODS

This section contains the methodology applied on this paper.

1.1 Isotropic model of Stanford bone remodeling

There are different types of bone remodeling models. The model proposed for Jacobs et al. (1995), which uses the formulation of Beaupré et al. (1990), considers that the bone has an isotropic, elastic and linear behavior. It is based on strain energy density remodeling theories and takes on that the bone responds to changes on the daily stress stimulus, ψ_t, as

$$\psi_t = \left(\sum_{days} n_i * \bar{\sigma}_{t_i}^m \right)^{1/m}, \tag{2}$$

where n_i is the number of daily cycles of i loadings, m is an empirical constant of the material and $\bar{\sigma}_{t_i}$ is the effective stress in the tissue region. The rate of bone remodeling, $\dot{r}$, is a function of remodeling speed, c, dead zone interval, W, and the reference value, ψ_t^*, that set the constant level of daily stress stimulus that will not change bone density.

$$\dot{r} = \begin{cases} c\left[\psi_t - \left(\psi_t^* - W\right)\right] & if \ \psi_t < \left(\psi_t^* - W\right) \\ 0 & if \ \left(\psi_t^* - W\right) \le \psi_t \le \left(\psi_t^* + W\right). \\ c\left[\psi_t - \left(\psi_t^* + W\right)\right] & if \ \psi_t > \left(\psi_t^* + W\right) \end{cases} \tag{3}$$

The effective stress, $\bar{\sigma}_t$, can be related with stress in a continuum level, $\bar{\sigma}(\rho)$, its apparent density, ρ, and the cortical bone density, ρ_c, and it is defined as (Beaupré et al. 1990).

$$\bar{\sigma}(\rho) = \left(\frac{\rho}{\rho_c}\right)^2 \bar{\sigma}_t. \tag{4}$$

On the other hand, the continuum level of effective stress, $\bar{\sigma}(\rho)$, can be determined as

$$\bar{\sigma} = \sqrt{2EU}, \tag{5}$$

that is, defined as a combination of Young's modulus, E, and strain energy density, U, with E calculated as:

$$E(\rho) = b(\rho)\rho^{\beta(\rho)}, \tag{6}$$

where b and β are empirical constants in function of material density, as shown in Table 1. The table also displays how Poisson's ratio changes in function of bone density.

The density rate, $\dot{\rho}$, is obtained by the remodeling rate, $\dot{r}$, cortical bone density, ρ_c, active surface, k, and the surface area available for bone remodeling, S_V. According to Martin (1984) and after improvement by Aznar et al, (1999), surface area can show a satisfactory value by a fifth order polynomial equation in function of bone porosity. Corso (2006) made an approximation in function of the apparent density and it can determined as

$$S_V = -0.07 + 8.1\rho - 7.2\rho^2 + 5.1\rho^3 - 2.1\rho^4 + 0.23\rho^5. \tag{7}$$

Thus, density rate is determined as

$$\dot{\rho} = k\, S_V\, \dot{r}\, \rho_c. \tag{8}$$

Finally, the updated bone density, ρ_{n+1}, is shown in Eq. (1) as a sum of actual the density, ρ_n, and a multiplication of density rate, $\dot{\rho}$, and the time interval of bone remodeling, Δt, that is, the frequency in which the process of remodeling occurs.

Table 1. Constants values of b, β and ν in function of density value

Constants	$\rho \leq 1.2e-6\ [kg/mm^3]$	$\rho > 1.2e-6\ [kg/mm^3]$
b	2014	1763
β	2.5	3.2
ν	0.2	0.32

1.2 Computational Implementation

The computational analysis run with a tridimensional model of a human femur, built from a real tomography. The flowchart on Fig. 1 shows how the three software (Matlab, Abaqus and Fortran) are coupled to generated the analysis, also where bone remodeling, FEM analysis and smoothing treatment are applied.

First Matlab loads the data and initial parameters of the 3D model for FEM simulation, as well as, the time interval in which bone remodeling occurs, Δt. Then, it opens the software Abaqus that, together with the subroutine in Fortran, runs bone remodeling process, where the densities field is updated and exported for every step. Finally, Matlab reads the densities field and compute the mass variation of the femur and its Eulerian norm for each step.

The study of B.R. frequencies is made for six different time intervals as shown in Table 2. The remodeling process ran for a minimum of 1000 days, with slight variation for those time interval values that are not multiples. That being so, the number of steps to get to a thousand days decreases as the time interval increases and, in the end, there are a reduction of the data processing time. An analysis of iterative B.R. frequency is also applied. For it, the simulation starts with a daily Δt, and change to higher frequencies according to the results from previous analysis, aiming to understand how prior variations affects the result.

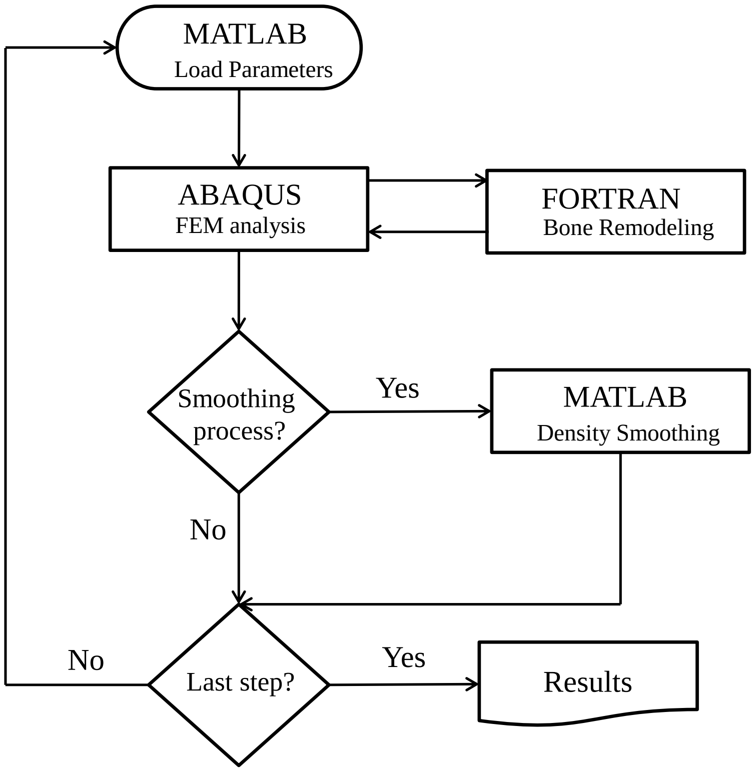

Figure 1. Process Flowchart

Table 2.Steps and days for bone remodeling frequencies

Δt [days]	1	2	5	7	15	30
Number of steps	1000	500	200	143	67	34
Total of days	1000	1000	1000	1001	1005	1020

For every step, we calculate the mass variation and the Eulerian norm of mass vector in order to compare the behavior for all time intervals. On other words, the software Abaqus export the density field generated after the bone remodeling process, and, on Matlab, we calculate the difference between the new and the old density field, which multiplied by the elements volume, provides a mass variation for the actual step. The Eulerian norm of this allows us to compare the results of bone remodeling frequencies in a better way than by using the mass variance values, because the last one shows curves that crosses the axis of days, suggesting that in one step there are none mass variance.

The subroutine in Fortran language, called UMAT (User Material), brings the parameters and equations of isotropic model of Stanford bone remodeling. The parameters used to calculate the new density for each element of the bone are described on the Table 3.

Table 3. Parameters of isotropic model of Stanford Bone Remodeling

Parameter	Value	Unit
n_i	3000	Cycles/day
ψ_t^*	50.0	MPa
W	$0.125\times\psi_t^*$	MPa
m	4.0	-
c	2.0e-5	(mm/day)(MPa/day)
ρ_c	2.0e-6	kg/mm³
k	1.0	-

Initially, the computational analysis starts with a homogeneous density of $1.0e^{-6}$ kg/mm³, which changes as the remodeling process occurs for every step. The maximum density that a bone can have is on the cortical bone region with $2.0e^{-6}$ kg/mm³ (Jacobs et al., 1995). In order to avoid numerical problems in computational algorithms, we estipulate a minimum bone density of $0.2e^{-6}$ kg/mm³ (90% of porosity (Hall, 2011)).

The loadings are applied on Abaqus and characterize the gait of an individual that walks 3 km per day, during 1000 days. The gait is divided in three movements (Gubaua, 2016; Dicati, 2015). The first is when the foot touches the floor. The second and third are the abduction and adduction movements of the lower limbs, respectively. There are six loadings, applied in pairs for each of the three movements: a compression, because of the contact between the femoral head and the acetabulum, and a traction force, due to muscle response on the greater trochanter. The intensity of the forces is according to Jacobs et al. (1995), the loadings directions are based on Bagge (1999) and the areas of loading application are according to Greenwald and Haypes (1972). Table 4 shows the intensities and directions for the six loadings, which can be seen on Fig. 2.

Table 4. Intensity and directions of loadings

Loads	Intensity [N]	Direction (x,y,z)	Area [mm²]
Compression 1	2317	Surface pressure	1541.05
Compression 2	1158	Surface pressure	1159.28
Compression 3	1548	Surface pressure	1315.61
Traction 1	703	(0.149,-0.06241,0.9869)	809.90
Traction 2	351	(-0.3232,0.3878,0.8632)	597.29
Traction 3	468	(-0.3827,-0.4073,0.8292)	707.21

The equilibrium of human femur is made by the knee joint. To reduce the stress concentrators a solid with linear and elastic behavior is fixed on femoral diaphysis where the homogenous boundary conditions are applied, as shown in Fig. 2. The mesh used has 147,638 tetrahedral linear elements and 27,819 nodes.

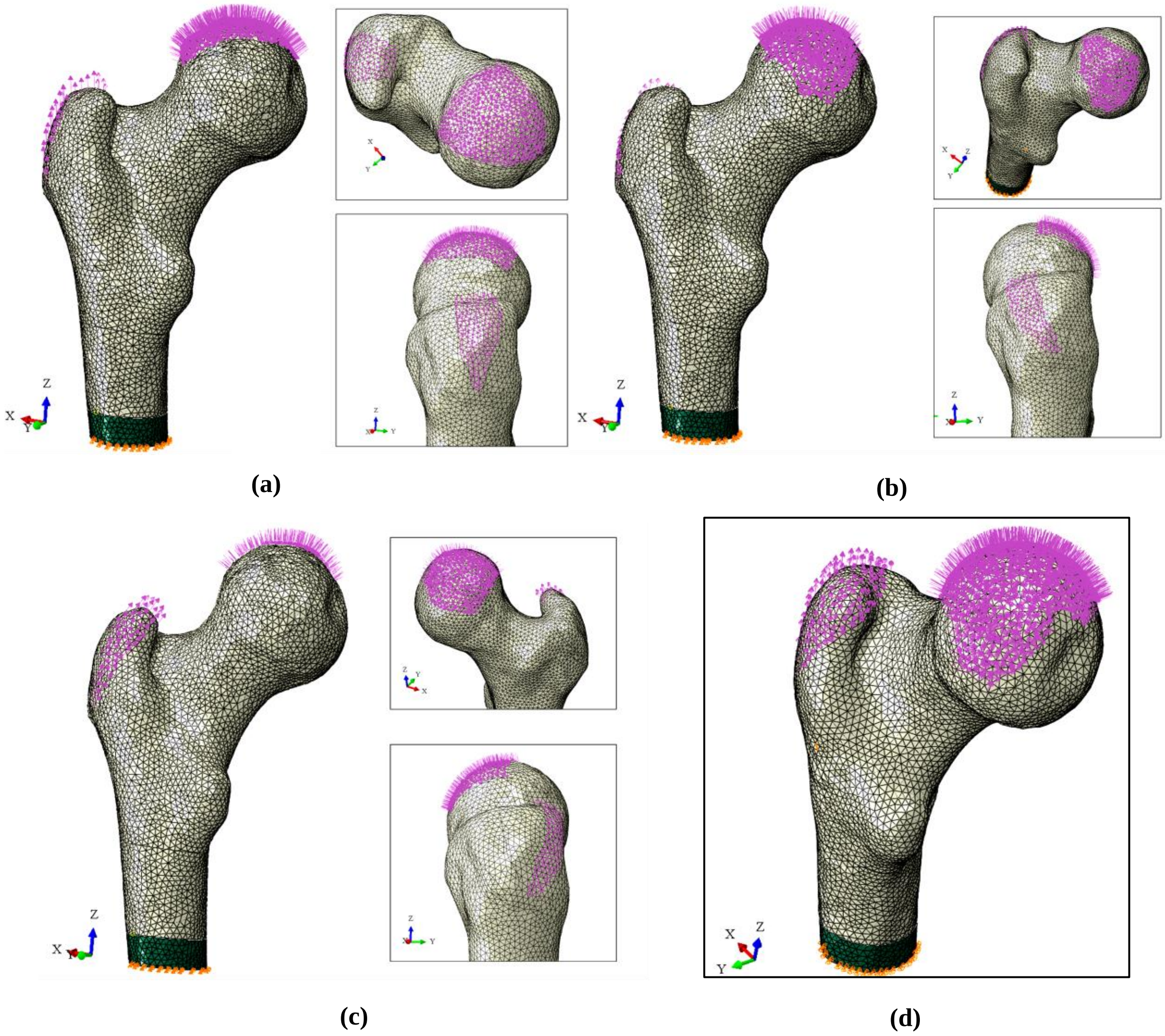

Figure 2. Loading application areas and boundary condition, with (a) Compression and traction 1, (b) Compression and traction 2, (c) Compression and traction 3 and (d) Three-dimensional view of Loadings and boundary condition.

In the end of remodeling process, it can be noted the presence of checkerboard pattern, a numerical problem found in FEM analysis of linear elements, in regions closed to the application of loads (Chen et al., 2007). Checkerboard masks the real results, showing a pattern that intercalates very low and high densities. There are many ways to control and reduce this problem. For example, it is possible to use quadratic elements instead of linear elements, or make a post-processing density smoothing treatment, or still make a stress smoothing treatment (SILVA et al, 2015). For this paper, we implement the density smoothing treatment during the process, but not for every step, because it tends to change the femur morphological aspect by increasing cortical bone area that overtakes regions where it is supposed to have just trabecular bone.

1.3 Density Smoothing

To reduce the final checkerboard, we choose to use the density smoothing treatment, during bone remodeling analysis. This method consists of using nodal density average for every node of the mesh. That is, a node, No_i, takes the density values of the elements connected to it and then, make the simple average in order to get a nodal average value, $\rho(No)_i$. This can be visualized as

$$\rho(No)_i = \frac{\sum_{j=1}^{Nel_i} \rho(el)_j}{Nel_j}, \tag{9}$$

where Nel_j is the number of elements connected to the node No_i, and $\rho(el)_j$ are the densities of every element . After that, every element assumes a density value from the simple average of the four nodes density, which belong to the element, and is represented by $\rho(el)_k^*$ as

$$\rho(el)_k^* = \frac{\left(\rho(No)_1 + \rho(No)_2 + \rho(No)_3 + \rho(No)_4\right)}{4}. \tag{10}$$

2 RESULTS AND DISCUSSION

The final density fields of the analysis for the bone remodeling frequencies, Δt , 1 and 2, 5 and 7, 15 and 30, are displayed in Fig. 3, respectively. These results show the formation of cortical bone structure on femoral diaphysis and other main aspects of bone morphology as trabecular distribution on proximal portion, formation of medullary cavity and Ward's triangle. As we can see on the images below, the density field is similar for a frequency of bone remodeling from 1 to 7, where the areas of cortical and trabecular bone have the same size. On the other hand, the B.R. frequency of 15 days presents yellow elements near to cortical bone, which differs from the daily remodeling. Moreover, a time interval of 30 days for B.R., besides the same aspect of 15 days, shows a growth of cortical bone thickness and a tendency to close the medullary cavity, what does not characterize the femur morphology.

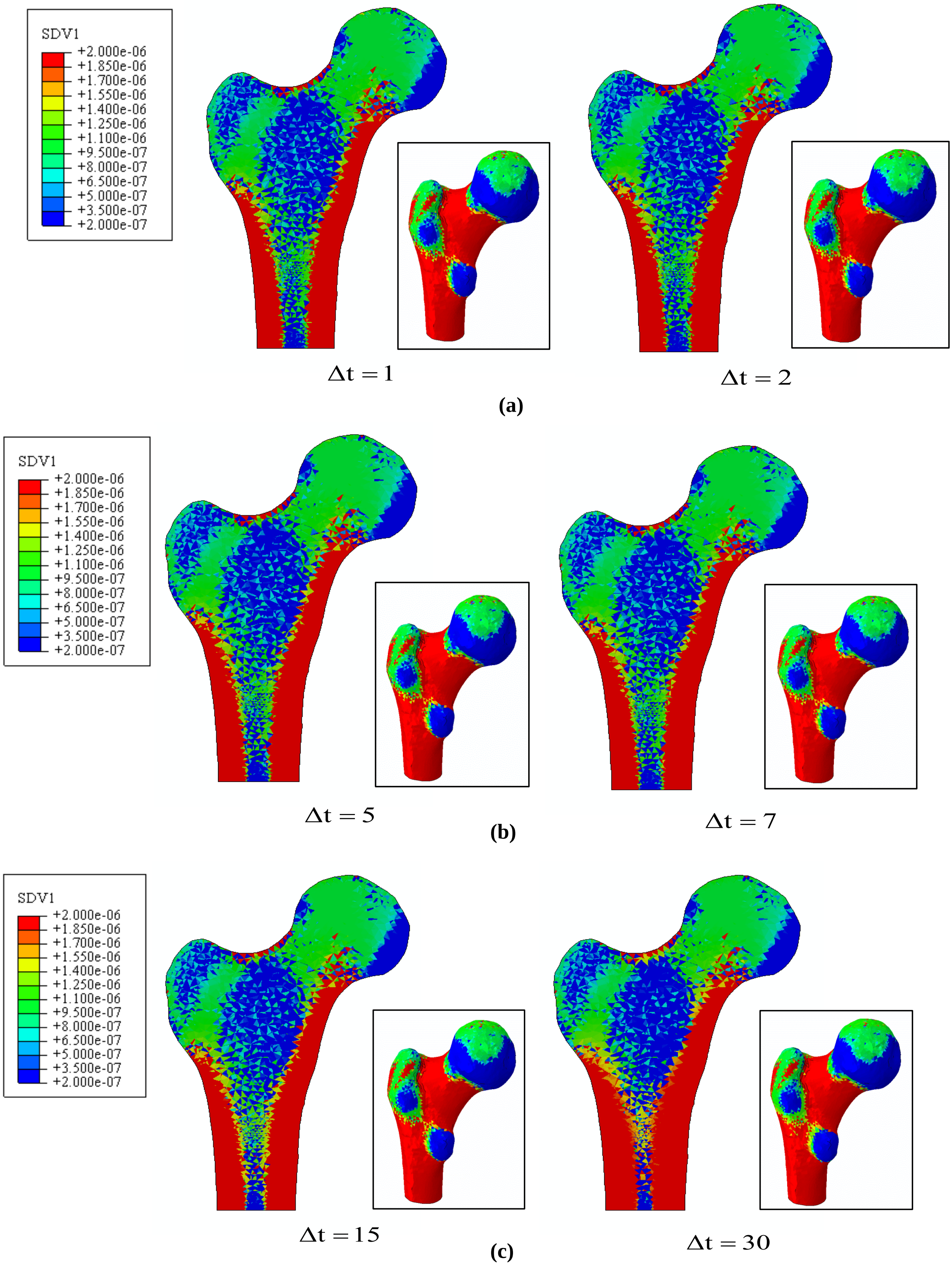

Figure 3. Final density fields [SDV1 in kg/mm] for 1000 loading days for different frequencies of bone remodeling (Δt), with Δt of (a) 1 and 2, (b) 5 and 7 and (c) 15 and 30 days.

In order to implement the iterative bone remodeling frequency, we use the difference of the Eulerian norm of mass variance between two steps, for every Δt. We estipulate that a difference lower than 1% between two steps is a reference value to change the B.R. frequency. That being so, Table 5 shows the frequencies applied, the days and steps that the exchange of them is made.

Table 5. Iterative B. R. frequency (Δt), based on prior results.

Δt	Initial Day	Final Day	Initial Step	Final Step
1	1	157	1	157
2	158	328	158	242
7	329	644	243	287
15	645	1005	288	311

The graphs below (Fig. 4 and 5) relates the value of Eulerian norm of mass variance vector between the old and new step of bone remodeling, and the days of loading, for every B.R. frequency. For frequency of 15 and 30 days, it is observed lower tendency to stabilize, compare to the others B.R. frequencies. There is a notable increased of mass in the femur when Δt is raised. On the detailed graph (Fig. 5), we note that the iterative frequency follow the same behaviour of the curves for the Δt implemented. That is, the distance between the curves does not reduce, thus the result in terms of Eulerian norm of mass variation is the same as the result of the last Δt implemented on a iterative B.R. frequency.

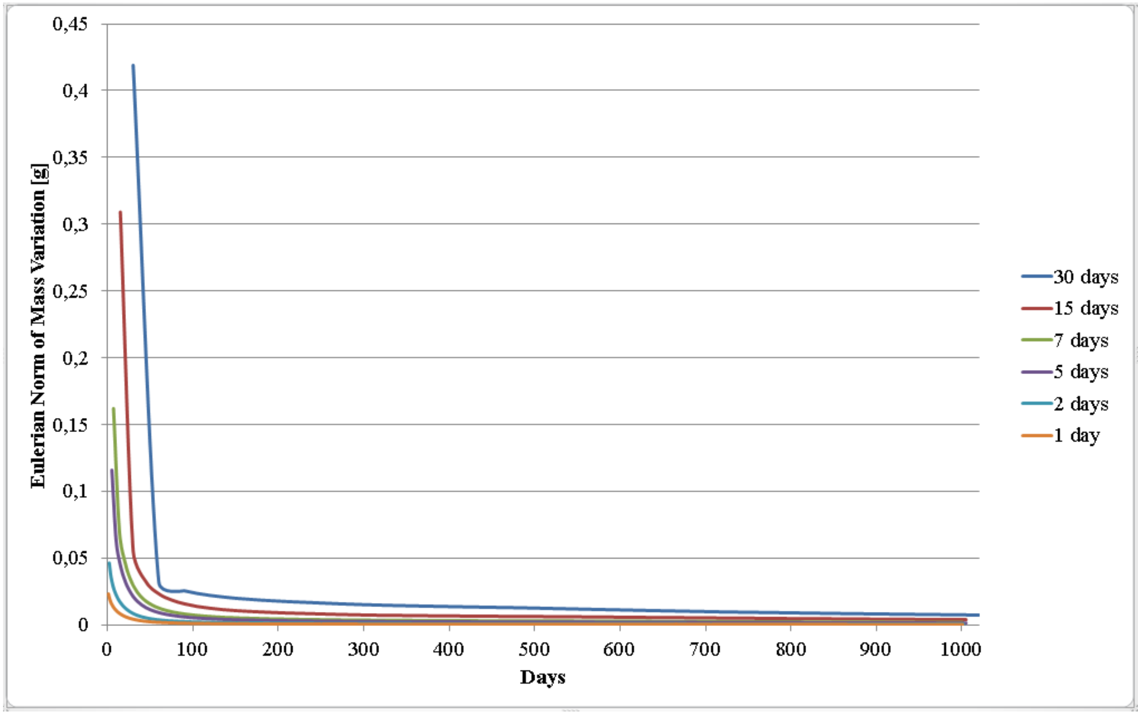

Figure 4. Comparative graph of mass variation for different frequency of B.R.

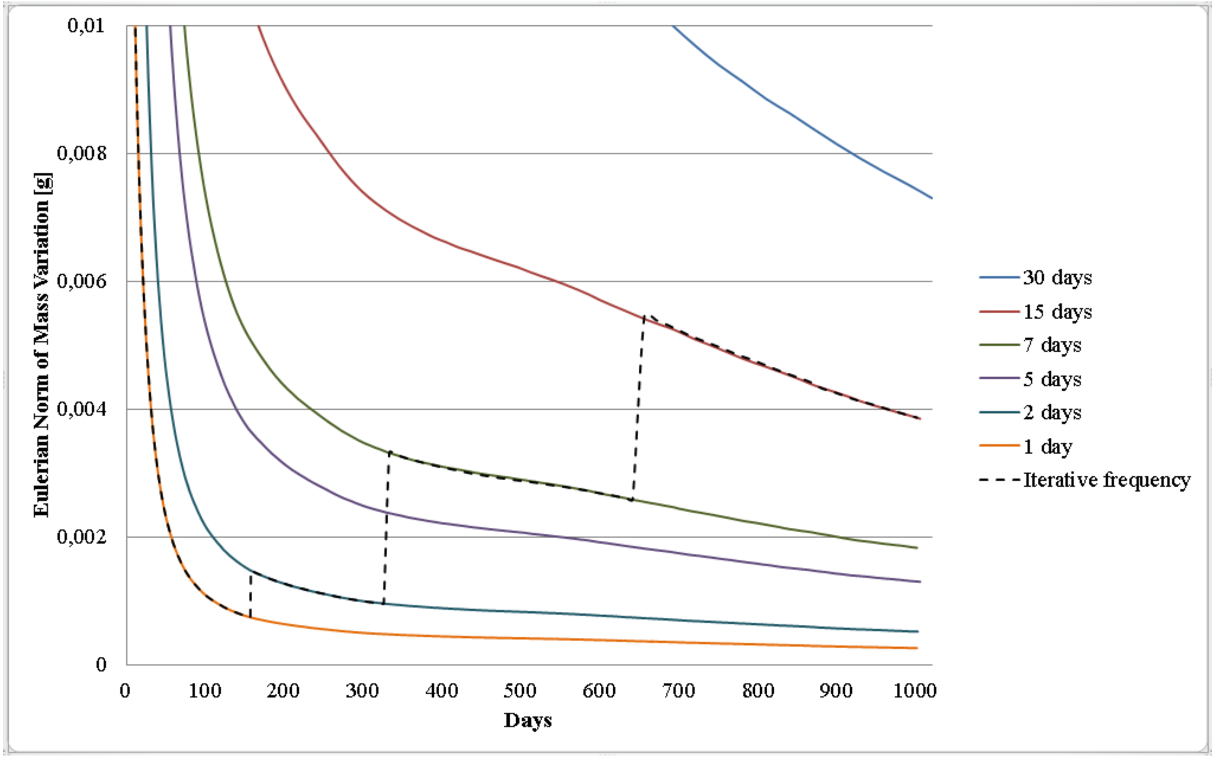

Figure 5. Detailed graph of Fig. 4, with every frequency of B.R. including a variable frequency

As Fig. 3 shows, the configurations of the femur after FEM simulation with linear elements present checkerboard and a non-continuum aspect. Therefore, using a B.R. frequency of 7 days (Δt =7), we apply density smoothing treatment every 10 steps, that is, every 70 days, in order to keep the femur morphological characteristics. Implementing, this treatment for every step, or yet, for every 3 steps (21 days), we have a femur with very tick cortical bone and a medullary cavity closed by it (Silva et al., 2015). By applying it for every 7 steps we already have good results for 1000 days of loading, however, reducing the number in which the computational treatment is applied, that is every 10 steps, we not only have better qualitative results, but also a reduction on data processing. On Fig. 6, it is possible to observe that the morphological aspects of bone are better preserve after a smoothing treatment.

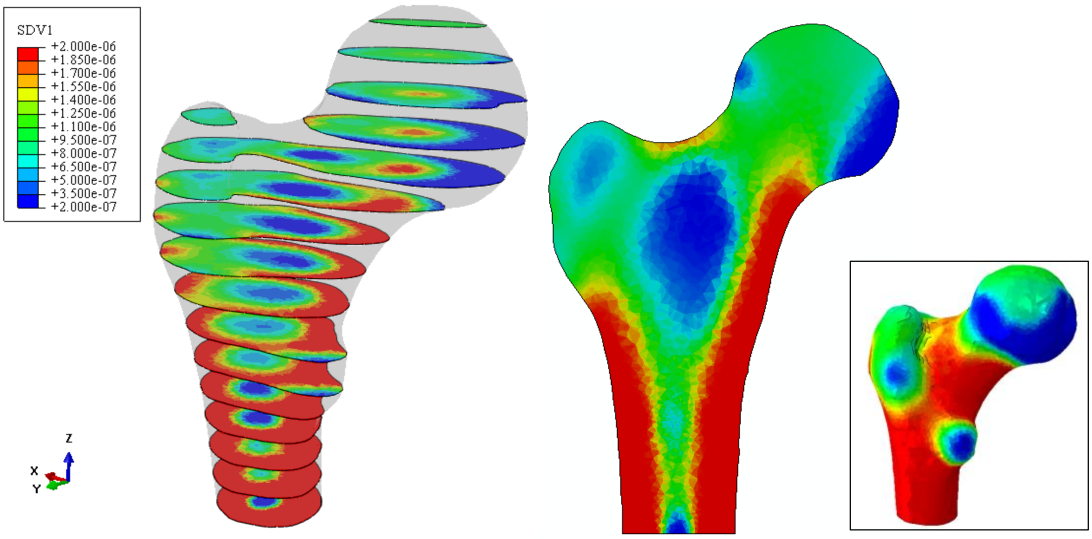

Figure 6. Densities field [SDV1 in kg/mm³] of femur model after B. R., with Δt of 7 days and smoothing treatment every 10 steps.

The graph of Fig. 7 compares the results for a bone remodeling frequency of 7 days with and without density smoothing treatment. Note that, on the day relative to the step in which density smoothing treatment occurs, there is a marked increase of the mass variation value followed by a decrease until it reaches the curve without treatment. We can see that, apart from the days of smoothing treatment, the curve has the same behavior as the one without the computational treatment. The reason that the end of the graph has more than one peak is because, after 1000 days, it is made one more density smoothing treatment in order to obtain a better final figure.

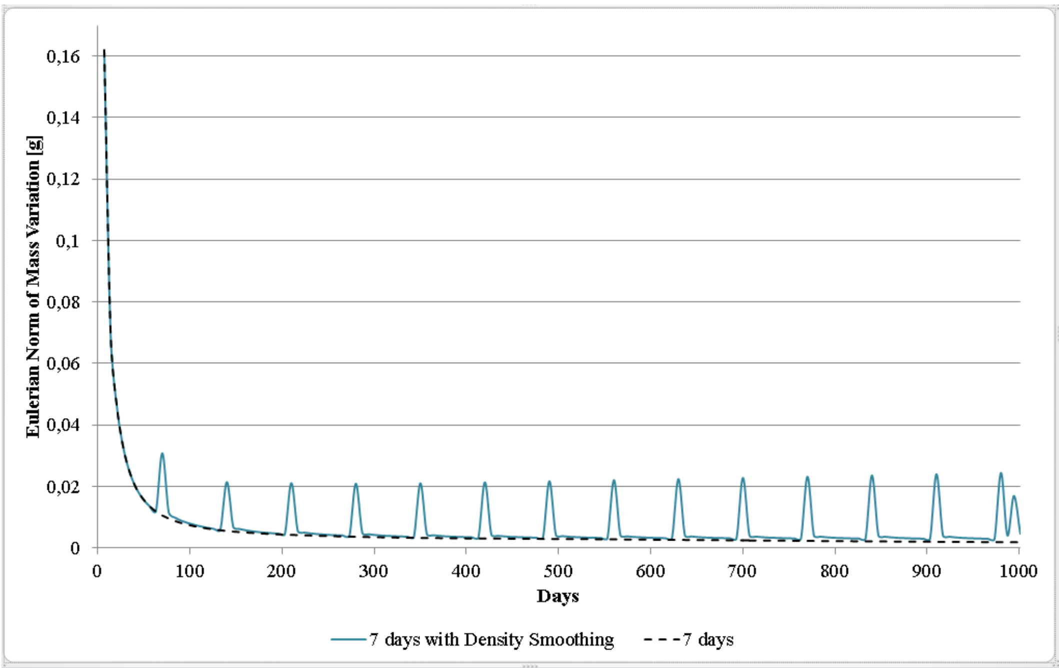

Figure 7. Comparative graph for bone remodeling frequency of 7 days, with and without density smoothing treatment

3 CONCLUSION

The result of the bone remodeling frequency of 7 days is the most significant, due to the reduction of the number of steps from 1000 to 143 for a thousand loading days. Furthermore, up to this frequency, density distribution keeps the morphological aspects of the femur. Although the curve show an inclination on Fig. 5, at the end of 1000 days the Eulerian norm of mass variation is under 0.002 g for a Δt of 7 days. According to the computational analysis, this femur model has 250 g, which means 0.0008 % of its mass variation between the steps. The Stanford isotropic model always tends to a low value of variance along the analysis but does not reach zero, that is, it will have always a slightly variation (Garijo et al., 2014). That being so, for our capacities of data processing none of the frequencies stabilizes. The iterative Δt is not a good choice, because it reaches the same value of the final frequency implemented. But, due to the application of more than one Δt, the number of steps and time of data processing are higher. Besides that, we consider absolutely necessary to use a smoothing treatment in order to reduce checkerboard. However, a density smoothing treatment processes the model after bone remodeling is concluded, and do not present good results for a treatment in every step, for example. For future works, the aim is to obtain results that are more reliable by implement method of smoothing treatment that acts during all bone remodeling, as stress smoothing treatment. Overall, by using a bone remodeling frequency of 7 days we have some advantages that go beyond the reduction of steps and time of simulation. During a week people usually do similar activities due to their routines. Thus, a frequency of 7 days keeps the quality of results and still considers the life aspects of people, knowing that the computational simulation should be as close to reality as possible. It is evident that daily bone remodeling would be the best choice for a model, if the time of data processing and computational analysis would not increase dramatically.

REFERENCES

Aznar, J. M. G., 1999. *Modelo de Remodelación Ósea: Análisis Numérico y Aplicaciones al Diseño de Fijaciones de Fracturas del Fêmur Proximal*. PhD thesis, University of Zaragoza.

Bagge, M., 1999. *Remodeling of bone structures*. PhD Thesis,Technical University of Denmark.

Beaupré, G. S., Orr, T. E., Carter, D. R., 1990. *An Approach for Time Dependent Bone Modeling and Remodeling – Theoretical Development*. Journal of Orthopaedic Research 8, pp. 651-661.

Chen, G., Pettet, G., Pearcy, M., McElwain, D. L. S., 2007. *Comparison of two numerical approaches for bone remodeling.* Medical Engineering & Physics, vol. 29, pp. 134-139.

Corso, L. L., 2006. *Aplicação de Procedimentos de otimização e remodelamento ósseo na simulação e análise em problemas de biomecânica*. Master thesis, Federal University of Rio Grande do Sul.

Dicati, G. W. O., 2015. *Análise comparativa entre diferentes abordagens de remodelação de tecidos ósseos em modelos de elementos finitos bidimensionais e tridimensionais.* Master thesis, Federal University of Paraná.

Garijo, N., Fernández, J. R., Pérez, M. A., García-Aznar, J. M., 2013. Numerical stability and convergence analysis of bone remodeling model. Comput. Methods Appl. Mech. Engrg, 271, pp 253-268.

Greenwald, A.S., Haynes, D.W., 1972. *Weight-bearing areas in the human hip joint.* The Journal of Bone and Joint Surgery, v. 54, p. 157-163.

Gubaua, J.E., 2016. *Análise numérica da influência da rigidez de próteses femorais no processo de remodelação óssea associado à técnica cirúrgica de artroplastia total de quadril.* Master thesis, Federal University of Paraná.

Hall, S. J., 2011. *Basic Biomechanics*. 6.ed. New York: Mc Graw Hill.

Jacobs, C. R., Leveston, M. E., Beaupré, G. S., Simo, J. C., Carter, D. R., 1995. *Numerical instabilities in bone remodeling simulations: the advantages of a node-based finite element approach*. J. Biomechanics, vol 28, pp 449-459.

Martin, R.B., 1984. *Porosity and specific surface of bone*. Critical Reviews in Biomedical Engineering, vol. 8, pp. 651-661.

Robling, A. G., Castillo, A. B., Turner, C. H., 2006. *Biomechanical and Molecular Regulation of Bone Remodeling.* Annual Review of Biomedical Engineering 2006.8: pp. 455-498.

Roesler, C. R. M., 2006. *Adaptação mecânica do osso em torno de implantes ortopédicos.* PhD thesis, Federal University of Santa Catarina.

Silva, J., Gubaua, J. E., Dicati, G. W. O., Pereira, J.T., 2015. *Análise de diferentes metodologias para evitar a formação do padrão similar de checkerboard em uma análise de remodelação óssea bidimensional.* XXXVI Iberian Latin-American Congress on Computational Methods in Engineering (CILAMCE 2015).