Simulation of long term behaviour of cement less Total Hip Arthroplasty based on biomechanical factors analysis

Tongtong Guo* — Frédéric Marin*— François Roux**
Marie-Christine Ho Ba Tho*

**Laboratoire de Biomécanique et Génie Biomédical*
CNRS UMR 6600, Université de Technologie de Compiègne
F- 60200 Compiègne

hobatho@utc.frr

*** Polyclinique St Côme*

ABSTRACT. *The objective of this study is to quantify the effect of three biomechanical factors, which include forces, bone material properties and bone remodelling coefficient, on the long term cement less Total Hip Arthroplasty (THA) results. Bone physiological remodelling algorithm is proposed to describe bone adaptation behaviour after operation. Two typical cases, which are obtained from simulated results, are compared with real clinical cases. Statistical analyses are performed to quantify the relationship between the long term variation of bone density and biomechanical factors. The results show that all the factors considered and their combination have relevant effects on the bone remodelling results.*

RÉSUMÉ. *L'objectif de l'étude est de prédire le comportement mécanique de la prothèse à partir d'une analyse factorielle de facteurs biomécaniques. Les facteurs considérés sont les forces articulaires, les propriétés mécaniques du tissu osseux et la constante de remodelage osseux. Un modèle élément fini incluant un algorithme de remodelage osseux a été utilisé pour simuler les différents résultats. L'analyse statistique a permis de quantifier la relation entre les variations des masses osseuses avec les facteurs biomécaniques. Les facteurs considérés et leur combinaison des facteurs ont un effet significatif sur le remodelage osseux.*

KEYWORDS: *bone material property, bone remodelling, FEA, THA, femur.*

MOTS-CLÉS : *propriété matérielle osseuse, remodelling osseuse, FEA , THA, fémur.*

1. Introduction

Total hip arthroplasty (THA) is a joint replacement by implants. This is undertaken for hip arthritis or the necrosis of the femoral head. With age or following rheumatoid arthritis the weight bearing surfaces of the hip joint become worn away. Joint replacement is then required. In the operation of THA, the doctor cut the head of the femur, and then implant the prosthesis into the medullar canal. Hip replacements have made this procedure in recent years very successful and the results are now very reliable. However, hip implant loosening occurs in 20% of the case. In fact, bone resorption and apposition around the prosthesis can be observed in a short or long term after surgery. In such surgery, the mechanical environment is changed. The load is distributed along the prosthesis instead of the head of the original femur. Bone has the ability to change its structure to adapt the alteration of mechanical environment, which is known as bone remodelling.

Studies were performed from different aspects to simulate bone structure after surgery under control of different factors. Many researchers studied the effect of mechanical environment to the long-term surgery results, such as contact force and muscle forces (Prendergast and Taylor, 1992; Mann *et al*., 1997, Duda *et al*., 1998; Stolk *et al*., 2001 ; Bitsakos *et al*., 2005) studied the effect of different amount of muscle forces. Muscle forces were found to be very important, and still simulated the bone loss on proximal and bone apposition on distal of the prosthesis. (Kleeman *et al*., 2003) have studied the effect of the offset of the prosthesis to the stress. They simulated the different THA results by changing the offset of the prosthesis. From all of these studies, mechanical environment is regard as an important role in bone remodelling and THA long-term operation results.

(Krischak *et al*., 2003) found that bone quality was important, it can predict the femoral prosthesis loosening. Their study was based on statistical analyses of their radio graphical long-term follow-up slices. (Kerner *et al*., 1999) found that the initial high bone density quality implies a reduce bone loss for younger patients.

In these studies, mechanical environment and bone material properties has been investigated but not simultaneously. Different FEA models were used (cement less or not) without clinical data , and clinical analyses used commonly statistics.

The objectives of this study are to quantify the effect and the relevance of different biomechanical factors, such as force, bone material properties and bone remodelling coefficient simultaneously on long term results of THA. The FEA and predictive results are performed from clinical data.

2. Materials and methods

Clinical data are provided by the Polyclinique St Côme. Preoperative and postoperative X-Rays data of 10 patients were analyzed.

Clinical classification was performed and three types of long-term operation results were identified: ideal, middle and bad result. The ideal result means that 10 years after surgery there is nearly no change of bone density in bone around the implant. The bad result means that there is resorption and apposition occurring in more than four of the six areas of the interest. Finally, the middle result is between ideal and bad result. The different steps of the methodology are to develop a FEA model and perform a factorial analysis on the following biomechanical factors: loads, mechanical properties and bone remodelling coefficient. The FE model is based on a X-Ray of a patient. Simulations were performed with different values of biomechanical factors in order to predict the three different cases.

2.1. *FE model*

Specific geometry model is built from clinical X-Ray image provided by the Polyclinique St. Côme. Our FEA model includes 565 2D quadrilateral elements. The pre and post processor used is Patran (MSC.Software). Different initial material properties, which include Young's modulus and density, are considered: cortical and spongy bone (table 1).

All the nodes at the bottom of the model are fixed. Contact and muscle forces are applied on the stem and on the bone respectively (Figure 1).

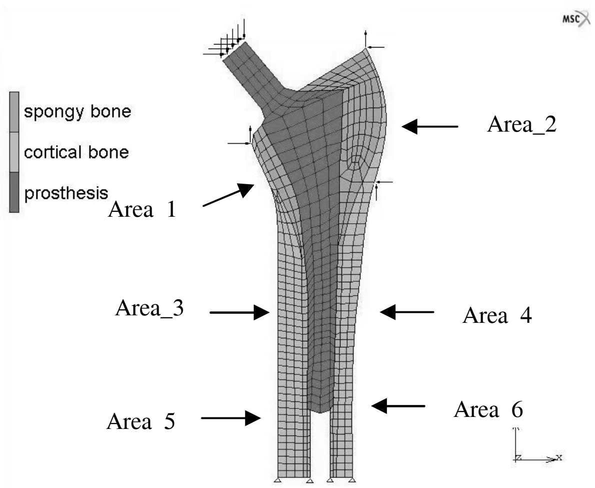

Figure 1. *FEA model with loads and boundary conditions and areas of interest*

Table 1. *Three levels of bone material properties (Ho Ba Tho* et al., *1992)*

Bone Density (kg/m^3)				Relationships between density and Young's modulus
	low	average	high	E(MPa)
Cortical	1581	1791	1996	$E=-6.142+0.014\rho$
Spongy	160	350	540	$E=0.58\rho^{1.30}$

Friction contact is defined between bone and prosthesis. Both parts are considered as flexible bodies. Non linear contact analysis is performed.

Marc.Analysis (MSC.Software) is applied. Six areas of interest are chosen to investigate the effect of biomechanical factors on bone density distribution.

Bone physiological remodelling equations are based on bone self-optimised equation provided by (Weinans *et al.*, 1992). Our model is considered with different bone remodelling threshold, which are described in equations [1] and [2].

$$\frac{d\rho(x,y,t)}{dt} = B\cdot\left(U(x,y,t)/\rho(x,y,t)-K_n\right) \quad [1]$$

$$K_n=\frac{1}{2\rho_0}\sigma\cdot\varepsilon_n=\frac{1}{2\rho_0}E\cdot\varepsilon_n^2 \quad [2]$$

U is the strain energy density. The density ρ_0 is the initial bone density. B is the bone remodelling coefficient. K_n is a value corresponding to bone remodelling physiological status with n varying from 1 to 4 (n = 1,2,3,4). These four values are related to the following levels of bone remodelling. The first threshold K_1 is corresponding to bone resorption for strain ε_1 of 200 με. The second threshold K_2 (ε_2=2000 με) is related to physiological bone remodelling, *i.e* balance between bone apposition and resorption. In that case, there is no variation of density. The third threshold K_3 (ε_3 = 4000 με) is related to bone apposition. Then the last threshold K_4 (ε_4=25000 με) is a bone fracture point. These values are provided by Frost (1997).

Bone remodelling algorithm is described in Figure 2. The time step is corresponding to 4 months.

Bone remodelling program has been implemented in Marc. Analysis using Python language. It describes the remodelling process under control of bone biomechanical adjusting and controlling system.

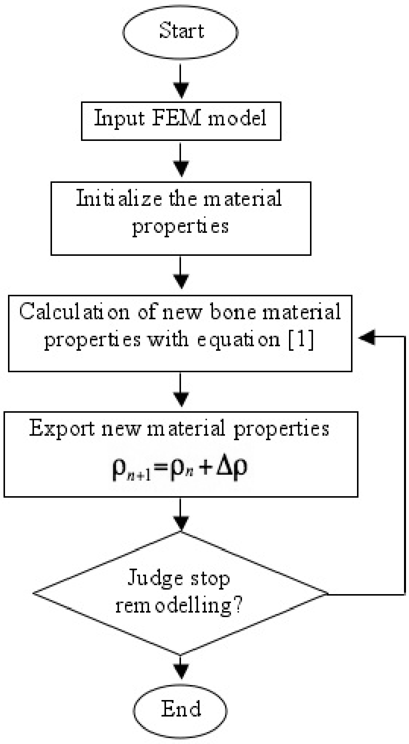

Figure 2. *Physiological bone remodelling algorithm (Guo* et al.*, 2004)*

2.2. *Factorial analysis*

Factorial analysis is applied to study the effect of the factors simultaneously. The levels considered represent the range of variation of these factors. Here three levels are considered for three factors, it implies 3^3 FEA simulations.

Biomechanical factors considered are: bone material properties, forces and bone remodelling coefficient with three levels (low, average, high). The values are provided by the literature.

a) Bone material properties: the values are summarized in Table 1.

b) Forces include the contact and muscle forces. Muscles forces are the Gluteus maximus, Gluteus medius, Gluteus minimus, psoas, illiacus and poriformis. Each force has three levels. The average force value is obtained for a person weighting 70 kg (Bitsakos *et al.*, 2005). The others are calculated by scaling the weight of 40 kg and 100kg.

c) The three levels of bone remodelling coefficient values are (0.002, 0.005, 0.008 (g $cm^{-3})^2$ (MPa*time unit)$^{-1}$.

Our bone remodelling simulation gives the variation of bone density of each of the finite elements. In order to reduce the number of variables but still keeping the focus on the clinical environment, we calculated the mean variation of the bone density in percent of six areas of interest (Figure 1).

Let $\Delta\rho_{Ci}$ be the mean variation of the bone density of cortical bone of the area of interest i and $\Delta\rho_{Si}$ of the spongy bone , $\Delta\rho_{Ci}$ and $\Delta\rho_{Si}$ be the output factors. The input factors are the normalized centers of the loading X_1 of the mechanical bone property X_2 and the remodelling coefficient X_3. Thus, for example the value of -1 of X_1 would correspond to the lowest level, 0 to the medium level and +1 to the highest level of loading.

Two statistical analyses were performed. The first one identified the most affected output factors due to the modification of the input factors. Therefore the inter quartile range (IQR) of the output $\Delta\rho_{Ci}$ and $\Delta\rho_{Si}$ has been calculated. Knowing that the IQR is the difference between the 75th and the 25th percentiles of output and thus presents a robust estimation of the data spread without any hypothesis on the distribution. The second statistical analysis quantified the effect of each input factor Xi on the output factors $\Delta\rho_{Ci}$ and $\Delta\rho_{Si}$. Therefore a quadratic response surface model has been computed. In our case the following equation [3] has been applied:

$$\Delta\rho_k = c_k + a_{1,k} X_1 + a_{2,k} X_2 + a_{2,k} X_3 + b_{1,k} X_1X_2 + b_{2,k} X_1.X_3 + b_{3,k} X_2.X_3 + c_{1,k} X1^2 + c_{2,k} X_2^2 + c_{2,k} X_3^2 \quad [3]$$

The best clinical outcome corresponds to a minimum variation of the bone architecture. In our case it corresponds to the result of all $\Delta\rho_k$ being close to zero simultaneously. For all calculations the Matlab statistical toolbox (Mathworks) has been used.

3. Results

According our statistical results, $\Delta\rho_{1S}$, $\Delta\rho_{2S}$ and $\Delta\rho_{5C}$ had the highest values of IQR. Subsequently, the quadratic response surface model have been computed only for these particular output factors (Table 2). The coefficient reflects the importance of the factors.

According to equation [3], $\Delta\rho_{1S}$, $\Delta\rho_{2S}$ and $\Delta\rho_{5C}$ are close to zero simultaneously, if $X_1 = 0.35$ $X_2 = 0.25$ and $X_3 = -1$. For the same condition , if $X_1 = 1$ and $X_3 = -1$, then $X_2 = 0.4$, and if $X_1 = -1$ and $X_3 = -1$ then $X_2 = -0.1$. That means that in order to get the ideal case (nearly no change of $\Delta\rho$) the following combination is to be obtained:

– low or average force **and** high or average bone material properties **and** low bone remodelling coefficient.

The simulation with one of these combinations is illustrated in Figure 4 in comparison with the clinical postoperative X-Ray data (10 years after surgery).

Table 2. *Quantification and relevance of the biomechanical effects on the density variation*

	Linear terms				Interaction terms			Quadratic terms		
	c_k	$a_{1,k}$	$a_{2,k}$	$a_{2,k}$	$b_{1,k}$	$b_{2,k}$	$b_{3,k}$	$c_{1,k}$	$c_{2,k}$	$c_{2,k}$
$\Delta\rho_{1S}$	-23.6	2.7	19.8	-6,0	-1.4	2.2	9.1	3.9	-10.3	9.8
$\Delta\rho_{2S}$	-18.0	1.0	2.5	-5.9	3.3	4.3	-2.9	-1.7	-4.3	11.9
$\Delta\rho_{5C}$	-12.9	-0.4	-6.5	-13.8	3.6	-1.7	-2.2	-2.9	-2.7	-4.1

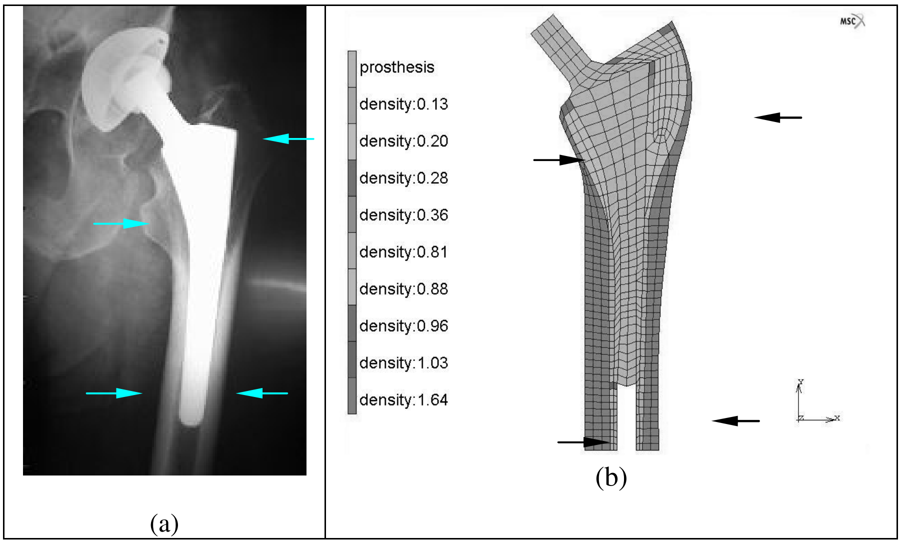

Figure 3. *Comparison of the ideal patient's X-Ray results 10 years after surgery (a) and visualization of simulated ideal result (b)*

The bad patient case may come from one of the following three biomechanical factors levels:

– high force **or** low bone material properties **or** high or average bone remodelling coefficient.

In the simulation illustrated in figure 5 (a), we can observe that serious resorption happened in the proximal and apposition happened in distal. Good agreement is noted with the clinical data.

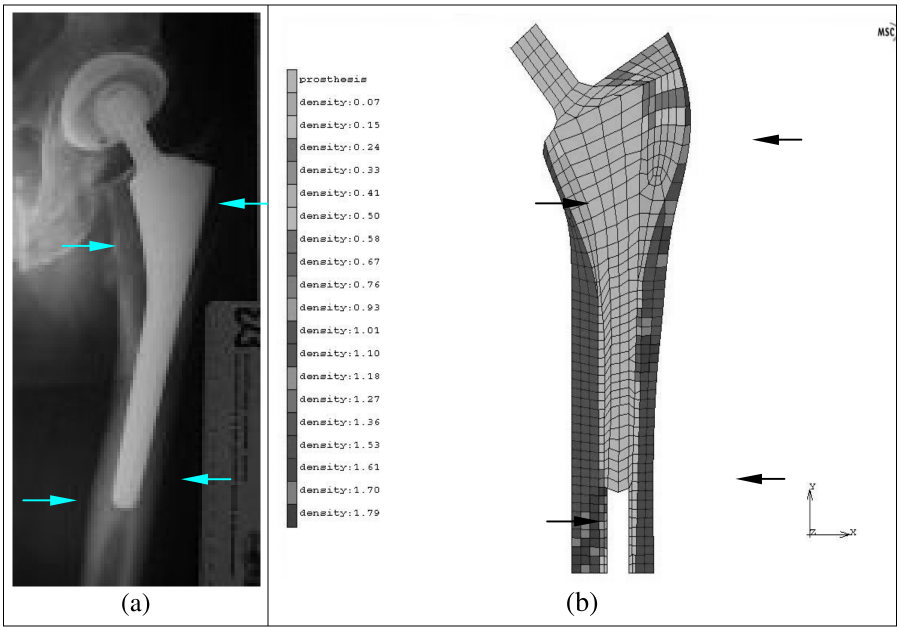

Figure 4. *Comparison of the bad patient's X-Ray results 10 years after surgery (a) and visualization of simulated bad result (b)*

4. Discussion

Factorial analysis allows to quantify the relationships between the three biomechanical factors and the variation of bone density. Our simulated results have good qualitative agreement with the long-term clinical results. From the comparison between our simulation results and clinical operation results after 10 years, we could suggest that each biomechanical factor had obvious effects to the simulation results. The significant effect of different patient's biomechanical factors on long-term THA results is described as following:

1) Force: is an essential factor, ideal patient case never can be got with high force.

2) Bone material properties: is an important factor, but not enough to obtain an ideal result.

3) Bone remodelling coefficient: is an important factor, too. Ideal results have low value of this factor.

The relationship between the factors and the variation of the bone density help us to confirm the significance of each biomechanical factors and their sensitivity to the results. The combination of factor is very important, different results come from the combination of these factors in their specific level.

The calculation of the IQR for each output factor permitted to identify which of the areas are the most affected by a modification of the input factors. In the present case the spongy bone of the internal and external proximal of the femur, and cortical bone gave the highest variations. This result is correlated with clinical observations which had already identified these zones actually presenting resorption and ossification phenomena.

The ideal clinical outcome would be the case with no modification of the bone structure at all corresponding to a minimal variation of bone density. For this case we find that the remodelling coefficient was on its lowest level whereas loading and mechanical properties of bone could have only a medium level. It appears that the mechanical property of the bone does not suffice to compensate by itself a variation of the bone density affect total hip arthroplasty (THA).

The models predict that for the high loading which could be due to ponderal surcharge or high muscular activity, the bone has to be of good quality with a low remodelling coefficient. Whereas for light subjects the mechanical property of the bone only needs to be normal.

According to our findings, a good outcome of the THA needs a low remodelling coefficient. This factor is related to the amount of bone formation with time with a stress condition.

The model with more meshes was tested, it showed that there was nearly no change in the results. Less meshes was tested also, it showed that if the meshes were too coarse, the results would be not precise enough, especially in the stress-concentration area. To save the calculation time of the remodelling process, and to get the precise results simultaneously, the FE model illustrated in Figure 1 was chosen. For the friction ratio, different friction ratios (0.2, 0.3, 0.5) were tested also, there were nearly no effects to the results. But if there are no friction between bone and prosthesis, fixed boundary was applied, the results would be quite different. Effects of the different boundary conditions on the remodelling results have been performed in a previous study (Guo *et al.*, 2004).

One should note that for the purpose of the study, the factors must be considered as uncorrelated although biology would suggest the opposite. Biomechanical factors of patient are only considered, that means that implant design. As mentioned previously, the same surgeon has been using the same design implant and clinical observation confirms the assumptions used.

This study provides nearly all the possibilities of the long-term results. Factor analysis allows to quantify the effect of patient’s initial biomechanical factors on bone density variation.

The method allows us to predict and explain surgical results according patient’s initial biomechanical conditions.

Acknowledgements

The financial support of CNRS is gratefully acknowledged.

5. References

Bitsakos C., Kerner J., Fisher I., Amis A., "The effect of muscle loading on the simulation of bone remodelling in the proximal femur", *J. of Biomechanics*, Vol.38, No.1, 2005, pp. 133-139.

Duda G. N., Heller M., Albinger J., Schulz O., Schneider E., Claes L., "Influence of muscle forces on femoral strain distribution", *J. of Biomechanics*, Vol. 31 No. 9, 1998, pp. 841-846.

Frost H.M., "Defining Osteopenias and Osteoporoses: Another View (With Insight From a New Paradigm)", *Bone*, Vol.20 No.5, 1997, pp. 385-391.

Guo T., Su J., Ho Ba Tho M. C., Zhu X., "The effect of interfacial factors on bone remodelling", Proc. July 2004, *14th ESB*, s'Hertogenbosch.

Hobatho M.-C., Rho J.Y., Ashman R.B., "Atlas of mechanical properties of human cortial and cancellous bone", In *Vivo Assessment of bone Quality By Vibration And Wave Propagation Techniaues*, Part 2, 1992, Editors: Van der Perre G., Lowet G., Borgwardt Christensen A., pp. 7-38.

Kerner J., Huiskes R., van Lenthe G. H., Weinans H., van Rietbergen B., Engh C. A., Amis A. A., "Correlation between pre-operative periprosthetic bone density and post-operative bone loss in THA can be explained by strain-adaptive remodelling", *J. of Biomechanics*, Vol. 32 No. 7, 1999, pp. 695-703.

Kleemann R.U., Heller M.O., Stoeckle U., Taylor W. R., Duda G. N., "THA loading arising from increased femoral anteversion and offset may lead to critical cement stresses", *J. of Orthopaedic Research*, Vol. 21, No.5, 2003, pp. 767-774.

Krischak G. D., Wachter N. J., Zabel T., Suger G., Beck A., Kinzl L., Claes L. E., Augat P., "Influence of preoperative mechanical bone quality and bone mineral density on aseptic loosening of total hip arthroplasty after seven years", *Clinical Biomechanics*, Vol. 18 No. 10, 2003, pp. 916-923.

Mann K., Bartel D., Ayers D., "Influence of stem geometry on mechanics of cemented femoral hip components with a proximal bond", *J. of Orthopaedics Research.*, Vol. 15 No. 5, 1997, pp. 700-706.

Prendergast P.J., Taylor D., "Design of intramedullary prosthesis to prevent bone loss: predictions based on damage stimulated bone remodelling", *J. of Biomedical Engineering*, Vol. 14, 1992, pp. 499-506.

Stolk J., Verdonschot N., Huiskes R., "Hip-joint and abductor-muscle forces adequately represent in vivo loading of a cemented total hip reconstruction", *J. of Biomechanics*, Vol. 34, No. 7, 2001, pp. 917-926.

Weinans H., Huiskes R. Grootenboer H.J., "The behavior of adaptive bone-remodelling simulation models", *J. of Biomechanics*, Vol. 25, No. 12, 1992, pp. 1425-1441.