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Numerical analysis of the biomechanical complications accompanying the total hip replacement with NANOS-Prosthetic: bone remodelling and prosthesis migration

Abstract: Aseptic loosening of the prosthesis is still a problem in artificial joint implants. The loosening can be caused by the resorption of the bone surrounding the prosthesis according to stress shielding. A numerical model was developed and validated by means of DEXA-studies in order to analyse the bone remodelling process in the periprosthetic bone. A total loss of about 3.7% of the bone density in the periprosthetic Femur with NANOS is computed. The bone remodelling calculation was validated by means of a DEXA-study with a 3-years-follow-up. The model was further developed in order to be able to calculate and consider the migration of the implants. This method was applied on the NANOS-implant with a computed total migration of about 0.43 mm. These calculations showed good results in comparison with a 2-year-follow-up clinical study, whereby a RSA-method was used to determine the stem migration in the bone. In order to study the mutual influence between the implant migration and the hip contact forces, a software is developed by our scientific group to couple a multi body simulation (MBS) of human lower limbs with the FEA of the periprosthetic Femur.

Keywords: finite element; prosthesis migration; NANOS; multi body human simulation; bone remodelling

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1 Introduction

The implantation of artificial joints has been developed over the last decades into a routine procedure. More than 150,000 primary hip replacements are performed each

year in Germany alone [1]. Despite all the technological and medical advances, the lifetime of the implants is still limited [2]. The most common reasons for implant failure are the aseptic loosening and the migration due to stress shielding [3], which leads to unstable anchoring of the prosthesis in the bone tissue [4]. In addition and due to the changes in the boundary conditions of the replaced hip joint the gait of the patient and thus the load on the hip joint varies [5]. The optimization of the prosthetic design has largely been based on the practical experience of manufacturers [8]. Extending this knowledge and experience with numerical methods can realize a time-saving, cost-effective and patient-friendly development methodology [7]. The finite element method (FEM) has been widely used in this field [6]. The aim of this study is to calculate the bone remodelling around the NANOS prosthesis in the femur and to numerically map the migration of this implant using the numerical model developed at IFUM. Furthermore, the FEA for mapping the NANOS shaft migration was coupled with a MBS of human lower limbs, which is supplied with a hip prosthesis to determine the mutual influence between the shaft migration and the hip contact forces.

2 Methods

Based on the Wolff's law [8], different mathematical theories have been proposed with respect to bone remodelling. One of them is the model of Behrens et al., which is developed at IFUM in Hanover [9]. According to this model, the changes of the bone density depend on a stimulus ξ , which results from the time-varying strain energy density in the bone tissue. A detailed derivation of the stimulus ξ can be found in [10]. The model presented has already been used and validated for the numerical description of bone remodelling in the periprosthetic femur with different types of implants such as METHA®, Bicontact® prostheses [11]. By means of this model, the bone remodelling was numer-

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ically investigated around the NANOS prosthesis in the femur. The FE-model of the periprosthetic femur was created using HyperMesh® software (Altair, USA) with the NANOS prosthesis virtually implanted in a femur. Based on a CT data set of human patients, the femur geometry was created. In this case, an image analysis program (Yadiv®, Welfenlab, Hanover) was used to generate the 3D mesh model of the femur. Based on the HU values of CT images the calculated bone density is automatically assigned to the voxels of the finite element model. The FE model was implemented into the simulation system of MSC.Marc® (MSC.Software, Santa Ana, California, United States) to simulate the bone remodelling. The elastic modulus E of the bone is calculated by an integrated subroutine in the simulation using the following equation 1 [12]:

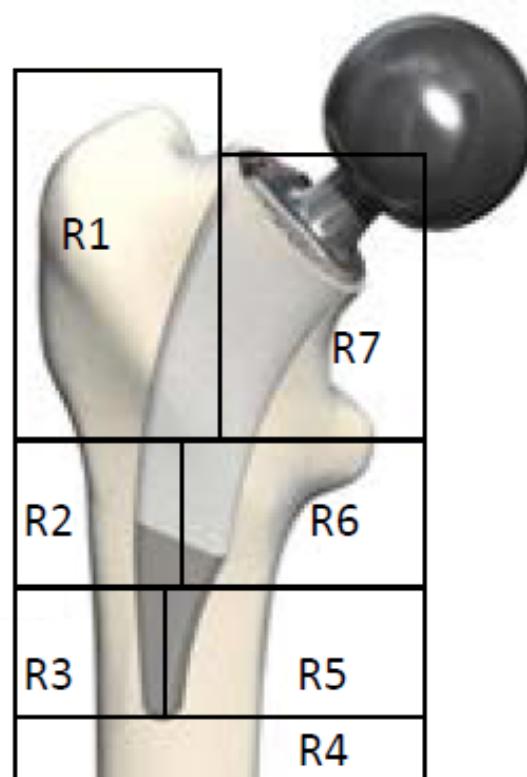
$$E = 3790\rho^3 \quad (1)$$

The NANOS-prosthesis was modelled with a titanium alloy Ti6Al4V, which is characterized by a homogeneous and isotropic material behaviour. The physiological boundary conditions were assumed according to Speris et al. [13]. Furthermore, a reduced muscular system is added to the femur model suggested by Heller et al. [14]. The muscular system consists of the abductors, the tensor fascia lata, the vastus medialis and the vastus lateralis muscles. The resulting hip contact force was taken from a validated multi-body-simulation carried out at the IFUM in cooperation with the clinic of small animals at the University of Veterinary Medicine Hannover, Foundation [15]. The multi-body-model is generated using gait analysis data at the speed of 0.8 m/s.

To calculate the density of the bone in different regions of interest (ROIs), the elements were stored in individual sets, corresponding to the distribution of the ROIs (see Figure 1). The contact between the NANOS-prosthesis and the bone tissue was modelled with a no-slip condition at the coated areas of the prosthesis. In uncoated areas, a frictionless contact is assumed.

So far, the bone remodelling in the periprosthetic bone tissues is calculated without changing the bone geometry. Thus, an aim of this study is to model the prosthetic migration by means of updating the bone geometry in contact with the prosthetic as a function of the density values of the bone tissue. However, no study or equation connects the dismantling of the tissue around the implants with the reduction of bone density. Based on the equation 1, the changes in the bone density can be translated into changes in its E modulus and thus into changes in the elastic strains ε of the bone tissue as a reaction to the hip contact forces. The change in the strain can be calculated from the simulation with an appropriate subroutine,

which stores the changes in the element positions and considers these changes to create new sets of elements using a remeshing function before starting the new simulation increment. Using this method it is now possible to model the changes of bone geometries numerically considering only the mechanical factors that lead to the prosthetic migration and ignoring biological influences.



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Figure 1: The NANOS-Prosthesis and the distribution of the ROIs in the Femur.

The influence of the prosthetic migration on the hip contact forces has already been investigated and confirmed at the IFUM using the MBS model of the human lower extremities [15]. Thus, it is very important to model the implant migration considering the changes in the hip contact forces caused by the migration itself. For this purpose, online coupling software is created between the multibody simulation software LifeMOD, in which the hip contact forces will be determined, and the FE-software MSC.Marc, where the prosthesis migration can be calculated. The coupling is realized through a software written in the programming language Python. The coupling ends

when the FE-calculation of bone remodelling converges and the change in position of the prosthesis is too small.

3 Results

3.1 The bone remodelling

The numerical calculation of the bone remodelling needed 48 increments to reach the state of convergence. The loss of bone density in the entire femur is about 3.7 % (see Figure 2). The FE analysis shows that the bone density in R7 is significantly reduced, where the loss is about 42.6%. Figure 3 shows the changes in the calculated bone density and the following Table 1 summarizes the calculated changes in the bone density in the individual ROIs according to the finite element analysis.

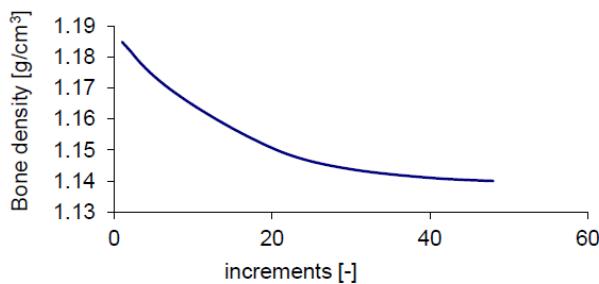


Figure 2: Calculation of the bone remodelling convergences in 48 increments.

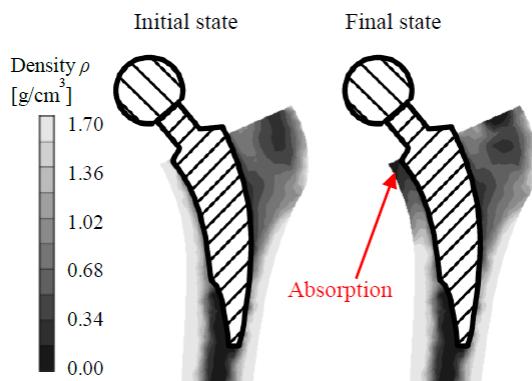


Figure 3: Bone remodelling a) at the initial state and b) in the final state with the largest bone density loss area highlighted in red.

Table 1: Calculated changes in bone density in percent.

ROIs	1	2	3	4	5	6	7
Density [%]	12.8	12.2	2.64	-0.04	0.08	1.18	42.6

3.2 Implant migration

The numerical simulation of migration of the NANOS stem revealed that the remeshing function affects the density of the elastic strain energy in the elements of the FE model. This leads to a delayed convergence of the calculations, since the calculation of bone remodelling is based on the change in the strain energy density. The calculation converges after 52 increments. Here, the bone density of the femur decreases by 3.82%. The simulation results show a caudal (distal) shaft migration of 0.366 mm, a lateral migration of 0.17 mm and a posterior migration of 0.02 mm. The FE-calculations of the NANOS migration, taking into account the changes in hip contact forces induced by this migration, shows differences in the migration patterns to the ones calculated without the coupling with the MBS-simulation. Under these circumstances, the calculated implant migration in distal direction is 0.39 mm, while it is 0.2 mm in lateral direction and 0.04 in posterior direction. Figure 4 shows the overall NANOS-migration with and without coupling with the MBS.

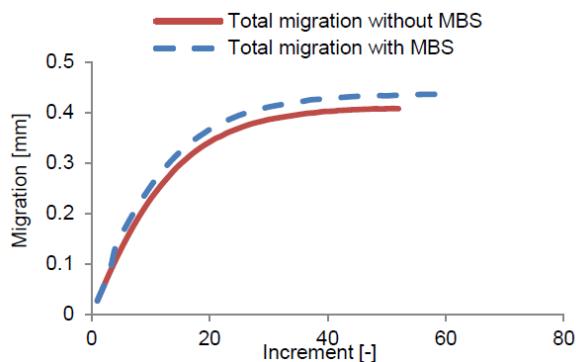


Figure 4: The progression of the NANOS-migration in the Femur bone tissue.

4 Discussion

In order to validate the bone remodelling calculations, the numerical results of the changes in the bone density were compared to those measured by the 3-Years follow-up DEXA investigations of Zeh et al. [16] on patients with

Table 2: Calculated and measured changes in bone density in percent.

ROIs	1	2	3	4	5	6	7
Density-FEM [%]	12.8	12.2	2.64	-0.04	0.08	1.18	42.6
Density-DEXA [%]	15.3	5.03	1.77	1.41	0.47	-12.0	11.8
Deviation	2.5	7.17	0.87	1.45	0.39	13.18	30.8
Avg.					8.05		

NANOS hip prosthesis. The following Table 2 summarizes the results of this validation.

From Table 2 it can be seen that the numerical calculation shows a slight deviation from the results of the DEXA study in the regions R1, R2, R3, R4 and R5. In this case, the difference between the measured and the calculated BMD is about 2.5% in average. This increases to about 13 % in R6. Remarkably the deviation is about 30% in R7. According to the FE-calculations, the hip contact stress is induced through the prosthesis in R7 area, which leads to a high stress shielding effect and thus to bone resorption. The reason of the high deviation could be the changes in the R7 scanned area during the DEXA-investigations, which is detected by Lerch et al. with his DEXA-Study [11]. This decrease in the R7 area leads to misread the BMD value of R7 and makes it higher than it really is. However, no information about the scanned area of R7 are provided in the paper of Zeh et al. The average deviation in all regions is about 8 %, which confirms the validation of the numerical simulation of the periprosthetic femur bone remodelling with the NANOS-prosthesis. To validate the numerical investigation of shaft migration, the study of Budde et al. [17] were used. In this clinical study, the X-ray stereo photogrammetric analysis (RSA) was used to determine the NANOS-shaft migration in the femur within the first 2 years postoperative. In this study a total migration of 0.49 ± 0.31 mm has been detected, while the numerical investigation has determined a total migration of 0.4 mm without coupling with MBS and 0.43 with coupling with MBS. This comparison confirms the validity of this numerical modelling of the NANOS-shaft migration in the femur bone tissue and emphasizes the importance of the mutual influence between the implant migration and the hip contact forces.

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Author's Statement

Conflict of interest: Authors state no conflict of interest.

Material and Methods: Informed consent: Informed consent has been obtained from all individuals included in this study. Ethical approval: The research related to human use has been complied with all the relevant national regulations, institutional policies and in accordance the tenets of the Helsinki Declaration, and has been approved by the authors' institutional review board or equivalent committee.

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