VIBRATIONAL BEHAVIOUR OF AN INSERTED FEMORAL STEM:
ADDED MASS EFFECT VERSUS ADDED STIFFNESS EFFECT

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SUMMARY
To understand the influence of changing contact conditions at the bone-implant interface on the vibrational behaviour of the femur-implant structure, modal analyses on finite element models were performed in various contact situations. The results are in agreement with previous observations: contact increase causes positive resonance frequency shifts and, in general, the higher modes are more sensitive to the contact change.

Vibration analysis can be regarded as a very useful tool in assessing the stability of orthopaedic implants.

INTRODUCTION
For clinicians, implant designers, and implant manufacturers the measurement of the stability of orthopaedic implants in vitro and in vivo is a research topic for many years. Both the migration of the implant in time and the implant relative movements (micromotion) induced by load are important for the stability assessment and for loosening detection and prediction [1, 2].

Vibration analysis has been successfully applied in biomechanics to determine bone mechanical properties [3], to monitor fracture healing [4], and to assess the stability of dental implants [5] and femoral stems in vitro and in vivo as well [6-8].

To better understand the influence of changing contact conditions at the bone-implant interface on the resonance frequencies of the femur-implant structure a finite element analysis (FEA) was set up.

The implanted stem influences the resonance frequencies of the femur in two ways mainly:

- The added mass determines a resonance frequency decrease, while
- The added stiffness implies a resonance frequency increase [9].

The research hypotheses are:

- The proportion between these two contradictory influences is strongly dependent on the mode shapes of the femur-stem structure and on the amount of contact existing between the bone and the implant.
- Contact increase causes positive resonance frequency shifts.
- Higher modes are more sensitive to the change in contact area.

This paper presents the results obtained by performing modal analyses on a finite element model of a femur-stem structure having different contact configurations at the bone-implant interface.

METHODS
A finite element model of a femur with an implanted intra-operatively manufactured prosthesis (IMP) [10] was created to provide insight into the dependence of the dynamic behaviour of the system on system parameter variations.

The geometry of the parts was created, based on CT scans of an artificial human femur (Sawbone® nr. 3306) and Standard Tessellation Language (STL) files of a corresponding IMP (courtesy of Advanced Custom Made Implants, Leuven, Belgium), by using the software Magics® and Mimics® (Materialise, Haasrode, Belgium). The femoral cavity was obtained by applying a boolean operation that extracted the prosthesis volume from the femur. The created shapes were meshed using Patran® (MSC.Software, Gouda, The Netherlands). To generate the solid mesh a 3D 4-node linear, tetrahedral element was chosen. Orthotropic, linear elastic behaviour was selected for the bone mechanical properties [11]. The prosthesis material (Ti6Al4V alloy) was considered isotropic and linear elastic.

Situations of partial contact were simulated by varying the contact tolerance option in Marc FE software (MSC.Software, Munich, Germany). This option allows the user to set the distance below which the software considers a node and a surface in contact. Because of the meshing procedure, this distance varies over the geometry of the prosthesis. The contact configuration could be changed without altering other system parameters. The highlighted zones on figure 1 represent, the elements of the femur in contact with the prosthesis.

![Figure 1: Progressive increase of general contact](image-url)
Modal analysis has been used to calculate the resonance frequencies and to obtain the vibrational mode shapes between 0 and 10 kHz. In a first stage the femur and the prosthesis were analysed separately. In a second stage, modal analyses on the stem-femur structure were performed. The prosthesis was fully inserted and the overall contact area changed from 15% to 98%.

RESULTS AND DISCUSSION

The resonance frequency shifts between the femur-implant structure at different sizes of contact surface and the femur prepared for stem implantation are presented in figure 2 for the first 65 vibrational modes.

Analysing the graphs presented in figure 2, it can be observed that the resonance frequencies corresponding to the first six modes of the system femur-implant are lower than the respective first six resonance frequencies of the femur, indicating that the influence of the added mass is more important than the influence of the added stiffness. Moreover, for these modes, the contact area increase results in relative small resonance frequency increase.

Starting with mode #9 the resonance frequencies of the femur-implant structure at 98% contact are always higher than the corresponding resonance frequencies of the femur, indicating a strong influence of the added stiffness. For few modes (#15, #23, #30, #33) the influence of the added mass is still superior to the influence of the added stiffness, but only for lower values of contact area, i.e. 15 - 38%.

Although the influence of the added stiffness is relatively important for the higher and complicated modes, the sensitivity to the size of contact surface is variable. For example, the modes #20 and #32 are very sensitive to the contact change. The frequency shift between 15% and 98% contact is 174 Hz for mode #20 and 164 Hz for mode #32. The presence of the prosthesis and the contact change clearly influence these two mode shapes of the femur. Such modes are very important for the assessment of the stability of the implant. Figure 3 presents the influence of the inserted stem on the shape of mode #20.

Figure 3: Vibrational mode #20 (left: femur without stem, middle: femur with stem at 15% contact, right: femur with stem at 98% contact)

CONCLUSIONS

The results confirmed the research hypotheses and are in agreement with observations from previous experimental work: contact increase causes positive resonance frequency shifts and higher modes are more sensitive to the change in contact area [7,8].

Although the finite element analysis did not establish a monotonous relationship between the mode number and the magnitude of the resonance frequency shift, in general, the torsional and higher bending and complicated modes are more sensitive to the change in contact area which is in agreement with other finite element studies [12]. This phenomenon can be understood from the fact that in the lower bending modes the prosthesis moves as a rigid body and only exerts an added mass effect whereas in the higher modes the interaction between the stem and the femur becomes more complicated and the interface conditions affect the resonance frequencies.

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REFERENCES