A framework to evaluate bone growth after Total Hip Arthroplasty through Finite Element Method

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Abstract

Total Hip Arthroplasty (THA) is an orthopaedic procedure that is available to reduce pain and restore the functionality of hip joints. THA has been successfully implemented for the last 30 years. However, after more than 30 years of design and implementation, premature loosening of the femoral stem still occurs due to the stress shielding. Stress shielding effect can be reduced if the implant stiffness is close to the stiffness of the human femur bone. This however could increase the micromotion and interface debonding between the stem and femur bone. The finite element analysis framework presented in this paper can be used to establish a stem-design adequacy check in preclinical testing protocols. The overall goal of this framework is to reduce the need of revision surgery due to stress shielding related problems.

Keywords: Total Hip Arthroplasty, finite element analysis, femoral stem, stress shielding, aseptic loosening

1. Introduction

Degenerative diseases such as osteoarthritis and osteoporosis are very common globally, especially among the elderly population. Osteoarthritis causes gradual wear and damage to the joint whereas osteoporosis is a condition where bones become weak and brittle. These may cause the hip joint to be weak and THA becomes unavoidable. Besides diseases, hip fracture due to accidents can also lead towards a THA. According to the epidemiologic projections, by 2050 the total number of THA globally will reach 6.26 million. It has been reported from data collected that the revision rates for THA is about 6% after 5 years and 12% after 10 years of surgery. Revision surgeries are costly and have high risk of complications.

Bone growth and density is dependent on the load bearing capabilities (Wolff's Law). Loading stimulates bone to remodel and become stronger over a period of time. If loading activity decreases, bone becomes weak. In hip implants, stress shielding is a mechanical phenomenon where the stiffer prosthesis takes the role of carrying the body weight, with little load sharing with the femur bone itself. This causes poor mechanical stress distribution on the femur bone. As a result, the density of the bone close to the implant starts to decrease. The consequence of this is aseptic loosening of the hip joint, which is one of the major factors for revision surgeries for THA.

A lot of research work has been done on femur stem design to reduce stress shielding [1]. These research works focused on designing new implant geometries and material distribution strategies to reduce stress shielding. Even though significant reduction in stress shielding were obtained, not much was discussed on the side effects of such reductions, i.e. the increase of micromotion between the stem and the femur. The level of micromotion affects the growth of soft tissue [2]. As shown in Fig. 1, when the implant is hammered into the medullary canal, portion of the femur bone is damaged. The location of the damaged bone due to prosthesis insertion will cause soft tissue growth. The growth of the soft tissue that forms between the stem and the femur bone should not be ignored, as this is the initial stage of bone growth (tissue differentiation process). It is the aim of this paper to develop a framework for estimating bone growth through the means of finite element analysis whilst considering reduction in stress shielding.

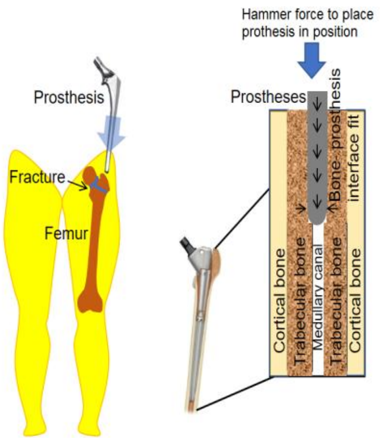

Figure 1: Placement of prosthesis into the medullary canal

2. Finite Element Model

The finite element analysis that consists of an actual femur bone geometry and a prosthesis is computationally heavy due to the number of elements, interaction constraints and complexity in geometry. To simplify this, in this study the bone and prosthesis geometry was assumed cylindrical. Details of the simplified geometry along with the finite element model is shown in Fig. 2. The finite element analysis was conducted on two different prosthesis material (one being five time stiffer than the other). The outcome of the analysis shows (Fig. 3) that the lower stiffness prosthesis reduced stress shielding. The maximum stress in the prosthesis and bone is around 37 MPa and 32 MPa respectively. In the stiffer prosthesis, the maximum stress in the prosthesis and bone is around 112 MPa and 23 MPa respectively. When we investigated the micromotion between

* This work was supported in part by the NPRP under Grant # NPRP 8-876-2-375 from the Qatar National Research Fund (a member of Qatar Foundation). The statements made herein are solely the responsibility of the authors.

the prosthesis and the bone, the stiffer prosthesis had a maximum micromotion of 18.6 μm whereas the lower stiffness prosthesis has a maximum micromotion of 65.1μm. This shows that even though the less stiff prosthesis managed to reduce stress shielding, the micromotion was much higher. The magnitude of prosthesis micromotion has a statistically significant effect on the tissue differentiation [3]. Besides this, Fig. 4 shows that the stress and micromotion distribution is non-uniform from the proximal-distal and medial-lateral directions.

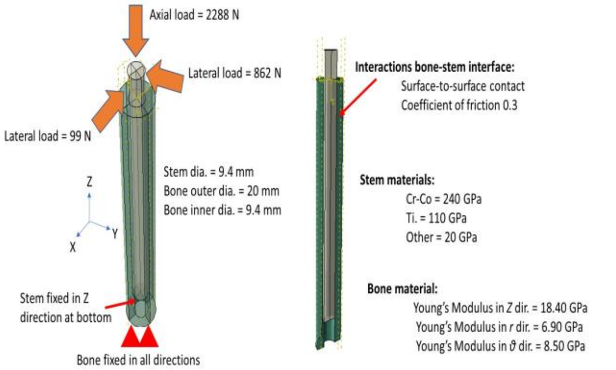

Figure 2: A simplified finite element model for the femur-prosthesis

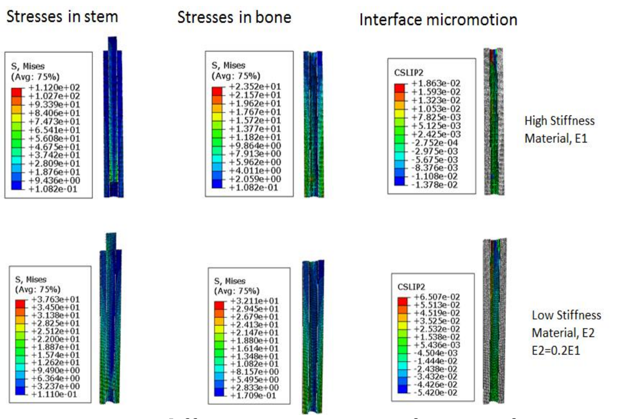

Figure 3: Tissue differentiation process as function of strain

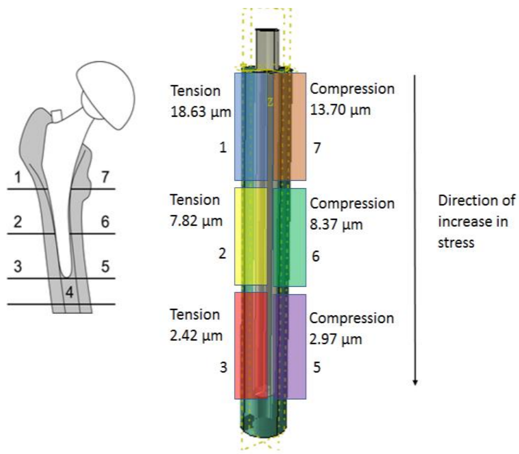

Figure 4: Non-uniform micromotion and stress distribution

3. Bone Growth Framework Proposal

The design question is how engineers can reduce stress shielding while having sufficient micromotion to promote bone growth around the prosthesis, taking into account the non-uniform distribution of micromotion and stress as shown in Fig. 4. This requires the usage of a bone growth a mechano-regulation algorithm to study the tissue differentiation process. A mechano-regulation theory with deviatoric strain was selected for this study [2]. The algorithm used for the mechano-regulation is shown and the tissue differentiation process (tissue phenotype) are shown in Fig. 5.

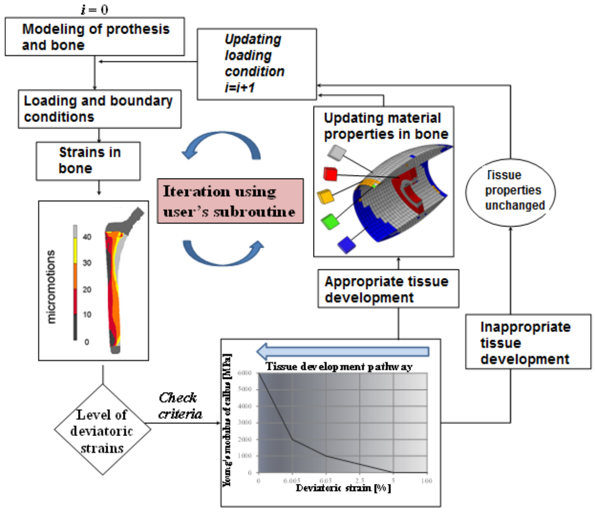

Figure 5: Bone growth a mechano-regulation algorithm through finite element methods

4. Conclusion

This study showed that reducing stress shielding by designing the prosthesis alone is not sufficient. The associated micromotion has to be considered as well. The level of micromotion affects bone in growth. Hence, this paper suggests an algorithm to compute bone in growth as a function of deviatoric strains. With is algorithm, it will be easier to design a functionally graded prosthesis (proximal-distal and lateral-medial direction) that best meets the stress and micromotion constraints.

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