EFFECTS OF MICROMOTION ON BONE INGROWTH PREDICTED BY A MECHANO-REGULATORY TISSUE DIFFERENTIATION ALGORITHM

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INTRODUCTION:

Cementless orthopaedic implants that function as load transfer structures typically achieve long-term fixation via bony ingrowth into a porous scaffold on the implant surface. Early ingrowth of bone tissue is important to achieve implant stability, which is crucial for the success of joint arthroplasty, as most implants with evidence of early micromotion go on to clinical failure.[1] In the long term bone tissue inside and around implant scaffolds undergoes adaptive bone remodeling. However, in the earlier stage following surgery, bony ingrowth is achieved by a process similar to primary bone fracture healing.[2] Damage to the tissue adjacent to the prosthesis stimulates the formation of a hematoma and development of mesenchymal tissue followed by tissue differentiation – the change of tissue phenotype from progenitor cells to osteoblasts, fibroblasts or chondrocytes. The type of tissue that is formed depends on the cells available, the chemical environment, and the imposed mechanical stimuli.

Studying the mechanisms by which interfacial micromotion acting on the bone tissue guide the tissue differentiation inside the scaffold into bone or fibrous tissue could provide insight into how implant design affects osseointegration. Several models have been developed to simulate mechanically regulated tissue differentiation.[3, 4] These models have been successfully used to simulate bone fracture healing and other tissue differentiation processes. The goal of this study is to apply a quantitative mechano-regulatory tissue differentiation algorithm to predict bony ingrowth into an implant surface with a sintered bead porous coating. Specifically, tissue ingrowth was predicted for three levels of micromotion at the bone-implant interface.

METHODS:

The tissue differentiation algorithm developed by Lacroix et al. was applied.[5] All tissues involved in the process were modeled as poroelastic materials and the Octahedral shear strain, γ, and fluid flow rate, ν, were used to calculate the mechanical stimulus acting on the tissue. The tissue phenotype was determined for each element depending on its position in the mechano-regulation diagram.[4] The net effect of mesenchymal cell proliferation and migration was described as cells advancing into areas of low density, modeled by the diffusion equation.[5]

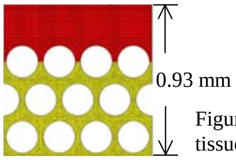

Figure 1: Initial FE model with granulation tissue filled in space between beads.

A two-dimensional finite element model representing a beaded scaffold filled with granulation tissue adjacent to bone tissue was created (Fig. 1). The beads, with diameter 200 μm, were assumed to be packed in a body centered cubic (BCC) manner, which has a similar volume fraction to sintered bead porous coatings. The two-dimensional model simulated a plane cutting through the center of a unit cell with the middle layer shifted half a unit length laterally to account for the randomness in real scaffolds. The bone tissue was assumed to initially fill the top half layer of the scaffold to simulate the effect of press-fit during surgery.

Frictionless sliding contact between the tissue and the fixed rigid beads and the fixed rigid bottom surface simulating the prosthesis substrate was assumed. Both mesenchymal cells and fluid were assumed to originate from the surrounding bone tissue. For a specific element, when the calculated stimulus indicated that a new cell phenotype would be favored, the material properties of that element were changed. To account for the delay between the time that stimuli first act on a cell and the process of differentiation into a new phenotype, a smoothing procedure was implemented. The material properties of the mixture of granulation tissue and the new tissue were calculated based on cell density using the rule of mixtures.[5] Material properties for each tissue were taken from the literature.[5]

The top surface of the bone tissue was subjected to a compressive stress of 5 MPa, simulating the press-fit process, combined with lateral displacement of 5, 10 and 20 μm respectively to study the effect of different levels of micromotion. The effect of mesh density on the tissue differentiation pattern was also investigated using models with three different mesh densities, with average element sizes of 95, 24 and 6 μm^2. The total number of elements in each case was 49,551, 198,204 and 792,816 respectively. The models were solved in ABAQUS (ABAQUS, Inc., Providence, RI) iteratively until the differentiation pattern reached equilibrium. The solutions required an average of 3, 15 and 110 minutes of CPU time per iteration on an AMD Opteron processor for the 95, 24 and 6 μm^2 meshes respectively.

RESULTS:

Finite element models with different mesh densities predicted similar quantities of bone ingrowth. However, mesh density did affect the predicted differentiation pattern, especially in earlier iterations. More fluctuation was observed in the coarse mesh than in the other two meshes. Since the tissue differentiation patterns were similar qualitatively between the 24 and 6 μm^2 meshes, the 24 μm^2 mesh was used for all the models in the rest of this study to save computational time.

The 20 μm lateral displacement combined with 5 MPa pressure resulted in formation of a gap in the top layer of pores (Fig. 2). With the same normal pressure, as micromotion decreases, the gap became less visible in the model with 10 μm lateral displacement and disappeared in the model with 5 μm lateral displacement, in which full bone-ingrowth occurred following initial stabilization by fibrous tissue.

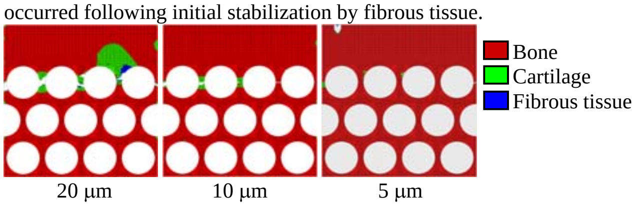

Figure 2: Predicted tissue differentiation patterns for different levels of micromotion (iteration No.30).

DISCUSSION:

Twenty microns of micromotion has been used as a threshold to predict whether osseointegration will occur in cementless implants.[6] The mechano-regulatory tissue differentiation algorithm predicted bone formation in the lower levels of the scaffold with this level of micromotion. However, a band of soft tissue, and ultimately tissue resorption, at the top layer of the porous coating would ultimately lead to resorption of the bone and a weak interface. As such, consistent with clinical observation, the interface will fail. In comparison, when micromotion was 5 μm, a contiguous region of bone formation is predicted.

In future applications of this algorithm, appropriate finite element mesh density needs to be selected based on convergence studies of different mesh densities. Although bone ingrowth fractions after convergence was reached were similar for the three mesh densities studied, the ingrowth pattern did exhibit dependence on mesh density.

Tissue differentiation models can improve our understanding of osseointegration of implants. Such models can be used to optimize the porous scaffold morphology or its location on the implant.

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