Journal of Biomechanics 39 (2006) 1873–1882

JOURNAL OF BIOMECHANICS

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Biomechanical analysis of the shear behaviour adjacent to an axially loaded implant

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Accepted 18 May 2005

Abstract

Good mechanical fixation of an implant to the surrounding bone is important for its longevity, and is influenced by both biological and mechanical factors. This study parametrically evaluates the mechanics of the interface with a computationally efficient analytic structural model of the shear stress field and global shear stiffness of an axially loaded implant. The utility of the analytic model was first established by validating its assumptions with a case-specific finite element model. We then used the analytic model for a sensitivity analysis of the relationship between the pattern of tissue growth and shear properties of the interface for our previously reported loaded in vivo experimental micromotion device. The bone located directly at the implant surface was found to be the most effective site for increasing interface stiffness. This suggests that the implant surface is the most desirable site for bone growth, yet is also the most mechanically challenging environment due to its maximal shear stresses. Thus, these findings support the further investigation of osteo-conductive coatings and other biological stimuli to overcome the challenging mechanics, and to promote bone growth directly at the implant surface. The model also demonstrated that the mechanical contribution to the global implant shear stiffness of a commonly observed isolated sclerotic bone rim is very limited. The results of this sensitivity analysis agree with experimental studies with the micromotion device, and with clinical studies reporting good results with osteo-conductive coatings.

Keywords: Joint replacement; Bone-implant interface; Shear behaviour; Bone distribution pattern; Analytical model

1. Introduction

The quality of the fixation of an implant to its surrounding bone determines its clinical longevity. While this fixation quality is determined primarily by the bone and tissue anchoring the implant, many factors (including mechanical, biochemical, biological, patient-related) influence the effectiveness of this tissue. It is known that different factors in different settings will direct the formation of specific types, amounts and locations of anchoring tissue. For example, experimental and clinical studies have shown the effects of implant coatings, interface motion, fluid pressure, and growth factors on implant fixation (e.g. Bechtold et al., 2001; Jones et al., 2001; Mouzin et al., 2001; Skripitz and Aspenberg, 2001; Toksvig–Larsen et al., 2000; Van der Vis et al., 1998; Willert and Buchhorn, 1999). Furthermore, numerical models of the bone–implant interface have been useful in parametric evaluations of the effects of implant design variables (e.g. Chang et al., 2001; Prendergast, 1997; Stolk et al., 2002; Weinans et al., 1993, 2000).

Knowledge of mechanically advantageous locations for bone to grow, and factors that influence these mechanics (the objectives of this study), combined with knowledge of typical bone growth patterns (existing experimentally derived information) will suggest

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0021-9290/$ - see front matter
doi:10.1016/j.jbiomech.2005.05.027

potentially beneficial strategies to promote high–quality fixation. This can facilitate better targeting of implant-surface treatments and biological interventions.

In our previous in vivo studies with an experimental micromotion device representing the interface of a human implant loaded in shear (Fig. 1a), we have identified an association between the sites where periimplant bone forms and the experimentally determined mechanical properties of the resulting interface. Specifically, we found experimentally that bone located near or on the implant surface better anchors the implant as compared with the same volume of bone growing from the machined bone surface towards the implant (Søballe et al., 1992a; Bechtold et al., 2000).

We hypothesize that this experimentally observed better fixation with bi-directional bone growth is represented in mechanical models as higher mechanical interfacial properties. In other words, bi-directional bone growth from the implant surface towards the bone and bone towards the implant will be associated with high mechanical fixation parameters, and when the bone is only growing towards the implant surface from the surrounding bone the fixation will be inferior. The clinical corollary to this hypothesis is that implant design strategies that promote bone growth at the implant surface (such as osteo-inductive and osteo-conductive coatings) could be preferred strategies of improving implant fixation.

We developed a simplified analytic model of the shear behaviour at the bone–implant interface in an attempt to better understand the consequences of different patterns of bone and tissue growth on their corresponding mechanical implant fixation (with the ultimate aim being to use this information to target improved implant design).

2. Methods

The analytic model is based on our existing micromotion device. The output of the model is confirmed by correlating its derived shear stiffness and stresses with a specific-case finite element (FE) model. The confirmed analytic model is then used for a sensitivity analysis to systematically rank different bone growth patterns with regard to their ability to anchor the implant. Specifically, the model allows the variation of the location, size and material properties of the overall bone distribution, as well as the size of the gap. The sensitivity analysis is based on typical geometries of observed in vivo bone growth patterns, and is also shown to be representative of sizes of implants and interface regions typical for human prostheses.

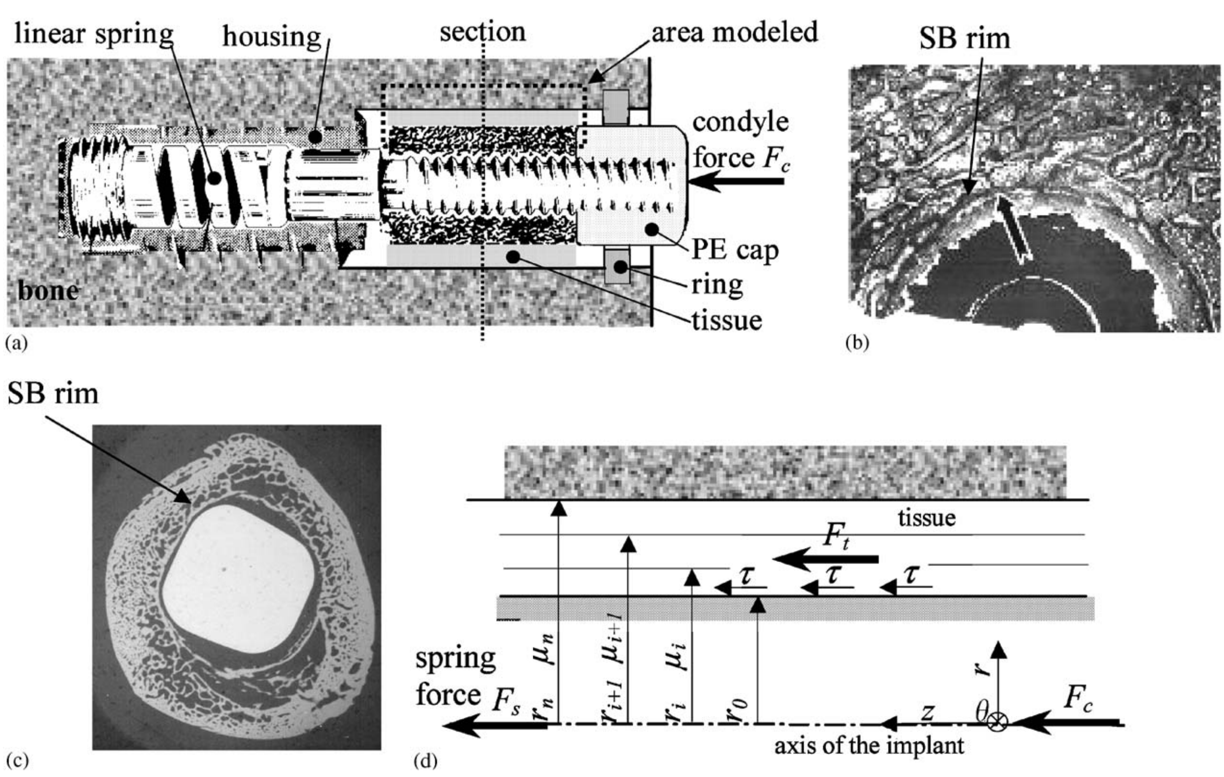

Fig. 1. (a) Loaded micromotion implant, (b) Experimentally observed sclerotic bone rim (SBrim), (c) Human implant retrieval showing SB rim, (d) Mechanical model.