IMECE 96 - BED Vol. 33

BIOMECHANICS-BASED PRE-OPERATIVE PLANNING IN THR - APPLICATION OF FICTITIOUS DOMAIN METHOD

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INTRODUCTION

Typical pre-operative planner in total hip replacement (THR) surgeries includes only geometric templating capabilities that are used, invariably, to find an appropriate match between the femoral and acetabular implants and their respective receiving bones. Such systems lack the predictive capabilities that could conceivably be offered by pre-operative planners enhanced with biomechanical evaluation modules. For the augmented pre-operative planners to be of clinical use, the underlying analysis tools need be reliable, fast and accurate. However, most analysis tools are designed and tested outside the context of a pre-operative planner and in an ad-hoc way that is difficult to automate, if one were to meet the severe demands of a patient-specific pre-operative planning environment. Furthermore, the typical modeling pipeline that is the backbone of the analysis part of a biomechanical evaluation module, is burdened by the introduction of approximation errors. We report here on a novel approach that greatly simplifies the typical modeling pipeline.

METHODOLOGY

In order to illustrate the proposed methodology we focus on a prototype problem, that is, on the implantation of a femoral prosthesis. The goal is to model the bone/implant system and subsequently study numerically the mechanical effects of the implantation. To this end we turn to methods known as fictitious or domain embedding methods [1-3]. Their primary advantage and appeal lies in the fact that one need not respect the geometric constraints in the way one need do with standard finite element methods. Instead, one can use structured meshes that do not necessarily follow the geometric boundaries of the solids under analysis. Consider the two-dimensional femoral cross-section shown in Fig. 1a: the elements of the background grid correspond precisely to the pixels of a CT-scan slice. The closed curve denoted by γ in Fig. 1a represents the implant. In the cementless press-fit case displacements are prescribed on γ to represent the press-fit (implant oversizing) amount. Notice (Fig. 1b) that only the geometry of the implant's cross-section need be known; moreover, its discretization is independent from that of the background grid. In contrast, traditional finite element methods would require the extraction of the boundary from the CT-scan data and the discretization of the area between the external bone boundary and the boundary of the implant.

NUMERICAL RESULTS

The two-dimensional case assisted in comparing the proposed methodology against more conventional approaches. Accordingly, in order to simulate the effects of a press-fitted implant the femoral cross-section depicted in Fig. 1a was subjected to a press-fit of 0.25mm along the circular implant boundary γ. We assumed that the equations of linear elasticity can adequately describe the behavior of the bone/implant system. The results of simulations by three methods are shown in Figs.2a-f. Figures 2a,b depict the x (horizontal) and y (vertical) displacement components, respectively, as obtained by the standard finite element method applied to the domain exterior to the implant boundary γ (unstructured mesh). Figures 2c,d depict the same displacement distributions as obtained after extracting the external bone boundary and solving for the contained domain (unstructured mesh). Finally, figures 2e,f depict the distributions obtained by the proposed fictitious domain method (structured mesh). There is satisfactory agreement among all methods.

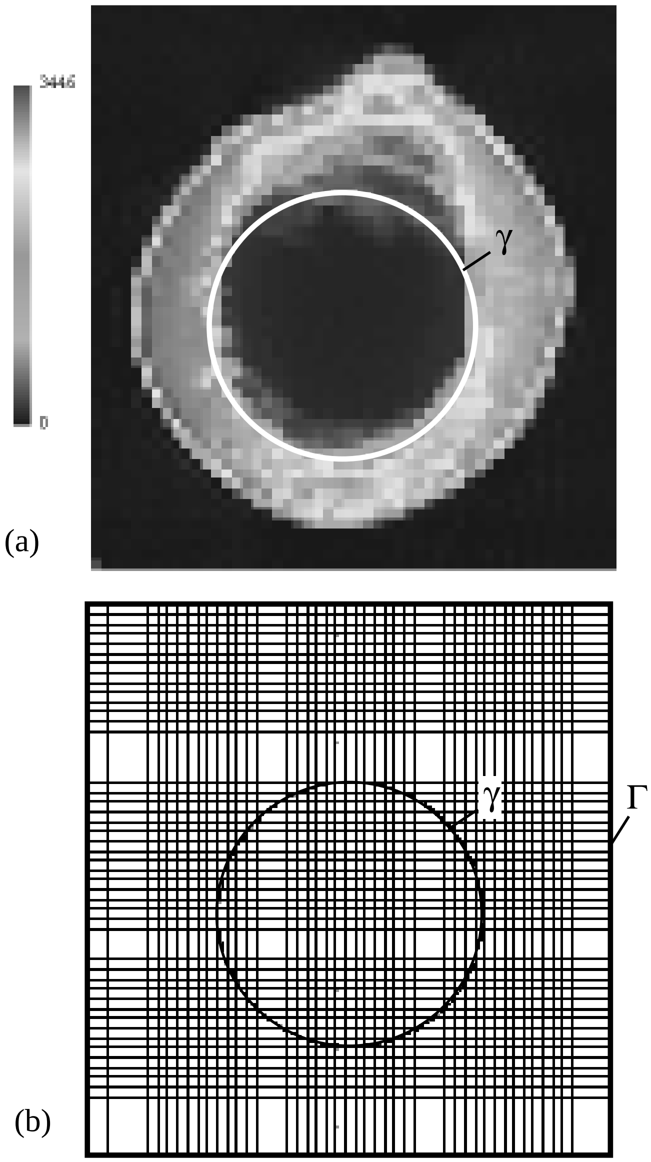

Figure 1. (a) Femoral CT-scan slice; (b) Problem geometry

DISCUSSION

The standard modeling pipeline for predicting and assessing the mechanical effects on the bone of a femoral implant originates from planar tomographic images of the patient's femur; it also includes noise-filtering of the images, boundary extractions via edge detection algorithms, planar contour generation, connection of the contours across consecutive tomographic planes via surface reconstruction algorithms, volume and canal identification and finally canal preparation and simulation of the femoral neck osteotomy. The end product of the standard pipeline is a solid model of the femur/implant system and the final modeling step requires the meshing of the solid model. All steps involve approximations which introduce errors and distort significantly the original data set (CT-scan data). In contrast, the fictitious domain approach sidesteps most of the steps and the errors of the standard modeling pipeline, while remaining faithful to the original data set; therein lies its promise to deliver a robust, accurate and fast analysis tool that can be used as part of an enhanced pre-operative planner.

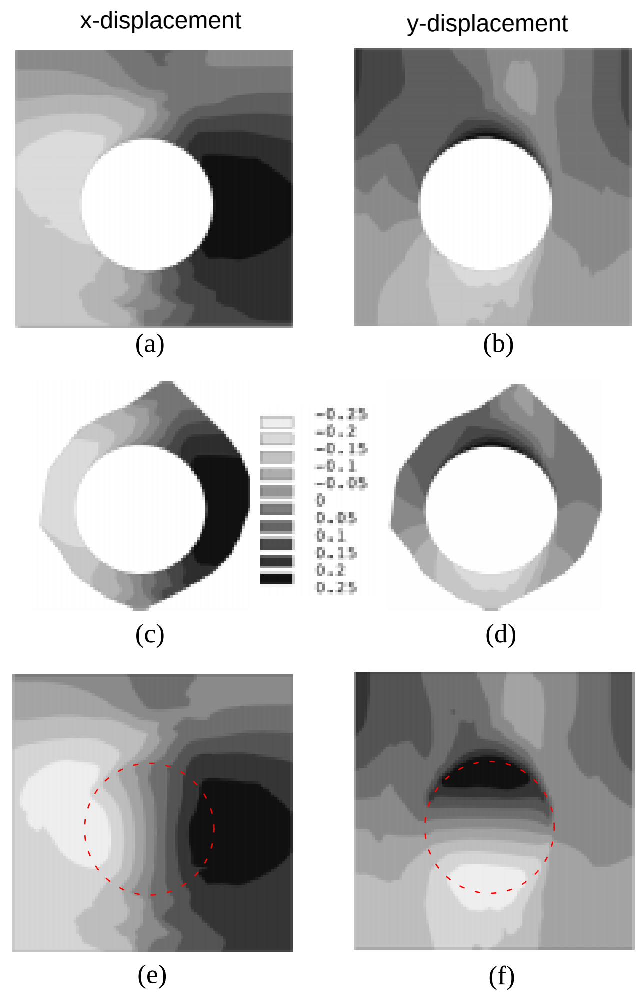

Figure 2. (a)-(d) Unstructured standard finite element methods; (e)-(f) Structured fictitious domain method

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ACKNOWLEDGMENT

This work was supported in part by a National Challenge grant from the National Science Foundation (ECS-9422734) and by a grant from the Arthritis Foundation.