Available online at www.sciencedirect.com

ScienceDirect

Clinical Biomechanics 23 (2008) 1192–1199

CLINICAL BIOMECHANICS

www.elsevier.com/locate/clinbiomech

A new meshless approach for subject-specific strain prediction in long bones: Evaluation of accuracy

Fulvia Taddei [a,*], Martino Pani [a,b], Luigino Zovatto [b], Enzo Tonti [b], Marco Viceconti [a]

[a] *Laboratorio di Tecnologia Medica, Istituti Ortopedici Rizzoli, Via di Barbiano, 1/10, 40136 Bologna, Italy*
[b] *Engineering Faculty, University of Trieste, Italy*

Received 29 January 2008; accepted 11 June 2008

Abstract

Background. The Finite Element Method is at present the method of choice for strain prediction in bones from Computed Tomography data. However, accurate methods rely on the correct topological representation of the bone surface, which requires a massive operator effort, thus restricting their applicability to clinical practice. Meshless methods, which do not rely on a pre-defined topological discretisation of the domain, might greatly improve the numerical process automation, but currently their application to biomechanics is negligible.

Methods. A meshless implementation of an innovative numerical approach based on a direct discrete formulation of physical laws, the Cell Method, was developed to predict strains in a cadaver femur from Computed Tomography data. The model accuracy was estimated by comparing the predicted strains with those experimentally measured on the same specimen in a previous study. As a reference, the results were compared to those obtained with a state-of-the-art finite element model.

Findings. The Cell Method meshless model predicted strains highly correlated with the experimental measurements ($R^2 = 0.85$) with a good global accuracy (RMSE = 15.6%). The model performed slightly worse than the finite element one, but this was probably due to the need to sub-sample the original data, and the lower order of the interpolation used (linear vs parabolic).

Interpretation. Although there is surely room for improvement, the accuracy already obtained with this meshless implementation of the Cell Method makes it a good candidate for some clinical applications, especially considering the full automation of the method, which does not require any data pre-processing.

Keywords: Bone biomechanics; Numerical model; Computed Tomography; Validation; Meshless methods; Cell Method

---

1. Introduction

Subject-specific numerical prediction of mechanical strains from Computed Tomography (CT) data could be a valuable tool in many clinical application, such as risk of fracture prediction in osteoporosis, management of the rehabilitation therapy in complex skeletal reconstructions, evaluation of the mechanical stability of joint prosthesis etc. At present the numerical method of choice is the Finite Element Method (FEM) (Cody et al., 2000; Little et al., 2007; Taddei et al., 2003), which can replicate bone morphology and mechanical properties accurately (Taddei et al., 2006). The most recent works (Schileo et al., 2007) indicate that a high accuracy in the predictions of strains can be obtained ($R^2 > 0.9$, RMSE < 10%) well enough to allow, in principle, the application of the method to study real clinical cases.

However, to be used routinely in the clinical practice, a numerical method beside being general, accurate and robust should prove also to be automatic (Viceconti et al., 2004). In particular the time needed to build the model, run the simulation and obtain the predictions should be compatible with the clinical needs. At present the methods that have shown a sufficiently good accuracy

---

[*] Corresponding author.
E-mail address: taddei@tecno.ior.it (F. Taddei).

0268-0033/$ - see front matter © 2008 Elsevier Ltd. All rights reserved.
doi:10.1016/j.clinbiomech.2008.06.009

rely on the correct topological representation of the bone surface (Anderson et al., 2005; Gupta et al., 2004; Schileo et al., 2007). This usually implies a three-step process that involves the segmentation of the bone, which at best can be semi-automatic, the generation of a mathematical representation of the bone boundary, the mesh generation, which can at present be handled with automatic software, and the mapping of the mechanical material properties onto the mesh. This process, although greatly improved over the past few years, still requires a massive operator effort, and typically it takes a few days to generate a complete model. This makes it practically impossible to apply such methods to the study of large populations, or to give real-time answers to clinicians, for example on the primary stability of a planned joint replacement operation.

In this particular field of application, however, the original data, which is typically a Computed Tomography (CT) dataset, is *per se* a discretised volume, where the physical information, i.e. the radiation attenuation coefficient, is sampled on a regular grid. A method, which could rely directly on the native data representation, not requiring the generation of the topologically correct solid bone model, might greatly reduce the effort needed to generate the model and hence the time to perform the analysis.

This idea is the basis of all voxel-based methods (Keyak et al., 1993; Keyak et al., 2005) that exploit the intrinsic topology of the CT dataset to discretise the volume of interest without the need for segmentation and geometrical modelling. Despite being highly automated, the voxel method has shown limited accuracy in the prediction of strains in whole bones (Keyak et al., 1993).

Over the past few years there has been a growing attention in several engineering fields (e.g. fracture mechanics, large deformation models, fluid-structure interaction) to the development of meshless methods that, without the need for topological discretisation of the continuum in a pre-defined mesh, might predict accurately the distribution of mechanical stresses and strains in a however complex domain (Idelsohn et al., 2003; Li and Belytschko, 2001; Rabczuk and Belytschko, 2004). Since 1976, when the first meshless (or mesh-free) formulation (Smoothed Particle Hydrodynamics) appeared (Gingold and Monaghan, 1977; Lucy, 1977), several methods have been formulated that differ in the theoretical approach and/or philosophy of the integration of differential equations to solve. Although there is still some debate on the correct definition of what is a "meshless" method (some authors claim that their approach is "truly meshless" as opposed to others), it can be stated (Idelsohn and Onate, 2006) that "a 'meshless method' is an algorithm in which the definition of the shape function depends only on the node position and the evaluation of the nodal connectivity is bounded in time and linear with the total number of nodes in the domain".

Although potentially powerful in many applications, these methods have never gained the popularity of FEM, which is demonstrated by the absence of widespread commercial meshless codes, apart from some finite volume implementation in the fluid-dynamic field (sometimes referred to as meshless method) and some *quasi-experimental* codes. This is probably due to the main problems experienced by the meshless methods. They often encountered stability problems in their first implementations (Smoothed Particle Hydrodynamics and other mesh-free methods based on Eulerian kernels) (Swegle et al., 1995). In addition, even for those methods that solved the original instability problem (such as Element Free Galerkin, Finite Point Method, Meshless Local Petrov Galerkin Method) a very important limit was the difficulty in imposing the essential boundary conditions (Fernandez-Mendez and Huerta, 2004). Several solutions have been proposed to overcome this limit, but usually at the cost of great complexity, and this is still a matter of study (Cai and Zhu, 2004; Gavete et al., 2000; Xiong Zhang, 2001). Coherently, the adoption of such techniques has interested those fields where the limitations posed by the finite element method were too constraining (for example High-Speed Impact, metal forming and crack propagation).

Very recently some alternative meshless methods have been proposed to solve the boundary condition problem without introducing high complexity: the Natural Element Method (NEM) (Sukumar et al., 1998) and a meshless formulation (Zovatto and Nicolini, 2003; Zovatto and Nicolini, 2006) based on the Cell Method (CM) (Tonti, 2001).

Some of the above-cited techniques have already found an application in biomedical engineering, especially in fields such as surgical simulations (Lim and De, 2007), or the simulation of soft tissue failure (Ionescu et al., 2006), where FEM is inadequate to simulate very large deformation or the loss of domain continuity. Although potentially they could be applied to the investigation of bone biomechanics, their use is still very limited.

Only three studies, to the authors' knowledge, have been published so far on meshless methods adopted for the prediction of the mechanical behaviour of bone. The first, Liew et al. (Liew et al., 2002), adopted a reproducing kernel particle method to investigate the stress distribution in the proximal part of a human generic femur simulating the effects of aging and necrosis. Although interesting, as it was the first application of the method to biomechanics, the marked simplifications adopted (two-dimensional homogenous model) limit the clinical relevance of this work. Doblaré et al., instead, applied the NEM method to a variety of cases (adaptive bone remodelling, hyperelastic tendons under large strains, poroelastic articular cartilages) and showed the possible advantages of using meshless methods in biomechanical simulations (Doblaré et al., 2005). Again, however, a three-dimensional model of a bone segment at the organ level was not attempted. In the last published work Lee et al. (Lee et al., 2007) applied the implementation of the moving least square approximation technique to the analysis of the mechanical behaviour of a spongious bone specimen loaded in compression. Their model, indeed three-dimensional, showed the great potentiality of directly applying a meshless method to the original dataset (in this case micro-CT).