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Meshless Methods: The Future of Computational Biomechanical Simulation

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Abstract

Meshless methods are advanced discretization techniques, which permit to discretize the problem physical domain with an unstructured nodal cloud. This discretization flexibility allows obtaining the geometrical model directly from medical images, such as computerized axial tomography (CAT) scans or magnetic resonance imaging (MRI) techniques. Then, it is possible to analyse straightforwardly the biomechanical behaviour of biological structures. When compared with other mesh-dependent discretization techniques, meshless methods are capable of producing smoother and much more accurate stress and strain fields. The literature shows that meshless methods have the potential to be the future of biomechanical computational simulation.

Keywords: Meshless methods; Biomechanics; NNRPIM; Radial basis functions

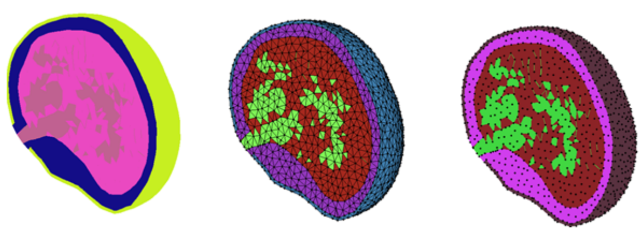
Introduction

In computational biomechanics there are three important phases: the modulation, the simulation and the analysis. In order to perform them, it is necessary to use a discretization technique. This design process is naturally recurrent and strongly depends on the selected numerical methodology. The research community continuously seeks the best numerical approach to reproduce *in-silico* the studied biological phenomenon.

Presently, there are many numerical methods available and capable to successfully handle the previously mentioned phases of the bioengineering design.

However, the different numerical approaches described in the literature are fundamentally very dissimilar, which lead to distinct numerical performances.

Nowadays, the finite element method (FEM) is the most popular discretization technique available in the literature [1]. The FEM replicates the physical domain with a geometrical model constructed with finite elements that do not overlap each other and do not present any gap disrupting the model continuum. In Figure 1a is represented the geometric model of a half human head, which was obtained directly from a CAT scan, and in Figure 1b is shown the corresponding 3D element mesh. This discretization technique requires a heavy pre-processing phase to build a balanced element mesh. The FEM performance relies strongly on the model's mesh quality. Additionally, any mesh modification or mesh refinement during the analysis represent an extra (heavy) computational cost, which is a significant drawback in biomechanics.



(a) (b) (c)

Figure 1: (a) Physical domain of a half-brain. (b) Element mesh. (c) Nodal discretization.

Recently, within the computational mechanics scientific community, meshless methods became a focus of interest for solving partial differential equations. Since in meshless methods the rigid concept of element, in meshless methods the solid domain can be discretized with an unstructured cloud of nodes [2-6]. In Figure 1c is represented the nodal discretization of a half human head. Truly meshless methods [5-11] allow to acquire the nodal cloud directly from the CAT scan or the MRI by considering the pixels (or voxels) position and then obtain the nodal connectivity, the integration points and the shape functions using only the nodal spatial information [5]. Using the grey tones of medical images, truly meshless methods are even capable of recognizing distinct biomaterial and then affecting directly to the nodes the corresponding material properties, Figure 1c.

Meshless Methods in Biomechanics

Meshless methods possess several advantages over the FEM, such as the remeshing efficiency, which permits to simulate explicitly fluid flow (the hemodynamics, the swallow, the respiration, etc.) and to deal with the large distortions of soft materials (internal organs, muscles, tendons, skin, etc.). Furthermore, the smoothness and the accuracy of the solution fields (displacements, stresses, strain, etc.) obtained with meshless methods are very useful to predict the remodelling process of biological tissues and the rupture or damage of such biomaterials. Additionally, recent works show that the combination of medical imaging techniques (CAT scan and MRI) with meshless methods is more efficient than using the FEM [12,13].

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The work of Doweidar et al. [14] showed that meshless methods possess clear advantages over the FEM in biomechanical problems dealing with large strains, such as in the simulation of the human lateral collateral ligament and the human knee joint. Additionally, Zhang et al. [15] extended a meshless method to the nonlinear explicit dynamic analysis of the brain tissue response. The results confirmed the accuracy of meshless methods to deal with highly demanding nonlinear hyperelastic biomaterials.

Furthermore, meshless methods are frequently used to simulate hemodynamics. In the literature it is possible to find research works in which meshless methods are used to simulate the motion of a deformable red blood cell in flowing blood plasma [16] or to study the effect of red blood cells on the primary thrombus formation [17].

Another popular computational biomechanical field in which meshless methods proved to possess clear advantages is the *in-silico* prediction of bone tissue remodelling [18]. The first work dealing with bone structures and using meshless methods was published by Liew et al. [19]. Then, other authors applied meshless methods to simulate the bone tissue remodelling process with success [20,21]. Recently, Belinha et al. [22,23] presented a new bone tissue remodelling algorithm relying on the meshless method accuracy. The methodology was capable to obtain numerical solutions very close with the clinical X-ray images of natural bones [22-24], Figure 2a, and natural bones with implants, Figure 2b [25,26]. The methodology was applied also to predict the bone biological behaviour dental biomechanics, with and without the presence of implants [27-30].

The simulation of the non-linear behaviour of biological material was also addressed with meshless methods. In this class of problems, due to its iterative nature, the precision and smoothness of the stress/strain field is very important to achieve stable and robust solutions. Belinha and co-workers have developed non-linear elasto-plastic constitutive models to reproduce the biomechanical behaviour of bone structures [29] and atherosclerotic plaque tissue [31], Figure 2c. These models were combined with meshless methods. The results allow to predict with precision the failure of those biological structures. Another interesting application of meshless methods is the simulation of endolymph, fundamental part of the vestibular system, which plays an important role in vertigo, Figure 2d.

Final Remarks

There are several research works available in the literature showing the numerical efficiency of meshless methods [5]. Based on those manuscripts and in my personal experience, I predict that in the near future meshless methods (or advanced discretization meshless techniques) will substitute traditional numerical techniques, such as the FEM, in the computational biomechanical analysis. There are several biomechanical computational fields waiting to be explored, combining distinct physics behaviours, such as: electrical, magnetic, chemical, thermic, biological and fluid/solid mechanics. Up to now, meshless methods proven to be capable to deliver an accurate solution to all mentioned physics problems. Combining the discretization flexibility of this innovating technique with its accuracy will permit to break the present science frontiers, offering new therapeutic solutions and predicting pathological conditions.

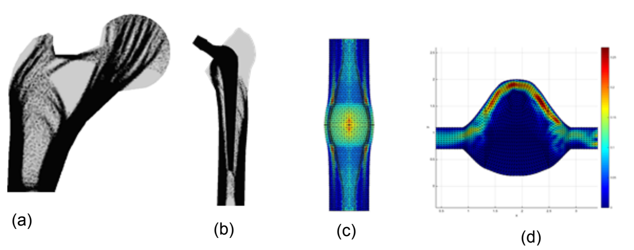

Figure 2: Meshless simulations: (a) Bone remodelling of a femur bone [22]. (b) Bone remodelling due to the presence of a femoral implant [26]. (c) Non-linear analysis of an artery with plaque tissue. (d) Endolymph flow (velocity profile) within the vestibular system.

- For instances, in the near future meshless methods will:
- Assist surgical operations, governing a virtual numerical model that will guide the surgeon in real-time;
- Permit to make hundreds of *in-silico* experiments, testing the effects of new drugs at the micro-scale level (cellular level) and at the macro-scale level (muscles, bones, tendons, etc.)
- Predict the regeneration of soft and hard tissues, allowing to select the most efficient physical or chemical therapy.
- Assess the health or the risk of failure of all biological structures after a complete CAT scan.
- Design patient specific instrumentation or prosthesis much more adapted to the patient physiognomy.

With meshless methods, there is no limits in computational biomechanics. The limit is bounded by our imagination and necessity.

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