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Fast computation of soft tissue deformations in real-time simulation with Hyper-Elastic Mass Links

François Goulette*, Zhuo-Wei Chen

MINES ParisTech, PSL Research University, Centre de Robotique, 60 Bd St Michel 75006 Paris, France

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Abstract

Virtual surgery simulators show a lot of advantages in the world of surgery training, where they allow to improve the quality of surgeons' gesture. One of the current major technical difficulties for the development of surgery simulation is the possibility to perform a real-time computation of soft tissue deformation by considering the accurate modeling of their mechanical properties. However today, few models are available, they are still time consuming and limited in number of elements by algorithm complexity. We present in this paper a new method and framework that we call 'HEML' (*Hyper-Elastic Mass Links*), which is particularly fast. It is derived from the finite element method, can handle visco-hyperelastic and large deformation modeling. Although developed initially for medical applications, the HEML method can be used for any numerical computation of hyperelastic material deformations based on a tetrahedral mesh. A comparison with existing methods shows a much faster speed. A comparison with Mass–Spring methods, that are particularly fast but not realistic, shows that they can be considered as a degenerate case of the HEML framework.

Keywords: Real-time simulation; Hyperelasticity; Soft tissue; HEML

1. Introduction

The simulation of surgical systems which provides visual and haptic feedback using fast computational algorithms has developed rapidly in the last two decades to facilitate the surgical training process [1]. To have a real-time performance, these systems must compute the force of deformed soft tissue at rates of more than 25 Frames Per Second (FPS) for visual display (25 Hz) and provide it to the surgeon through haptic feedback at frequencies of at least 500 Hz [2].

In this work, we focus on the simulation of soft tissue deformation in the context of surgical simulators, which show many potential interests in educational, practical, ethical and economical issues. The real-time computation of soft tissues may have many applications in several medical domain, such as visceral surgery, brain surgery, gynecology and childbirth, and urology. The real-time constraint on such simulators depends on the minimal computation time

* Corresponding author. Tel.: +33 1 40 51 92 35; fax: +33 1 43 26 10 51.
E-mail address: francois.goulette@mines-paristech.fr (F. Goulette).

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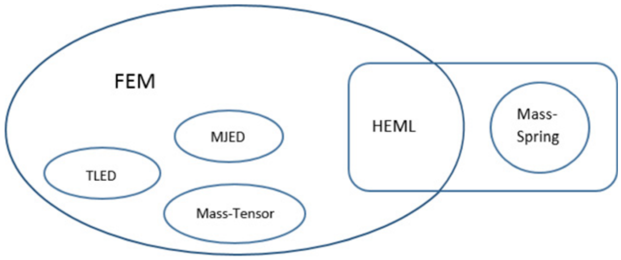

Fig. 1. The HEML method compared to other frameworks.

for discrete differential equations that accurately model the mechanical properties of soft tissues. However, the complexity of soft biological tissues' mechanical behavior makes the simulation in real-time a very challenging task. In gynecology, the vaginal tissue, for instance, shows a nonlinear relationship between stress and strain levels and a visco-hyperelastic behavior [3–5].

Several computational methods and models have been developed to simulate soft tissue deformations in real-time. Early model used linear stress–strain models and constrained themselves to small deformations to calculate a fast solution. In surgery simulation, scientists have mainly focused on the mass–spring models [6–8], due to their simplicity of implementation and their low computation complexity properties. However, they suffer from a lack of realism, which led to further research on extensions of the model. Cotin et al. [9] proposed a so-called mass–tensor model which is based on continuum mechanics and linear elasticity theory; this model has been developed further to handle large deformations and large displacements with the Saint Venant–Kirchhoff constitutive law [10,11]. However, this model is limited to a specific material. The requirement of a nonlinear geometric and material algorithm for soft tissue simulation led to the work of Miller et al. [12], in which they presented a Total Lagrangian Explicit Dynamic (TLED) algorithm based on the Finite Element Method (FEM). This algorithm shows better mathematical performance in each time step. An algorithm allowing real time computation of geometric nonlinearity for virtual surgery simulation by using the point collocation-based method of finite spheres (PCMFS) is proposed by Lim et al. [13], however, a linear stress–strain law is used in this context. Other possible approaches as the Proper Orthogonal Decomposition (POD) and the Proper Generalized Decomposition (PGD) methods can be found in [14,15]. More recently, Marchesseau et al. [16] proposed a Multiplicative Jacobian Energy Decomposition (MJED) method for discretizing hyperelastic materials on linear tetrahedral meshes which leads to faster matrix assembly than the standard FEM. Though this approach is not limited to one specific hyperelastic material but cannot reach the ideal 25 frames per second needed for the real-time simulation. Other studies of deriving discrete computational algorithms from the equations of continuum mechanics based on the FEM which tend to obtain real-time computations can be found in [17–21]. However, the heavy complexity of these methods makes computation time a real challenge.

For these reasons, we tried to find a compromise between biomechanical accuracy and computational efficiency to realize a real-time simulator. We propose to design a fast algorithm to compute the elastic force field for any hyperelastic model, handling large deformations and large displacements. The algorithm is designed under the P1-finite element approximation in homogeneous isotropic cases. Hyperelastic models include the Saint Venant–Kirchhoff constitutive law (used in mass–tensor), and other important hyperelastic constitutive laws such as Neo-Hookean and Mooney–Rivlin. We chose to call this approach *Hyper-Elastic Mass Link* (HEML), for the following reasons: '*Link*', because forces at a given node are given as a sum of forces function of the links (vectors) to all connected neighbors. '*Mass*': as in mass–spring or mass–tensor, masses are affected to the mesh nodes, used in the discrete differential equations. '*Hyper-Elastic*', because the framework presented may be used to design algorithms for computation of any hyperelastic material. We propose a schema to illustrate the position of HEML method compared to other methods (Fig. 1). HEML is an extension of the mass–spring method. The mass–spring method may be seen as a degenerate case of HEML (demonstrated later). In the meantime, HEML is derived from the finite element method which includes many other methods like mass–tensor, TLED, MJED, etc. The novel contribution in the HEML method is that the computations are based on local displacements, as in mass–spring method. This feature presents advantages in terms of numerical robustness for large displacements of objects.

The HEML method is generated with the idea of constructing a physically realistic mechanical model of soft tissue for an educational simulator equipped with a haptic device. In such a case, the model should be as realistic as possible,