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An Interactive Web-based Simulation Tool for Surgical Thread

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***Abstract*—**Interactive web-based computer simulations are needed by the medical community to replicate the experience of surgical procedures as closely and realistically as possible without the need to practice on corpses, animals and/or plastic models. In this paper, we offer a review on current state of the research on simulations of surgical threads, identify future needs and present our proposed plans to meet them. Our goal is to create a physics-based simulator, which will predict the behavior of surgical thread when subjected to conditions commonly encountered during surgery. To that end, we will i) develop three dimensional finite element models based on the Cosserat theory of elasticity ii) test and feedback results with the medical community and iii) develop a web-based user interface to run/command our simulator and visualize the results. The impacts of our research are that i) it will contribute to the development of a new generation of training for medical school students and ii) the simulator will be useful to expert surgeons in developing new, better and less risky procedures.

***Keywords*—**Cosserat rod-theory, FEM simulations, Modeling, Surgical thread.

I. INTRODUCTION

IN the area of medical simulations, the last 15 years have witnessed a series of efforts in several research institutions and training hospitals worldwide but the modeling of tissues and organs [1]-[4] has received more attention than the modeling of surgical instruments [5] and surgical thread [6]. We have initiated a consortium research program between Texas A & M at Qatar (TAMUQ), Cornell University (Ithaca) and Weill Cornell Medical College in Qatar (WCMCQ) with the aim of developing the necessary mathematical and physics-based tools to simulate the deformations of surgical thread during surgical suturing. The anticipated outcome is a user-friendly, low cost, realistic, interactive, web-based simulation software that will be used by medical school students to practice the technique of suture as an alternative to traditional surgical training methods that use plastic or foam models, animals and/or corpse (refer to The National Library of Medicine, History of Medicine website [7]). These methods are known to have limitations such as: i) dead tissues do not exhibit the same response as healthy ones, ii) humans and animals have different physiologies, iii) plastic or foam models lack realism, iv) novice trainees have a higher risk of being exposed to contaminated blood while manipulating sharp instruments, v) experiments on animal raise ethical considerations and vi) students of Muslim or Jewish faith may have religious conflicts in practicing on porcine tissues [8].

Our research has three major components i) we use the dynamic Cosserat rod theory of elasticity to model the deformation of the thread, ii) we test and feedback the results with the local and international medical community and iii) we develop a web-based user interface to run/ command our simulator and visualize the results. With the input from the medical community in our consortium, we will develop a hierarchy of suturing tasks from most simple to most complex (or relevant to useless) and translate them into their corresponding mechanical action. We will also rely on our collaboration with the medical community to provide us with clinical data as well as materials parameters (skin, thread, soft tissue, needles, etc.).

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II. METHODOLOGY

Detailed description of the Cosserat theory [9] can be found in [10, 11]. To summarize, the theory takes into account the couple-stresses (moment/unit area) in addition to the usual stresses (force/unit area). The couple-stresses are the result of allowing gradient of forces between two opposite surfaces of an element which produce a rotation of the element, so in essence the point behaves like a (small) rigid body (Fig. 1). Six degrees of freedom (-three components of displacement and three components of rotation) instead of the typical three displacements have to be recorded. The theory is perfectly suited to describe surgical threads which have one dimension (-the length) much larger than the other (-the diameter) and can be approximated as a one dimensional structure while still exhibit three dimensional characteristics as a result of bending and twisting deformations (Fig. 2). Other fields as diverse as the automotive industry [12], the textile industry [13], marine engineering [14] and more recently bioengineering [15] have become familiar with the usefulness of the Cosserat theory to describe the behavior of long, flexible structures (termed rods).

The primary reasons for choosing the Cosserat rod theory among other theories are that it allows a treatment of dynamical deformations and that it can accommodate material non-linearity (i.e. finite strains) unlike the Kirchhoff-Clebsh theory [16]. In addition, Cosserat theory includes shear strains and rotational inertia as in Timoshenko's (1918) [17] but unlike in the Euler-Bernouilli theory (1795) [18].

The dynamic Cosserat rod model is essential to capture the complex time-dependent boundary conditions encountered in surgery and to model torsional collapse into self-contact observed in knot-tying as well as dynamics transitions that occur in looping [35]. These cannot be captured with static models. A dynamic rod model is also needed for running the simulations in real-time (or close to real time). Regarding non-linearity, a pre-packaged surgical thread is on an average 75 cm long and changes in configurations during suturing can be substantial. Thus geometric non-linearity (i.e. large deformations) are likely to occur even though the material can still exhibit elastic linearity (i.e. small strains at every point). However, there is no experimental evidence to support the small strain assumption, so non-linear stress-strain constitutive equations are necessary. Our collaboration with the surgical community will provide elements for evaluating the presence of large strains if any. The Cosserat rod theory can accommodate non-linear constitutive equations unlike the Kirchhoff-Clebsh (1876) rod theory [11] which employs linear constitutive equations for bending and twisting. We stress that with the assumption of material linearity, the two theories are equivalent in their formulation for both statics and dynamics. For a treatment of non-linear constitutive equations in Cosserat rod theory, consult O'Reilly (1996) [19]. In general, surgical threads do not stretch nor break so the constraints of inextensibilty and/or unshearabilty are applicable. This results in a set of coupled nonlinear partial differential equations (PDE) in space and time which can be solved with appropriate boundary and initial conditions.

The finite difference method (FDM) and the finite element method (FEM) are two competitive approaches that are both fast and accurate and can be used to solve the system of PDE's numerically.

III. Literature review

The literature reviews shows that FEM methods have been used more extensively to handle the complex geometries of tissues and organs [20-21]. On the other hand, Pai (2002) [22] models surgical thread and employs FDM algorithms to solve the system of ODEs resulting from the static Cosserat rod theory. While the results are quite satisfactory, the weakness is in the treatment of the boundary conditions which are modeled as very simple and not likely to represent a surgical scenario. Specifically, the system of ODEs is solved as two-point boundary value problem: one condition is specified at the point where the thread is attached to the needle and the other at the point of contact with the skin. Goyal et al. (2005) [23] have also used a FDM method to solve for the looping of filaments, but we anticipate that FEM will allow for a simpler treatment of external stimuli i.e. a simpler treatment of the boundary conditions. Another concern is that the static case limits the implementation of a user-interaction procedure and thus lowers the potential of achieving a realistic model. In summary, using the dynamic Cosserat theory enables to account for all aspects at one time, and convergence to quasi-static conditions and/or recovery of linear-material behavior can be checked easily. The other reason why we favor the FEM over the FDM method is its usability and commercialization and because a non-uniform and an adaptive meshing can be achieved in a user-friendly manner.

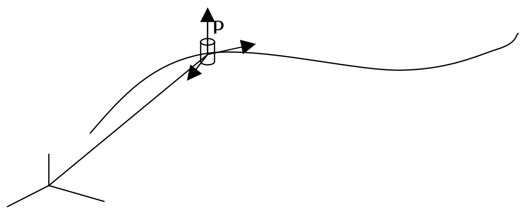

Fig. 1 The Cosserat theory of rod which treats a point as a small rigid body.

Fig. 2 The thread deforming in a three-dimensional space and its idealization as a one-dimensional rod-like structure.

The finite element meshing can be adjusted to emphasize the type of output desired. Meshes can be static (i.e. meshes that do not change), dynamic (i.e. changing meshes) or a combination of both. Examples where static meshes can be used are for closure of tissues while dynamic meshes are more appropriate in case of tissue cutting. On the other hand, the mesh needed to discretize the surgical thread must be very fine and the large number of material parameters at each node becomes cumbersome for real-time interactive simulations. One interesting approach to decrease the computation time is by Berkley et al. (2004) [24]. To solve for the deformation of the thread, a classical finite element analysis is implemented but the output is determined on a "need to know basis". The underlying idea is that only a selected number of variables, not all, need to be computed. For instance, it may not be necessary to calculate the displacement at some interior points, nor may it be worthy to know the stress or strain field at these particular points. In the same spirit, reaction forces need to be only computed when the user touches the thread. Real-time aspect of the simulation is even more important when simulation knot formation since a skilled surgeon will be able to tie five to eight knots per minute.

Mathematically, knots are based on the theory of bifurcation [25] and simulating knots is viewed as particularly difficult. A complete guide of knots used in surgery can be found in [26]. A knot is the result of a complex crossing during which loops are formed. In the process of tying, some part of the thread becomes in contact with other part of the tread (self-collision) or collides with other objects (skin tissues). The model of Phillips et al. (2002) [27] is based on a spline of linear springs but it takes several minutes of computation to tie a simple knot which does not render the algorithm time efficient. Lenoir et al. (2002)[28] have used Lagrange multipliers to take into account the constraints during collision. Wang et al. (2005) [29] use a model for knots tying that is dynamic and that takes into account bending, twisting and contact forces but the model is not based on a continuum approach. An example of the models for knots-tying based on the Cosserat theory is by Brown et al. (2004) [30] who use the algorithm developed by Pai (2002) [22]. The mechanisms of untying knots are even more complex and have been addressed in research articles by Lai et al. (2003) [31], Ladd and Kavraki (2004) [32] and Wakamatsu et al. (2006)[33]. (Also see Look and al.(2001) [34].). Goyal et al. [35] developed a continuum rod model to simulate the non-linear dynamics of filament-like structures with self-contact and intertwining.

Another approach that has been taken for real-time simulation of one-dimensional deformable bodies is based on spring-mass chains or in the same spirit on rigid cylinder-segments connected by balls joints [Hergenroether et al. (2000) [36]). These methods are simple in the sense that they are based on polynomial interpolation but they do not use a continuum theory and this limits their potential to capture physical realism. Furthermore, these methods have been employed for the most part to model bending deformations except for Grégoire et al. (2006) [12] who implement both bending and twisting deformations in the spring-mass system and use a Cosserat-based model. Grégoire et al. [12] work follows experimental results on thin twisted rods by Goss et al. (2005) [37] (Refer to the experimental work on bones by Lakes et al. [38] who has details on the deviation of experimental and (classical) analytical results). The work of Goss et al. [37] refers to the specific problems of loop formations and plies encountered in marine cables or in the textile industry.

Particular to the suturing task is the fact that as the thread is inserted into the patient skin, the constraint point moves to a different location on the curve. Lenoir et al. (2004) [2004] have proposed new types of constraints for the thread but the model used is a spline model which also relies on polynomial interpolation. Also note that the models implemented by Pai (2002) [22] and Nocent et al. (2001) [39] are static.

IV. CONCLUSIONS

As seen from the literature review on surgical simulations, one aspect of the problem or another is emphasized but not all. This points to the need to research an alternative method of solution suited for modeling the deformations of surgical thread and capable of replicating the complexity of suturing scenarios.

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