Title:
Geometrical Modelling Effects on FEA of Colorectal Surgery

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Introduction:
Nowadays, Finite Element Analysis (FEA) has highly increased its applications in medical field, for designing and improving prosthesis, orthosis, implants, preoperative plans and for simulations of surgery [7].

In recent years, Minimally Invasive Surgery (MIS) has increased its applications, either using surgical assistant robot or following traditional (manual) way. Nevertheless, in parallel to the increase of application fields, new issues also arise. In particular, instruments must be inserted through a trocar to access the abdominal cavity, without capability of direct manipulation of tissues so that a loss of sensitivity occurs. This loss is caused by the absence of a direct force-feedback, resulting from the interaction between surgical instruments and soft tissues. More in detail, the lack of force-feedback is a problem present in several areas that are strongly linked to engineering, for instance: Preoperative planning, surgical simulator, teleoperation, and surgical robot assistant. In this field, FEA may take an important role, helping us to understand the distribution of stress-strain and the contact force in devices as well as in tissues. In addition, it can help to develop or optimise related surgical devices [9]. To get useful results using FEA, it is mandatory to take account of: (a) the mechanical behaviour of tissues, (b) the geometrical model and boundary conditions of the anatomical district [6]. The digitalization of organs obtained by DICOM, using image segmentation, helps to approach a simulation capable of reproducing the effects of the real case, for example, non-linear geometrical effects in curved surfaces. Nevertheless, it is necessary to work with a simplified geometry in cases like experimental validation of material characterization, or fitting of load-deformation formulas useful to evaluate the stress-strain behaviour when a variation in specific parameters occurs (e.g. effects of changes in tissue thickness, or in the orientation of the surgical instrument that interacts with the tissue).

After the investigation about the proper material and geometrical models suitable for the analysis, as it was discussed in [6]. In this work, we are going to investigate the effects of geometrical and thickness changes of the organ on strain-stress distributions achieved by FEA, in order to understand the present effects during the interaction between surgical instruments and soft tissues.

In the next sections, after a brief resume of the state of the art concerning digitalization of geometry, and FEA on soft tissues like colorectal tissue, we present our specific case-study. The goal of the FEA sensitivity analysis we carried out together with its results and a discussion of their role in the study of the pre-operative plan.

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Setting up the FEA:

Generally, to carry out a FEA analysis of a specific anatomic district, large displacement and hyper-elasticity of the tissue have to be considered, together with a proper understanding of the constraints of the district. The adoption of realistic shape may represent a possible strategy for taking into account shape complexity, like curvatures, length/thickness ratio, and their related geometric non linearity. This can be achieved through digitalization, while material non-linearity is included through a proper material model.

Digitalization of geometry

Medicine is a constantly expanding field that applies several imaging and acquisition modalities (MRI, Computed Tomography (CT), Positron Emission Tomography (PET), X-RAY, and Ultrasound). In all of this case, final digitalization asks for image segmentation. It is a technique that deals with separating input data into meaningful objects with their respective borderlines. It is focused on increasing the quality of data in order to "understand the images" and diminish the misclassified pixels during the process [4]. According to [10], a precise and automatic segmentation of colon from images is a challenging problem of many clinical applications in colonography, including computer-aided detection of colon polyps, 3D virtual flythrough of the colon, and prone/supine registration, due to the presence of added noise, artefacts, limitations, and unclear edges. Automatic segmentation step provides computational models diminishing the time-consumption and laborious manual process. The manual process usually demands a lot of time to identify and draw borderlines around tissues present in a single tomographic image, because of the large number (300–600) of images that are required to span the head-to-foot anatomy of an individual through steps of about 3 mm. For this reason, in the recent past, semi-automatic and automatic segmentation have been extensively subject of research efforts.

Mechanical properties

Mechanical properties should be measured "in vivo", but this requirement demands a non-destructive method of material characterization. Unfortunately, the existing probes provide qualitative rather than quantitative information, since each tissue is connected by fasciae [9]. For this reason, most of the mechanical properties are measured "ex vivo" using destructive in vitro mechanical tests. Even today, it is difficult to characterise the mechanical behaviour of tissues. However, many laboratory tests [3],[8],[11], have been performed to determine the mechanical properties of soft tissues both in people and in animals. Generally speaking, soft tissues have a hyper-elastic behaviour.

Several FEA works have used different models of mechanical behaviour (linear elastic or hyper-elastic), trying to reproduce the real behaviour of soft tissues. The most suitable hyper-elastic models to reproduce soft tissue behaviour are: Mooney Rivlin model and Yeoh model, for small and large deformations respectively [6]. They are phenomenological material models used in FEA [12] to analyse large deformations of materials, such as rubber. Hyper-elastic models are described by the stored energy in the unit of reference volume of the material, in terms of strain. The Mooney Rivlin model is described through the first and second invariants of the Green deformation tensor while the YEOH model is described only through the first invariants of the Green deformation tensor. Despite those results, nowadays, the model to be used depends on the goal of the simulation. In fact, in case of simulations oriented to train new surgeons through virtual reality, a decrease of the computational cost for simulating in real time may ask for a linear elastic model. The Hyper-elastic models [2],[7],[9], are necessary when major accuracy is requested in the stress-strain evaluation, like in preoperative planning (tissue detachment, implant analysis, etc.) or force-feedback evaluation.

Case study and modelling:

The case study object of this paper is oriented to investigate the interaction between a surgical clamp and part of the colorectal tissue to analyse stress, strain and contact force when a variation of the tissue thickness occurs. It has been analysed on two different geometrical models of the surfaces, a simplified model and a digitalized model, to quantify the effect of the shape complexity.

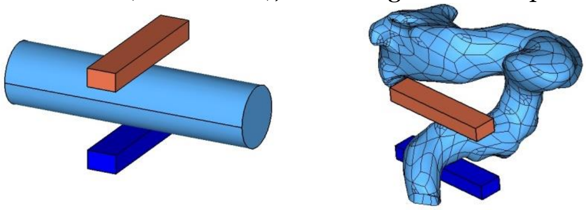
Geometrical modelling of the surfaces

Geometrical models studied in this paper represent a part of the entire colon, placed in the zone between the sigmoid area and the rectum area. We consider two different geometrical models:

- Cylindrical Surface (CS). It represents a simplified, symmetric and uniform geometry. It is an idealization of the colorectal tissue shape, modelled with an outer diameter of 25mm and a length of 100 mm, Fig. 1(a).

- MRI Surface (MRI). It represents a geometrical model obtained from the segmentation of MRI images, which does not take into account the circular folds, Fig. 1(b). MRI images were acquired by means a 1.5 T scanner (Sonata Siemens, Erlangen, Germany), with a phased-array body surface coil.

Analysing regular surfaces and shapes equivalent to the real organs can be useful in order to avoid errors caused by the natural asymmetry and irregularity or by a more difficult segmentation processes [15]. In our case, the use of a regular equivalent cylindrical surface (CS case) is aimed to estimate differences with the relative freeform surface, thus evaluating the influence of shape irregularity. The cylindrical surface is also convenient for analysis set-up, due also to the possibility of obtaining results in shorter time respect to the "real" geometry. In cases of MRI model, a semi-automatic segmentation was performed by means of Slicer3D (Version 4.5), according to DICOM procedures.



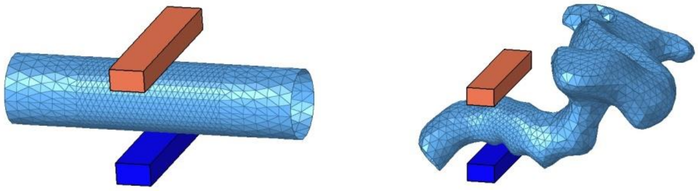
(a) (b)

Fig. 1: Geometrical models: (a) Circular Surface (CS), and (b) MRI Surface (MRI).

After segmentation, it was necessary to perform a post-processing of the geometrical model achieved by MRI, in order to check and optimise it. Then, the model was imported into CATIA. The optimisation process started from the STL tessellation of the 3D model adopting Reverse Engineering techniques for free-form modelling. Additionally, outliers' recognition, their deletion and hole recovery were necessary to model the colon tissues. Every geometrical model corresponded to a position prior to start the interaction with the surgical clamp, which, in Fig. 1, are represented through the blue and brown volumes. It is important to clarify that the surgical clamp has been assumed as a rigid body.

FEA set-up

The models were discretised using shell elements, with constant thickness. The surgical clamp was discretized by hexahedral elements. In this case, the fascia between organs was not considered. In a previous work [6], it is possible to observe a result convergence from a mesh length of 2mm. Therefore, in order to decrease the computational cost, a discretisation using a 2mm mesh-length has been carried out in the area subjected to the contact, larger up to 4 mm, outside, Fig. 2. For the mechanical behaviour, we selected the Mooney-Rivlin hyper-elastic model assigning to C_{10} and C_{01} the values of 0.083MPa and 0.0565MPa respectively [6],[13].



(a) (b)

Fig. 2: Geometrical models: (a) Discretized CS Model, and (b) Discretized MRI Model.

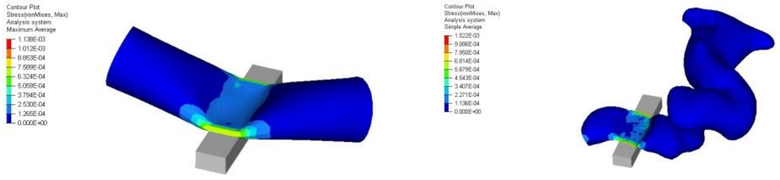
The two geometrical models were considered empty, Fig. 2, because patients generally have to comply with a pre-operative plan for emptying digestive system before the surgical operation.

Boundary conditions similar to real behaviour, are difficult to be defined. Thus, in order to recreate constraints similar to the tissue conditions while performing colorectal surgery, simplification of the boundary conditions has been performed at the ends of the geometries, releasing rotations in all axes, and displacement along colon axial direction. The recommended load for manipulating soft tissues without tearing is equal to 8gr/mm^2 [1]. This value represents the pressure exerted on the tissue by the contact with the surgical clamp during its motion.

Since one of the goals of the paper is the understanding of effects on stress and strain results related to shell thickness changes, we have considered thickness variations from 0.8mm to 2mm, as founded in literature [5],[8],[9],[11]. Every FEA has been carried out in Hyperworks, using the RADIOSS solver to analyse tissue deformation during surgical clamp motion. To conclude the FEA set-up, the contact condition was provided by simulating progressive contacts during motion, respectively between colon tissue and surgical clamp parts, and then, self-contact in colon tissues when the simulation leads to a contact between them, assuming, the surgical clamp as rigid.

Results:

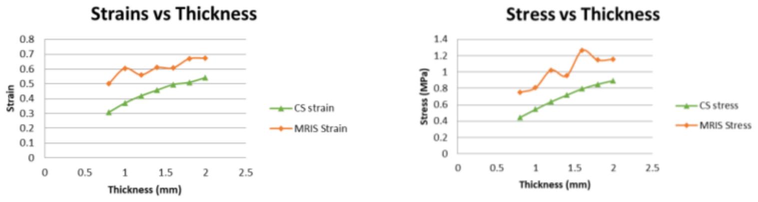
In this section, we analyse the influence of thickness. Results are discussed according to the achieved stress-strain distributions, as shown preliminarily in Fig. 3 and Fig. 4.



(a) (b)

Fig. 3: Stress Contour-Map: (a) Stress Contour-Map in the CS Geometrical model, and (b) Stress Contour-Map in the MRI Geometrical model.

FEA in Cylindrical Surface (CS) may help to understand the distribution of stress-strain without taking into account particular geometrical irregularities. Some works about FEA of soft tissues [9], recommend to study a simplified geometry, as uniform and symmetrical as possible, in order to understand the phenomena in a general way, and then, use this approach to extrapolate the results in the real patient case. Both geometrical models have the same load conditions, as described in the previous section.



(a) (b)

Fig. 4: Stress-Stain Curves: (a) Strain Vs Thickness, and (b) Stress Vs Thickness.

Fig. 4 shows some differences in stress and strain behaviour between the two geometrical models CS and MRI. It is possible to observe, in the CS model, a regular variation of stress and strain as a function of the thickness increment. On the other hand, in the MRI Model, the present variation is produced in an irregular way, probably due to the geometrical irregularity caused by the presence of folds. Generally, it can be said that when non-linear elastic behaviour is considered, large displacements can be seen before a stress gradient occurs, particularly when the shape is irregular.

Conclusions:

The two evaluated models help to understand the geometrical model influence in the stress-strain results. The variation present in the stress behaviour as a function of thickness helps to understand how important is to consider the thickness variation, mainly when the purpose is to simulate a damaged part of colon, which has an irregular distribution of thickness due to disease or inflammation. Because of this, next developments should be the set of different area of thickness inside a single case, also considering circular folds or polyps. The resulting differences may represent a variation in the force-feedback, useful for calculation of training devices based on haptic sensors, or surgical tool closure force.

The carried-out analyses depict that, a non-linear finite element analysis is still a challenge to perform a real-time Mooney-Rivlin (or hyperelastic in general) model that can be used by operators, also with simplified geometries. Waiting for more powerful and commercial solving capability, one of the possible solutions to this issue can be the adoption of fitting models that can bypass the FEA. In fact, from data obtained in terms of relation between thickness, pressure and stress (or strain or contact force), some analytic models can be developed in order to be used as black box instead of high time-consuming FEA analysis. This can be one of the future targets.

The future works will evaluate the force feedback, in order to manage reactions, that can be seen as input for the cinematic chain when the force has to be transduced and amplified to the haptic devices when the surgeons work with surgical robots.

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