A light sterilizable pipette device for the in vivo estimation of human soft tissues constitutive laws

P. Schiavone, T. Boudou, E. Promayon, P. Perrier and Y. Payan

***Abstract*— This paper introduces a new light device for the in vivo estimation of human soft tissues constitutive laws. It consists of an aspiration pipette able to meet the very severe sterilization and handling issues imposed during surgery. The simplicity of the device, free of any electronic circuitry, allows using it as an ancillary instrument. The deformation of the aspired tissue is imaged via a mirror using an external camera. The paper describes the experimental setup as well as the protocol that should be used during surgery. First feasibility measurements are shown for human tongue and forearm skin.**

Keywords – soft tissues modeling; constitutive law estimation; tongue; forearm skin; suction / aspiration method.

I. Introduction

COMPUTER assisted surgery (CAS) is a research domain aiming at assisting surgeons to improve diagnosis, therapeutic gestures and follow-up implementing rational and quantitative approaches [1]. The ultimate goal is to increase safety and accuracy in order to allow more minimally invasive surgery and consequently patient comfort. The CAS community is quite recent in the context of Computer Science since the pioneer works date from the 80's, and orthopedics was probably the first clinical domain addressed. The reason for this is probably that orthopedics mainly focuses on bones which are easily modelled into CAS application as a) they can be assumed to be rigid, i.e. with a fixed 3D geometry; b) they are strongly identifiable onto Computer Tomography exams; and c) their relative position during surgery is easily followed using optically tracked screwed-in rigid bodies. Biomechanicians were first asked to work onto CAS applications when orthopedic surgeons were looking for tools and methods able to predict risks of fractures. In that case, bony structures could not be considered as rigid but on the contrary had to be modeled as a deformable continuum with a non-homogeneous distribution of the internal stresses. More recently, arguing that most of the human body is made of soft tissues that can move as well as deform during surgical gestures, biomechanicians have worked even more closely with the CAS community. Indeed, sophisticated biomechanical models had to be developed to try to predict the way soft tissues are supposed to deform during surgery.

In the remaining, we consider a biomechanical CAS, using the Finite Element Method [2]. Building a patient specific biomechanical model is usually a delicate and time-consuming task. From imaging exams such as Computed Tomography or Magnetic Resonance, data can be collected through image segmentation, providing for example the external contour of an organ as well as intrinsic sub-structures. From these geometrical data, 3D meshes are built and used to discretize the mechanical formulation that describes the deformation of the soft tissues. Such a numerical simulation requires the definition (1) of modeling hypotheses, (2) of a material constitutive law and (3) of boundary conditions. While definition (3) mainly depends on the anatomical configuration and the surgical planning, definitions (1) and (2) must be a priori chosen by the biomechanicians according to their knowledge of the soft tissues. These choices are crucial as they have a strong impact to the predictions of the simulations. While most models assume an elastic behavior of the human soft tissues, two assumptions have to be made: one concerning the maximal level of strain that can be observed inside the body and the other concerning the material constitutive law. In the first assumption, if the strain level is less than 10% (i.e. if for any elementary vector inside the body its length does not vary by a factor that is superior to 0.1), the “small strain” hypothesis can be made, which assumes a linear geometrical resolution of the partial differential equations that govern the mechanical formulation. Otherwise, a “large strain” framework is necessary, which means a more complex resolution scheme of the numerical system. The second assumption concerns the material constitutive law, i.e. the “mechanical” relationship between strain and stress. If this relation can be assumed to be linear, an elasticity tensor is computed to link the stress and strain tensors. On the contrary, if a linear law does not account properly for the mechanical behavior of the tissues, a non-linear law can be chosen to account for the so-called “hyperelastic” behavior of soft tissues (see [3] for more details).

While a large amount of papers published in the literature have addressed the elaboration of 3D biomechanical models with focuses on 3D geometries, volume meshing, modeling hypotheses and numerical simulations, few papers have addressed the huge difficulty encountered when a patient-specific constitutive law has to be made. Moreover, this choice is even more complicated when it can only be done during surgery, i.e. when access to the organ is not possible pre-operatively (e.g. hepatic or neuro-surgeries).

This paper addresses this problem by introducing a new light pipette device based on the concept of tissue aspiration. Part II describes this device, while parts III shows the feasibility of measurements on two types of tissues (human tongue and forearm skin). Part III shows the practicability of the estimation of the constitutive laws in both tissues.

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II. PIPETTE ASPIRATION DEVICE

A. State of the art

Recent years showed the publications of studies dealing with the in vitro or in vivo soft tissues biomechanical characterization [4]-[8]. In vivo characterization is challenging since it is now established that the mechanical behavior of soft tissues can differ significantly between in-vivo and ex-vivo conditions [9]-[10]. Among others reasons, this can be due to the vascularization of the tissues..

The various excitation schemes range from suction to ultrasound with a variety of devices in each category. Aspiration/suction is probably the most widely used technique. Starting from the pioneering work by Grahame [11], several authors proposed suction cups differing mostly in the way the aspired height is measured (optically [12] or using ultrasound [13]) or their ability to accurately measure the dynamic response. Other excitation methods include indentation [14]-[16] using hand held or robotic indenter and torsion [17] or ballistometry [18] which consists in striking the tissue with a known mass and a known force. Ultrasound measurement [19]-[20] is another method linked with the emerging field of elastography. An alternative way of compressing the tissue was proposed by Brown et al. under the form of an endoscopic grasper [21].

A very serious issue hardly mentioned in the papers dealing with tissue characterization is sterilization. Indeed sterilization is carried out using very unfriendly processes such as steam under pressure, heat or chemicals under a liquid, gaseous or plasma form. The fragile parts of the measurement device can be easily damaged under these conditions, especially electronic parts such as sensors, actuators or circuitry which are very poorly resistant to such severe environments. Another issue is to take into account the relative displacement of in one hand the tissues and in the other hand the characterization device. This phenomenon can for example be observed during in vivo liver measurement: because of patient breathing the device must stay in contact at all time. This can highly complicate the experimental setup.

B. Device

We decided to base our device on the aspiration method, because of its simplicity and robustness. Moreover, contrary to indentation techniques, the device is permanently in contact with the tissues which guaranties that the measurements will not be perturbed by any displacement of the tissues in relation with the device.

In order to avoid any electronic part, the device was designed using a transparent suction cup, or pipette, coupled to a 45° mirror that allows imaging the deformed tissue using an external camera. A schematic drawing is given in Figure 1. The cup is terminated by a Luer lock. A single-use Luer lock tube is plugged onto the pipette connector. On its other side, the tube is connected to a manometer and a vacuum pump via a T shape Luer-lock connector equipped with taps. In our experiment, a simple syringe acts as a vacuum generator. Depending on the stiffness of the tissue to be characterized, the vacuum depression can vary between around 10mbars to around 120 mbars.

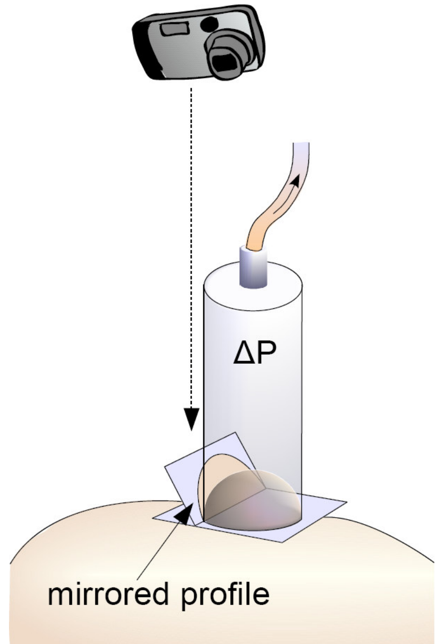

Figure 1: A small depression is generated inside a transparent pipette in contact with the material in test. The bump induced by the depression is imaged from the top using a standard digital camera in macro mode thanks to a 45° mirror

Figure 2: Image captured by the camera. The bump height is measured thanks to a calibration grid.

III. MEASUREMENTS

During the measurements, the suction cup is held in place by the clinician who is in sterile conditions. A second operator takes the picture of the aspired tissue while a third one is in charge of the aspiration and manometer under the instructions of the clinician.

The pipette device was used for two kind of soft tissues, namely the forearm skin and the tongue.

Figure 3 plots the forearm skin bumps measured with different levels of depression inside the suction cup.

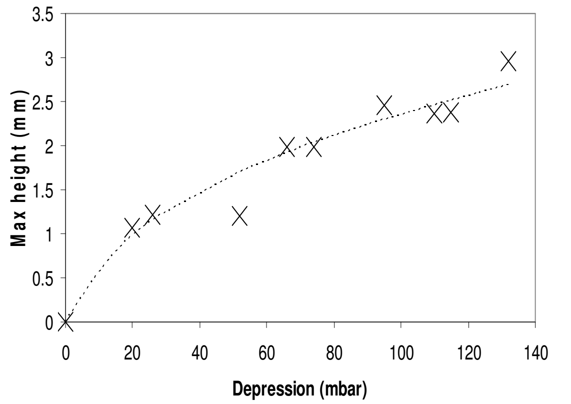

Figure 3: Skin bump height as a function of the depression inside the suction cup (each cross corresponds to a measurement). The dotted line plots the results simulated with the estimated constitutive law

Figure 4 plots the same kind of measurements obtained on the tongue tissues of a volunteer. In addition to characterizing the "passive" tongue stiffness, we asked the subject to try to stiffen his tongue in order to evaluate the stiffness differences between "passive" (measurements 1 & 2) and "active" tissues (measurement 3).

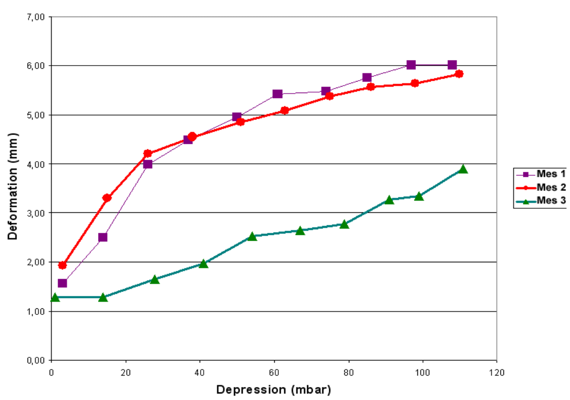

Figure 4: Tongue bump height as a function of the depression inside the suction cup: one subject in different conditions. The two upper curves are passive conditions, the lower curve is for an active condition (the subject was asked to activate its tongue muscles).

IV. Estimation of the Constitutive Laws

The aspiration experiment itself does not provide the constitutive law of the material. Indeed, the measurements only give the relationship between the local depression applied to the external surface of the body and the resulting displacement. To get the constitutive law from this aspiration experiment, i.e. the global relationship that can be assumed between strain and stress inside the body, an optimization algorithm based on an "analysis by synthesis" strategy was elaborated. It consisted in a four step loop : (1) assume a given constitutive law with a given set of parameters, (2) build and simulate a Finite Element Analysis (FEA) of the aspiration experiment, (3) compare the simulations provided by this FEA with the aspiration measurements, (4) from this comparison deduce better values of the constitutive law parameters in order to improve the FEA simulation/measurement fit. This loop is continued until the comparison carried out in (3) gives satisfactory results.

In our FEA, the tissue sample is represented by a thick circular slice of radius *a* and thickness *h*. The pipette is described by a rigid hollow cylinder of internal and external radii R and R_e respectively. Taking advantage of the axi-symmetric geometry of the problem, we reduced its mechanical study to a two-dimensional structural analysis (figure 5).

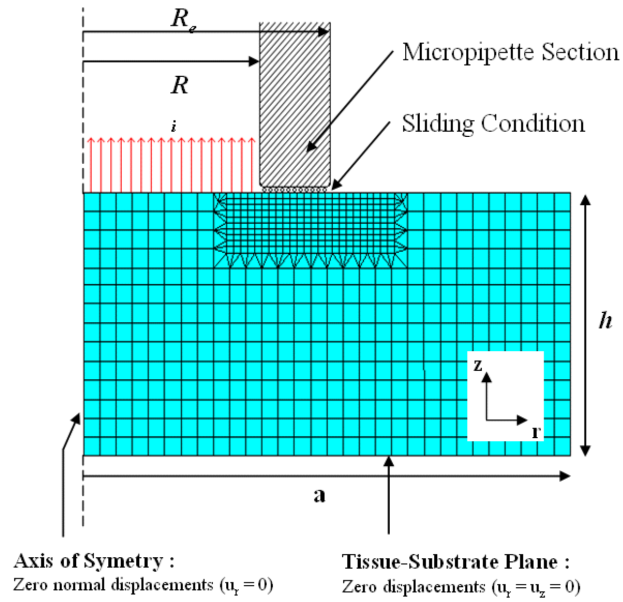

Figure 5: Finite Element Analysis of the aspiration experiment

According to Fung [22], a hyperelastic material seems to be well adapted for human soft tissues. A material is said to be hyperelastic if it is possible to find a function *W*, called the *strain-energy function*, which derivative with respect to the strain tensor ε equals the stress tensor σ. Among the various strain-energy functions which can describe such a mechanical response [3], we focused on the incompressible two parameter Yeoh strain-energy function *W*, already used to characterize tissues and living cells [23]-[24]. This strain-energy function is given by the following analytical expression [25]:

$$W = a_{10}(I_1 - 3) + a_{30}(I_1 - 3)^3 \qquad (1)$$

where a_{10} and a_{30} are the two material constants (having a unit of stress), while I_1 is the first invariant of the right Cauchy-Green strain tensor C ($I_1 = Trace(C)$). From this strain-energy *W*, it is therefore possible to compute the stress/strain relationship, i.e. the material constitutive law, and to simulate the corresponding depression/bump height curve (see figure 3 for such comparison in the case of forearm skin tissues).

Table 1 lists the a_{10} and a_{30} values obtained by our optimization process.

	a_{10} (Pa)	a_{30} (Pa)
Forearm skin	2000	400 000
Tongue$_{_Mes1}$	698	3049
Tongue$_{_Mes2}$	615	6854
Tongue$_{_Mes3}$	4439	7011

Table 1: Coefficients of the strain energy function after optimization

V. CONCLUSION

The aspiration technique appears to be a measurement method suited for an intra-operative use. Coupled with an optimization scheme based on FEM, an optimization procedure allows determining non-linear materials models. The optimization process is currently too long to be done intra-operatively and must be improved significantly to reach "interactive time" computation. Such constraints will be necessary in the context of tongue modeling for computer aided glossectomy surgeries [26]. As a perspective, first trials are currently carried out in order to intra-operatively measure patient specific brain tissues stiffness (see [27] for a description of our brain shift compensation project).

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