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Towards laparoscopic tissue aspiration

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ABSTRACT

The soft tissue aspiration experiment has been further developed for application during laparoscopic surgery. The new setup has been tested and validated under lab-conditions and came then to in vivo operation. It is to our knowledge the first time ever a mechanical experiment has been performed under laparoscopic conditions on the human, which enables determining corresponding constitutive model equations. As most important results, the feasibility of laparoscopic tissue aspiration has been demonstrated and, based on an ad hoc parameter for the tissue stiffness, the liver and the stomach gave significantly different responses. Furthermore, the determined constitutive behavior for one healthy human liver was in line with results obtained from tissue aspiration during open surgery. Eventually, laparoscopic tissue aspiration might qualify as minimally invasive testing method for tactile feedback systems. The presented results are preliminary and more research is required.

1. Introduction and motivation

Studying the nonlinear and time-dependent mechanical properties of human organs and tissues is fundamental for modern biomedical engineering and research. It is well known that soft biological tissues exhibit altered mechanical properties when excised from the living organism (e.g. Gefen and Margulies, 2004; Kerdok et al., 2006), therefore their mechanical properties must be acquired as close as possible to their physiological conditions, i.e. ideally *in situ* and *in vivo*. As an alterative, part of the physiological conditions can be simulated in the lab, whereby issues such as sample storage and tissue decomposition are introduced.

In this light, during the last decade several invasive methods and instrumentations have been presented for *in vivo* measurement of the mechanical properties of soft tissues; most of the presented instrumentation came to actual *in vivo* application on animals (e.g. Ottensmeyer, 2001; Brouwer et al., 2001; Kalanovic et al., 2003; Brown et al., 2003; Samur et al., 2007; Rosen et al., 2008) and a few on the human (e.g. Carter et al., 2001; Mazza et al., 2007; Nava et al., 2008; Schiavone et al., 2009, 2010). In order to perform intraoperative measurements on the live subject, the procedure must be absolutely non-traumatic, operate under sterile conditions and comply with the time- and space-limitations in the operating room, while at the same time allowing to maintain the appropriate control over the boundary and initial conditions and the course of the test itself. Alternatively, non-invasive methods have been presented also: in contrast to invasive methods, non-invasive methods rely on ultrasonography and magnetic resonance imaging to image tissue properties, usually referred to as elastography (Ophir et al., 1991; Sandrin et al., 2003; Rouvière et al., 2006; Greenleaf and Chen, 2007; Klatt et al., 2007, 2010; Mariappan et al., 2010). In order to excite internal organs, dynamic elastography methods rely on small strain wave propagation through the tissues and thus their mechanical behavior is typically observed for small strains only. Tissues within proximity of the skin can as well be characterized at larger strains by indentation of the skin and the underlying tissues against a bony substrate (e. g. Silver-Thorn, 1999; Zheng and Mak, 1996; Zheng et al., 2000).

With regard to laparoscopic measurements, Rosen et al. (1999) and Ottensmeyer (2001, 2002), and more recently Samur et al. (2005), proposed instrumentation which all came to application on the swine, in vivo or directly following euthanization (Brown et al., 2003; Samur et al., 2007; Rosen et al., 2008). Rosen et al. (1999) and Brown et al. (2002) developed a motorized endoscopic grasper with which a compressive force of 26 N (equivalent to 470 kPa nominal stress) could be induced into the tissue. The endoscopic grasper mainly consisted of a Babcock grasper and a force sensor mounted to its drive mechanism on the handle, and it could be attached to various laparoscopic instruments for accessing the

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insufflated abdomen for what it required a 10 mm trocar.[2] At full opening, the two grasping surfaces were 26 mm apart. More recently Fakhry et al. (2009) applied a measurement system using surgical forceps for real time evaluation of tissue compliance during endoscopic surgery on humans. This represents the first mechanical experiments performed under laparoscopic conditions on the human. Ottensmeyer (2002) presented an indentation probe named 'TeMPeST I-D' for the characterization of the tissues in their linear domain: it had a small range of motion of 500 μm at a high bandwidth of actuation up to 200 Hz, was equipped with a circular indenter tip of 5 mm diameter, could exert forces up to 300 mN, and was designed for application during laparoscopic surgery through a 12 mm trocar. Unknown boundary conditions is one of the major issues with in vivo indentation: knowledge not only of the time variable contact condition and the indentation-depth (near-field) are required, but similarly the organ geometry and its embedding in the abdomen (far-field) should be considered when performing an inverse analysis. This problem adds to the uncertainty associated with relative movements between indenter reference hold point and organs surface. Kalanovic et al. (2003) developped a rotary shear probe called 'ROSA-2', which was built to excite the tissue over a 6 mm diameter contact disc with rotation angles up to 15° relative to a concentric ring fixed to the tissue at a maximum of 20 Hz; no-slip contact was maintained using a densely packed array of fine needles or a tissue adhesive, and a calibrated galvanometer was used to exert defined torques on the disc while the disc oscillations were measured optically. Samur et al. (2005) developed a robotic indenter for measurements in the abdominal region. Their setup is operating table mount and consists of a robotic manipulator with position tracking and attached to it the indentation probe as a long solid cylindrical shaft with 4 mm diameter with a spherical tip, and a force–torque transducer installed between the indentation probe and the robotic manipulator. The probe can be used to apply static and dynamic indentations of up to 10 mm while recording force–displacement data.

Originally, we proposed the aspiration experiment for testing of abdominal organs during open surgery. To date it was used to perform 271 measurements on the liver of 49 patients during three clinical studies (Mazza et al., 2007; Nava et al., 2008; Hollenstein, 2011). As well variants of it are currently applied during clinical studies on the uterine cervix and the vaginal wall (Mazza et al., 2006; Bauer et al., 2009). With the trend towards minimally invasive surgery, it was indicated to adopt and further develop the aspiration setup for use during laparoscopy. In contrast to open surgery, minimally invasive approaches cope with small incisions or punctures, accessing the internal body typically through a trocar, which of course is more conservative in medical terms and leads to less tissue damage than any invasive method. On the one hand, the development of a laparoscopic aspiration probe will facilitate access to a larger number and also a wider spectrum of intraoperative measurements under conditions even closer to the real physiological situation. And on the other hand, the ability to measure the mechanical properties of soft tissues during laparoscopic surgery potentially enables to provide haptic feedback to the surgeon. In fact, one of the few disadvantages associated with minimally invasive surgery is the loss of tactile sensation and the possibility for the surgeon to directly palpate the organs. Palpation is a standard and important ad hoc technique for surgeons to assess the texture of a tissue, to locate the spatial coordinates of particular anatomical landmarks, and assess tenderness through tissue deformation. Any intraoperative force feedback system requires accurate and of course non-traumatic measurement of the mechanical response of the tissues to a particular excitation. This difficulty was already pointed out by several authors, amongst others Scilingo et al. (1997), Longnion et al. (2001), De et al. (2007), and Rosen et al. (2008). Tissue aspiration could provide the necessary means to furnish a tactile perception system for laparoscopic surgery with information on the mechanical response of soft tissues.

With these motivations in mind, the original aspiration control setup was completely revised and a new measuring probe was developed suitable for laparoscopic application.

In this paper the novel instrumentation with particular emphasis on the design of the measuring probe is described and first data acquired during laparoscopy on the human liver and stomach are presented. The liver data are compared with the previous results obtained during open surgery. To the best of our knowledge, this is the first time a mechanical test was realized on the human subject during laparoscopy. Validation of the laparoscopic instrumentation on synthetic specimens is provided in Section 4; proof-of-concept and proof of operational safety was given earlier in Bugnard (2007).

2. Technical equipment and experiment realization

The laparoscopic aspiration experiment is based on the same measuring principle, known as *pipette aspiration* (Aoki et al., 1997), as the previous setups developed for application during open abdominal surgery and gynecological inspection (Mazza et al., 2006, 2007; Nava et al., 2008). Basically, the measuring probe holds an opening in which the pressure can be controlled and an optical system is used to measure the deformations of the aspirated tissue. The experiment is performed by (i) establishing thorough contact between the probe head and the tissue, and (ii) creating a prescribed time-variable vacuum in the aspiration tube such that the tissue is sucked in through the aspiration hole. The time histories of applied negative pressure and resulting tissue deformation profiles are then used to determine parameters describing the mechanical behavior of the tissue. Constitutive model parameters can be determined using iterative numerical simulation of the measurement procedure, i.e. solving the so called "inverse problem".

The inner diameter of the access trocar for the measuring probe is a critical dimension as it limits the diameter of the aspiration hole and therewith determines the dimensions of the tested tissue volume. We decided to use a 12 mm instead of the standard 10 mm optical trocar, which does not implicate disadvantages for the patient; it is intended to position this trocar at the navel. Thus with regard to the technical equipment, the probe had to be designed to fit through a 12 mm trocar and allow positioning of the probe head relative to the organ to be tested. Relative positioning of the probe head is realized by tip-articulation, which allows the surgeon to swivel out the probe head once in the abdomen and position it properly by means of a joystick at the handle of the probe (Fig. 3b). Positioning of the probe head can be monitored and verified by a videoscope brought to the measuring site via a second optical port placed for example at the upper abdomen (Fig. 5a). Moreover, the aspiration pressure must be measured relative to the abdominal pressure. During laparoscopic surgery, a pneumoperitoneum[3] is created by insufflating the abdomen to facilitate visualization and surgical intervention; the insufflation pressure is normally in the order of 15–20 mbar.

Technical details for the measuring probe and the control setup are summarized in Table 1, whereas the performance data are given in Table 2.

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[2] A trocar is a sharp-pointed surgical instrument fitted with a cannula to insert the cannula into a body cavity allowing insertion of cameras and instruments as for example required during laparoscopy.

[3] A pneumoperitoneum is produced at typically 15–20 mbar whereby around 5.5 l CO_2 or N_2O are introduced into the abdominal cavity.