Understanding Perceptual Boundaries in Laparoscopic Surgery

Pablo Lamata*, Enrique J. Gómez, *Senior Member, IEEE*, Félix Lamata Hernández, Alfonso Oltra Pastor, Francisco Miguel Sánchez-Margallo, and Francisco del Pozo Guerrero, *Senior Member, IEEE*

***Abstract*—Human perceptual capabilities related to the laparoscopic interaction paradigm are not well known. Its study is important for the design of virtual reality simulators, and for the specification of augmented reality applications that overcome current limitations and provide a *supersensing* to the surgeon. As part of this work, this article addresses the study of laparoscopic pulling forces. Two definitions are proposed to focalize the problem: the *perceptual fidelity boundary*, limit of human perceptual capabilities, and the *Utile fidelity boundary*, that encapsulates the perceived aspects actually used by surgeons to guide an operation. The study is then aimed to define the *perceptual fidelity boundary* of laparoscopic pulling forces. This is approached with an experimental design in which surgeons assess the resistance against pulling of four different tissues, which are characterized with both *in vivo* interaction forces and *ex vivo* tissue biomechanical properties. A logarithmic law of tissue consistency perception is found comparing subjective valorizations with objective parameters. A model of this perception is developed identifying what the main parameters are: the grade of fixation of the organ, the tissue stiffness, the amount of tissue bitten, and the organ mass being pulled. These results are a clear requirement analysis for the force feedback algorithm of a virtual reality laparoscopic simulator. Finally, some discussion is raised about the suitability of augmented reality applications around this surgical gesture.**

***Index Terms*—Force feedback (FF), human factors, laparoscopy, virtual reality (VR) simulation requirements.**

I. Introduction

LAPAROSCOPIC surgery is becoming a preferable alternative to open surgery in many procedures. Its main drawback is its reduced working space and the consequent need of developing new skills. It requires a long and costly training process of surgeons, in which virtual reality (VR) simulation can play an important role [1], [2]. However, little effort has been done towards understanding the perceptual-motor and cognitive processes that contribute to laparoscopic skills learning [3]: how do surgeons perceive the laparoscopic operating theater? Do they develop special perceptual, sensorial, or cognitive skills? Can a surgeon's capabilities be enhanced with augmented reality (AR) features? Do these capabilities have to be increased or simply focused? These interesting questions are not easily addressed, since they are related to the subconscious processes of human beings.

The design of a VR laparoscopic simulator needs a deep understanding of the human factors in the laparoscopic interaction paradigm. The entire area of haptic abilities and their role in the psychomotor, visiospatial, and perceptual skills needs more research [4]. This is also interesting for the identification of improvements in haptic interfaces and for the use of illusions to aid the human user (sensory substitutions) [5]. Moreover, the understanding of current limitations of laparoscopic interaction can lead to the definition of AR applications in which computerized systems provide a kind of *supersensing* or *supervision* to the surgeon. The study of human factors in surgery has therefore an important impact and interest.

One of the most controversial dilemmas in VR simulation design is the incorporation of force feedback (FF). It has been studied how trocar friction could hide tactile information [6], but perception is enhanced with FF both in grasping [7] and pulling [8] maneuvers. One interesting methodological approach to assess the importance of FF is to compare user performance with and without FF, which has found results that supports the convenience of FF [9]. Following this line, degradation of haptic hardware has been modeled to explore the impact of its quality [10]. The approach taken in this study is to compare subjective perception of tissue consistency with objective force parameters, aiming to assess the fidelity boundary beyond which no more realism is necessary in simulation. This is an extension of our former work studying tissue consistency perception [8], and it also pursues some fundament for AR applications that solve perceptual or cognitive surgical limitations.

The principal aim is therefore the definition of those levels of realism that are required in laparoscopic simulation. Two concepts are defined in order to focalize this problem, with the idea of differentiating between what is not possible to be perceived (no need to be simulated) what can be perceived (it is convenient to be simulated but it does not require a high fidelity) and what is perceived and useful for the surgical procedure (it needs the highest degree of fidelity). First, the *perceptual fidelity boundary* is defined as the edge of our perceptual capabilities. It

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*P. Lamata was with the Grupo de Bioingeniería y Telemedicina (GBT), Universidad Politécnica de Madrid (UPM), Madrid 28040, Spain. He is now with Siemens Molecular Imaging, 23-38 Hythe Bridge Street, Oxford OX12EP, U.K. (e-mail: pablo.lamata@siemens.com).

E. J. Gómez and F. del Pozo Guerrero are with the Grupo de Bioingeniería y Telemedicina (GBT), Universidad Politécnica de Madrid (UPM), Madrid 28040, Spain. They are also with the CIBER-BBN Networking Research Center, Barcelona 08028, Spain (e-mail: egomez@gbt.tfo.upm.es; fpozo@gbt.tfo.upm.es).

F. Lamata Hernández is with the Grupo de Bioingeniería y Telemedicina (GBT), Universidad Politécnica de Madrid (UPM), Madrid 28040, Spain. He is also with the Hospital Clínico Universitario, Zaragoza 50009, Spain (e-mail: flamata@salud.aragon.es).

A. Oltra Pastor is with the Instituto Biomecánico de Valencia, Valencia 46022, Spain (e-mail: alfonso.oltra@ibv.upv.es).

F. M. Sánchez-Margallo is with the Minimally Invasive Surgery Center Jesús Usón (CCMI), Cáceres 10071, Spain (e-mail: msanchez@ccmijesususon.com).

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confines those aspects of the physical reality that are perceived by human beings. Interaction in laparoscopic theaters has to be characterized in order to define this boundary. Second, a *utile fidelity boundary* encloses those perceived aspects of reality that are actually processed by surgeons to guide an operation. Cognitive studies should be performed to clarify what are these pieces of information gathered from perception. And these are the aspects that should have the highest degree of realism. Both fidelity boundaries are supposed to be common to every surgeon, regardless the individual variability. According to these definitions, the present work addresses the assessment of the *perceptual fidelity boundary* in the gesture of laparoscopic pulling. Whereas the *utile fidelity boundary* would be more interesting, it is much more difficult to be approached.

The article is structured as follows. Section II describes the tools and methods used in the triple methodological approach which has been taken: 1) the characterization of the skill of tissue consistency perception; 2) the acquisition of *in vivo* interaction forces; and 3) the biomechanical characterization of the tissues involved in former studies. Section III describes the main results of these experiments, whose validity and scope are discussed in Section IV. The development of a force feedback model for simulation based on the definition of the *perceptual fidelity boundary* is presented in Section V together with some reflections about the suitability of augmented reality applications around this surgical gesture. Finally, some concluding remarks are presented in the last section.

II. Tools and Methods

Subjective tissue consistency perception in a laparoscopic setting is studied together with the acquisition of both *in vivo* interaction forces and *ex vivo* tissue biomechanical properties. Four tissues of the pig abdominal cavity are selected and studied: diaphragmatic crus (t1), esophagus (t2), gastric fundus (t3), and greater omentum (t4). Descriptions of these three experiments are made in following sections.

A. Consistency Perception Study

Tissue consistency is understood here to be the resistance felt against the withdrawal (pulling) of a grasper holding a tissue. A detailed description of this experiment is found in [8]. Consistency is measured on a scale from 0 to 10, where a value of 0 corresponds to movements with an empty grasper and a value of 10 corresponds to a grasper holding a rigid structure such as a ligament in its bone junction. A total of 29 different surgeons are enrolled in the study. It has different stages in which users assess tissue consistency with different sources of information. In this paper, we refer to the experimental condition in which the surgeon uses visual and tactile information simultaneously. Users follow a scale familiarization protocol in which they feel with their hand the touchstones "0," "5," and "10" in the consistency scale defined before. These three values correspond to three graspers holding nothing, 250 g, and a fixed structure (a mass of 1.1 kg tightly attached to the grasper), respectively. A fourth grasper is incorporated at the second session of the experiment: it holds a mass of 125 g, and users are asked to rank its consistency. This is done to have a better understanding of the perceptual capability of surgeons.

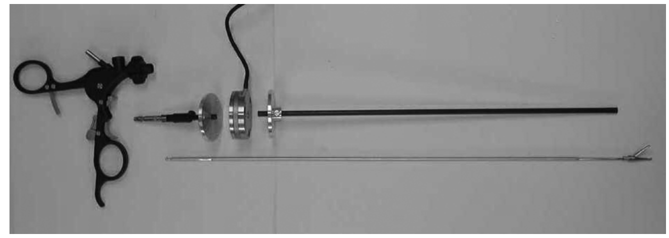


Fig. 1. Device designed to acquire *in vivo* laparoscopic interaction forces, which is shown dismantled into its different components. The black external tube of the grasper has been cut and two metal plates have been attached to fix the F/T sensor. The tool metal inner axis is introduced in the black tube and is responsible for the transmission of the grasping movements.

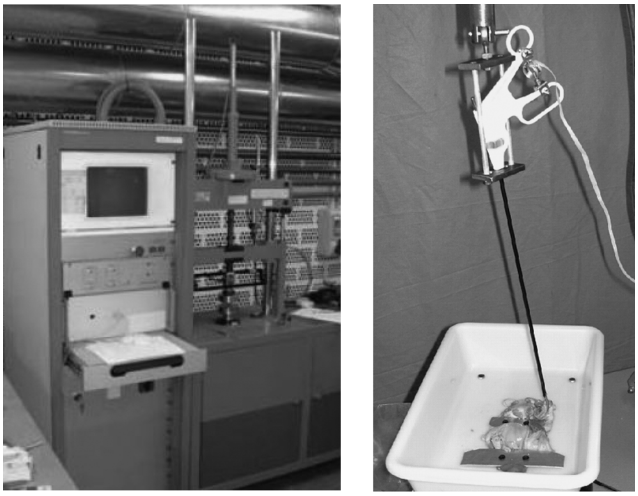
B. In Vivo Interaction Forces Acquisition

A laparoscopic grasper (Click Line, Storz Medical, Germany) is equipped with a Force/Torque sensor (Mini40 F/T, ATI, USA) as shown in Fig. 1. This system is built by cutting the outer black tube of the grasper (this grasper can be dismantled into three parts: the handle, the outer black tube, and the inner metal axis with the tip, which can be replaced) and mounting the sensor with two metal plates. This device is similar to that described in some works of the literature [6], [11]. It can be introduced through a trocar and can acquire forces of all degrees of freedom of the laparoscopic tool except grasping. The acquisition software allows a sampling rate of 8.5 Hz.

Nevertheless, this device has two limitations: the coupling of grasping forces with pulling forces and some overweight. The coupling is due to the mechanical transmission of grasping from the handle to the tip of the tool. This is done through the inner metal axis, which is coupled to the outer black tube to which the sensor is attached (see Fig. 1). In this manner, the gesture of closing a grasp is acquired as a pushing force, i.e., there is a coupling between these two degrees of freedom. On the other hand, the total weight of the device, 215 g, is more than double of that of the grasper alone (85 g). The device is therefore used in a controlled way to prevent the coupling of the degrees of freedom. This is achieved by fixing grasping before making pulling maneuvers in selected scenarios by using the built-in mechanism of the laparoscopic tool. An experienced surgeon is instructed in this way and performs three repetitions of five consecutive extractions (pulling) and insertion (recovering resting position) maneuvers holding each of the four tissues of the pig model (t1–t4) which makes a total of 15 pulling cycles per tissue. In each repetition, the tissue is grasped in a different place trying to bite the maximum amount of tissue. Measurements are made on one of the pig models used for the perceptual experiment.

Two parameters are obtained from each cycle of each force profile: peak to peak value (V_{pp}) and maximum temporal slope (m). It has to be regarded that V_{pp} is the sum of the tissue reaction force (F_{tissue}) and two times the trocar friction (F_{trocar}), since a complete pulling/pushing cycle adds F_{trocar} in extractions and subtracts F_{trocar} in insertions. Therefore, the pulling interaction force (F_{pull}) that a surgeon perceives, the addition of F_{tissue} and F_{trocar} in the extraction of a grasper, is assessed as the peak to peak value (V_{pp}) of each cycle minus the trocar friction as shown as follows:

$$F_{\text{pull}} = F_{\text{tissue}} + F_{\text{trocar}} = V_{pp} - F_{\text{trocar}}. \quad (1)$$



a) b)

Fig. 2. Experimental setting for the *ex vivo* characterization. (a) SERVOSIS universal testing machine used in the *ex vivo* experiment. (b) Grasper held by the machine and tissue sample.

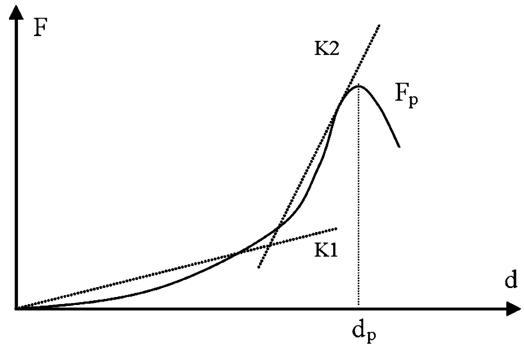


Fig. 3. Force-displacement characteristic curve of a generic tissue with its parameters: initial and final stiffness (K1, K2), peak force (Fp), and displacement for Fp (dp).

The device is also used to assess F_{trocar}. For simplicity, this parameter is considered constant and equal for every trocar, since they are all the same model (Versaseal 5.0 mm, AutoSuture Division, Tyco Healthcare), despite the fact that there are several factors that affects this friction [12]. A grasper is inserted and extracted repeatedly through one of these trocars, the peak to peak value of each cycle is measured and an average value is reached. F_{trocar} is the half of this mean value.

C. Ex Vivo Tissue Biomechanical Properties Assessment

Ex vivo samples are taken from the four studied tissues (t1–t4) and are mechanically characterized with force-displacement graphs. A universal testing machine SERVOSIS is equipped with a load cell 500 N interface (see Fig. 2). Mechanical trials are made with displacement control at a constant velocity of 0.05 mm/s.

Tissue portions are taken and prepared following a standard experimental protocol. Once cut, they are frozen down to -20 °C. At the experimental time, they are unfrozen and kept in a saline solution. Then they are secured to the testing machine in a manner in which fixing boundary conditions are minimized. A laparoscopic grasper attached to the testing machine is used to grasp and pull these tissues. The amount of tissue bitten is varied: claw full, half-full, and only the tip. The grasping force is controlled by an extensiometric sensor which is mounted at the handle of the tool (see Fig. 2).

Therefore, this experimental setup fixes an initial grasping force applied to the tool handle (F_{grasp}) and an amount of tissue bitten, the bite size (BS). It controls the displacement (deformation) that is caused to the tissue (d) and measures the resulting pulling force (F). F_{grasp} is fixed to three values (15.7 N, 31.4 N, 47.2 N), ranging from a minimum that holds tissues consistently enough to a maximum that shows the beginning of deformation of the grasper. BS is varied, as explained before, across "full claw," "half claw," and "only the tip."

A total of 108 trials are made, three repetitions with three grasping forces, and three bite sizes for four different tissues. Each force-displacement graph (Fig. 3) is characterized with four parameters [13]: the stiffness coefficients in two regions, initial (K_1) and final (K_2), the peak force (F_p), and the corresponding displacement at this point (d_p). These last two parameters define the peak point (F_p, d_p), which is reached when the bitten tissue is either released or torn.

TABLE I
RESULTS OF THE SUBJECTIVE PERCEPTION OF TISSUE CONSISTENCY AND THE OBJECTIVE PARAMETERS OBTAINED FROM THE INTERACTION FORCES PROFILES AND THE *EX VIVO* BIOMECHANICAL CHARACTERIZATION. VALUES SHOWS MEAN±STANDARD DEVIATION OF THE TOTAL "n" SAMPLES INDICATED (INDICATED VALUE IS FOR EACH TISSUE). $*$, $**$, AND $***$: AVERAGE VALUES OF THE "FULL CLAW," "HALF CLAW, " AND "ONLY THE TIP" BITE SIZE (BS) EXPERIMENTAL CONDITION

	t1	t2	t3	t4
Subjective perception of tissue consistency (n = 29)				
Perception (0 to 10)	8.3 ± 0.9	6.7 ± 0.9	3.1 ± 1.2	0.9 ± 0.8
In-vivo interaction forces measurement (n = 15):				
V_{pp} (N)	5.8 ± 1.2	3.3 ± 0.6	1.8 ± 0.3	1.6 ± 0.1
m (N/s)	7.4 ± 1.9	3.3 ± 1.1	0.9 ± 0.3	1.0 ± 0.2
Ex-vivo biomechanical characterization (n = 36)				
K_1 (N/mm)*	1.23±0.80	0.15±0.02	0.38±0.19	0.22±0.09
K_1 (N/mm)**	0,43±0.33	0.07±0.02	0.09±0.04	0.25±0.10
K_1 (N/mm)***	0.16±0.16	0.04±0.01	0.09±0.04	0.10±0.05
K_2 (N/mm)*	1.35±0.71	0.50±0.18	1.01±0.38	0.31±0.12
d_p (mm)*	4.02±0.00	10.2±4.19	4.91±3.90	11.9±7.85
F_p (N)*	6.25±1.52	6.60±1.20	7.94±2.56	2.13±1.09

Results are analyzed in order to determine if grasping force (F_{grasp}) and bite size (BS) are determining factors in the biomechanical characterization, that is, in the assessment of the four parameters: K_1, K_2, F_p, and d_p. Selected statistical test is a nonparametric Krustal–Wallis of K independent samples.

III. RESULTS

Three experiments are carried out in order to understand and model laparoscopic pulling forces. First, laparoscopic perception of tissue consistency is characterized as reported in [8]: surgeons are able to differentiate the four studied tissues and to rank them as shown in Table I. Another result is that the mass of 125 g of the scale familiarization protocol is assessed by 17 surgeons to have a consistency of 3.6 ± 1.4 $(\text{mean} \pm \text{SD})$.

Second, *in vivo* interaction forces are measured and registered in temporal profiles like those shown in Fig. 4. Two parameters, peak pulling force (assessed with V_{pp}) and maximum slope (m), are used to characterize each of the five pulling–pushing cycles

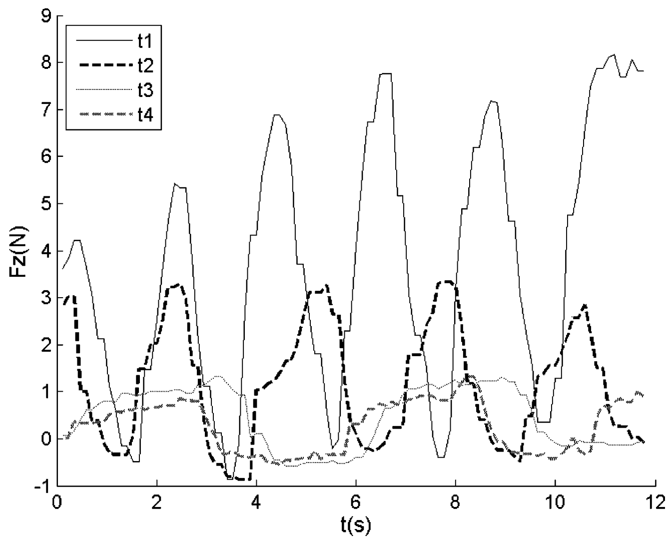


Fig. 4. Interaction *in vivo* force profiles studied for different tissues. Profiles of t3 and t4 are complete, whereas those of t1 and t2 only show the first two pulling and pushing maneuvers.

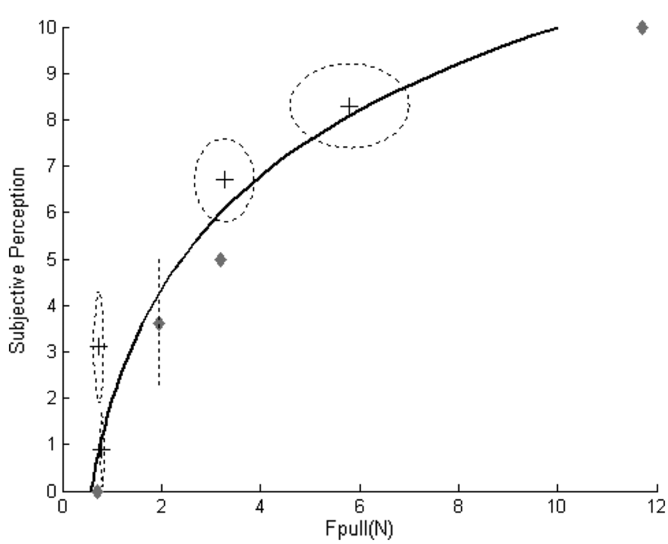


Fig. 5. Logarithmic regression curve between pulling force (Fpull) and subjective perception of tissue consistency. Dashed lines and ellipsoids reflect standard deviations of Fpull or subjective valorizations. Rhombuses represent the touchstones of the scale familiarization protocol.

of each of the three repetitions of each tissue. Average values (mean and standard deviation of 15 realizations) are compared to the subjective assessment of tissue consistency from former section as shown in Table I. On the other hand, trocar friction (F_{trocar}) is measured as 0.7 ±0.1. A logarithmic regression is made between pulling force, F_{pull} calculated as indicated in (1), and pulling perception (see Fig. 5). This regression takes also into consideration values of the protocol for scale familiarization. These touchstones, 0, 5, and 10 values, correspond to forces of 0.7 N (trocar friction), 3.2 N (a mass of 250 gr plus trocar friction) and 11.7 N (a mass of 1.1 kg and trocar friction), respectively. Analogously, the mass of 125 g correspond to a force value of 1.95 N.

Finally, the biomechanical characterization study assesses the stiffness (K_1 and K_2) and point of release or tearing (d_p and F_p) of tissue samples, showing a high variability in these values (see Table I). The Krustal–Wallis of K independent samples reveals how grasping force (F_{grasp}) is not a determining factor in the stiffness of tissues, whereas the amount of tissue bitten (BS) is (see Table II).

Therefore, and in order to have the highest similarity between experimental settings, the 36 trials corresponding to a full claw grasping are averaged independently in Table I. Only the K1 values from the other two experimental conditions are reported in order to be concise. It is remarkable how these K1 values show an average decrease of 45% with the change of "full claw" to "half claw" BS condition, and a decrease of 42% changing from a "half claw" to a "only the tip" BS condition. Finally, the peak point (F_p, d_p) is caused by a grasp release in t1, t2, and t3, whereas by a tissue torn in t4.

IV. Discussion

The objective of this work is the study and modeling of laparoscopic pulling forces. Three experimental conditions have been defined: a subjective perceptual analysis, and two objective sources of objective data, *in vivo* forces measurement and an *ex vivo* tissue characterization. Are data valid? Are they comparable? How can results be interpreted together? Are tissues perceived or hinder by trocar frictions? Can human perception be characterized?

A. Scope and Limitations of Experiments

The scope of the study is limited to one surgical maneuver, pulling. This is one of the most frequent maneuvers, but not the only one in which force information could be important. Nevertheless using conceived methodological approach with other delicate maneuvers is difficult due to the small value of forces.

There are many interrelated variables and factors that influence the generation of pulling forces: the kind of tissue, the anatomical point of grasping, the surrounding attached organs, trocar friction, the individual variability of each subject, the amount of tissue grasped, the grasping force, the conditions of the tissue (healthy or diseased, grade of inflammation...), etc. The complexity of a systematic study would be too high; therefore a simple approach has been taken: the comparison of perceptual information, ranked from 0 to 10, with *in vivo* temporal forces profiles and *ex vivo* tissue biomechanical properties.

Experiments have had some limitations. It has not been possible to make the *in vivo* forces characterization simultaneously with the perceptual analysis due to two limiting factors of the device built: the coupling of grasping with pulling and the overweight, which would distort perception. On the other hand, *ex vivo* biomechanical characterization has had a very high dispersion in the results despite having followed a defined protocol. This is caused by the extremely high sensitivity of tissues to experimental conditions and to the intrinsic variability of biomechanical properties, which is a common problem in this field of research [13].

B. Similarities Between Experimental Conditions

Surgeons performed free maneuvers in the perceptual analysis, whereas *in vivo* force profiles belonged to controlled uniform ones. This way, force profiles were acquired with an approximate uniform velocity, whereas surgeons used different ve-

TABLE II
STATISTICAL DIFFERENCES (KRUSTAL–WALLIS OF K INDEPENDENT SAMPLES) BETWEEN EXPERIMENTAL CONDITIONS FOUND IN THE BIOMECHANICAL PARAMETERS (K_1, K_2, d_p, AND F_p) OF THE FOUR TISSUES (t1–t4). THE FACTORS STUDIED ARE GRASPING FORCE (F_{grasp}) AND BITE SIZE (BS). EXPERIMENTAL GROUPS ARE CODED WITH NUMBERS 1, 2, AND 3 CORRESPONDING TO A F_{grasp} OF 47.2 N, 31.4 N, AND 15.7 N, RESPECTIVELY, OR A BS OF "FULL CLAW," "HALF CLAW," AND "ONLY THE TIP," RESPECTIVELY. $*$: NOT ENOUGH DATA FOR STATISTICAL ANALYSIS (NO CHANGE OF STIFFNESS FROM K_1 TO K_2 IN THE STRETCHING EXPERIMENT)

		t1	t2	t3	t4
Is F_{grasp} a determining factor?	… for K_1	-	-	-	-
	… for K_2	1-3	-	-	*
	… for d_p	-	-	-	*
	… for F_p	1-2,1-3, 2-3	1-3,2-3	-	-
Is BS a determining factor?	… for K_1	1-2,1-3	1-2,1-3, 2-3	1-2,1-3	2-3
	… for K_2	-	-	-	*
	… for d_p	-	1-2,1-3, 2-3	-	*
	… for F_p	-	1-3,2-3	1-3	-

locities and accelerations that enabled them to perceive the inertia of the mass held at the end of the tool. This means that force profiles do not capture the inertial effects of the organs held by graspers, what might be an important source of perceptual information. Despite this consideration, force profiles are directly comparable to subjective valorizations because they were acquired in the second session of the perceptual experiment, with the same pig model and trocars. There are other possible sources of differences, like the point of grasping the tissue or the possible variable conditions of the tissue held. Their influence should not be relevant, even more with the low resolution that surgeons have shown in consistency valorizations.

On the other hand, *ex vivo* and *in vivo* measurements are not directly comparable. Nevertheless, they are complementary for a better understanding of the behavior of tissues and the requirements for surgical simulation. The *ex vivo* experiment provides the characteristic isolated tissue stiffness, and the *in vivo* measurements add the boundary conditions of the abdominal fixation. This idea will be further explored in the development of the perceptual model, making a first assessment of the influence of the fixation of tissues in the abdominal cavity.

C. Surgical Perception of Pulling Forces

Surgeons are able to distinguish between four different tissue consistencies with only force information. Interaction forces are perceived despite friction, and these forces deliver information about tissue consistency, as we concluded in [8]. Relating this perception to the objective *in vivo* peak force yields a logarithmic law (see Fig. 5), something common to many sensorial human capabilities and related with the concept of the just noticeable difference (JND). Nevertheless, perception differences between t4 and t3 (0.9 and 3.1, respectively, a difference of 2.2 in a ten-point scale) are not clearly explained: measured pull force of these two tissues (0.9 N and 1.1 N, respectively, calculated as (1) with data from Table I) can be considered similar to the trocar friction (0.7 N, a good value for friction considering that this can be up to 3 N [6]). This apparent contradiction is probably due to the inertial mass that is not registered in force profiles as commented before (t3 is the stomach held by the fundus, and its inertia to changes in velocity could be a difference in its perception compared to t4).

The surprising aspect is that, despite the fact that interaction forces with t3 and t4 are similar to trocar friction, surgeons were able to distinguish between them. This leads to the hypothesis that "surgeons are able to differentiate tissues and perceive somesthesic information despite the presence of interfering trocar frictions." It seems that surgeons learn to distinguish between friction forces, which are similar in every pulling and pushing maneuver, and resulting forces from the interaction with organs. This is opposed to the idea that "it is unlikely that the operator will be able to discriminate between somesthesic information generated by the organ and that generated by the resistance of the wall" [6].

D. Collected Data for Simulating Interaction Forces

Interaction pulling and pushing forces of four different tissues have been characterized with their peak value and its maximum temporal slope (see Table I), which can be used as a basis for requirements of an FF algorithm. Force measurements agree with ranges described in the literature [6], [11]. Another interesting result has been the different tear and release thresholds. The *ex vivo* trials in which tissue portions were stretched finished with the release of the grasper or with the tearing of the tissue, determining the peak force ($\mathrm{F_p}$, see Fig. 3). t4 has found a tear threshold (2.13 N), and the other tissues (t1–t3) have found their correspondent release thresholds (see Table I). One of the reasons why tissues are released instead of torn is the low efficient transmission of grasping forces between handle and tool tip [15].

V. MODELING FORCE PERCEPTION

Results of former experiments are interpreted and generalized with the construction of a model that gathers the main parameters that influence the perception of pulling forces. Despite the high variability of forces and all the factors that affect them, human perception is quite rough. This indicates that this problem can be simplified. Therefore, the objective is to identify which are the more relevant factors, not only in the generation, but also in the perception of pulling forces.

Surgeons are able to distinguish at least four levels of force intensity, and trocar friction does not eclipse consistency information. The grasping force when holding the tissue with the grasper is not a determining factor in an *ex vivo* characterization of biomechanical properties, it affects mainly the point of release (see F_p in Table II). Thus, this is a variable that may not be relevant for the model. Another important result is that by comparing *ex vivo* characterization with *in vivo* force profiles, it can be noticed how measured stiffness does not correlate with peak-to-peak force values. For example, t3 is stiffer than t2, but t2 produced bigger interaction forces than t3 (see Table I). This difference is attributed to the grade of fixation of tissues to the abdominal cavity, which has therefore a big impact in resulting forces.

On the other hand, the amount of tissue held in the grasper, the BS variable, is also a factor to be taken into account. The *ex vivo* biomechanical characterization showed that tissue stiffness (K_1) depends on this parameter: tissues show a less rigid behavior when the amount of tissue grasped is smaller. For example, K_1 decreased by 45% on average from the "full grasp" to the "half grasp" condition. Finally, organ mass is also considered to be significant enough to be included in the perceptual model, but with less empirical evidence. This has been the only explanation found of the discordance found between objective force parameters and subjective valorizations in t3 and t4 (see former discussion section).

Therefore, the idea taken is that there are four main factors to be considered: the kind of tissue (its stiffness), the grade of fixation of the tissue to the abdominal cavity, the amount of tissue bitten, and the organ mass being pulled. The proposed model is shown in (2). It indicates that the force exerted by surgeons (F_{pull}), what is the force perceived with the hand following Newton's third law, is a function of the grade of fixation (gf), the stiffness of the tissue (K) that is dependant on the bite size (BS), the distance pulled or pushed (x), the mass held (m), and the resulting acceleration caused to this mass (a), plus the friction of the trocar (F_{trocar}). The grade of fixation is a variable without dimension from 0% to 100%. This can be seen as a linear elastic model, chosen for simplicity reasons, with an equivalent apparent stiffness $K' = gf \cdot K(BS)$

$$F_{\text{pull}} = gf \cdot K(BS) \cdot x + m \cdot a + F_{\text{trocar}} \tag{2}$$

It has to be regarded that (2) is a representation of the main parameters that, under our results and interpretation, affects the perception of pulling forces. It is not a mathematical model of all factors that influence the generation of these forces. Such a model would also need the velocity component at least.

A. Use in a VR Surgical Simulator

We think that the proposed model (2) has a reasonable guarantee of offering the necessary level of realism in a laparoscopic surgical VR simulator. It represents a clear requirement analysis for its force feedback algorithm. Some implementation issues are provided in this section.

First, we address the assessment of the grade of fixation gf. It is defined by the relation between the characteristic tissue stiffness (K) and the apparent stiffness (K') found in pulling experiments $(K' = gf \cdot K)$. A first approximation of this parameter is given for the four studied tissues (t1–t4) with available experimental data. K' is calculated assuming a linear elastic model, dividing the average pulling force obtained *in vivo* (F_{pull}, calculated as (1) with data from Table I) by the average displacement made to each of the tissues in the *in vivo* study, which was roughly measured in the experiment (1.5, 4, 6, and 10 cm corresponding to t1–t4). This K' is then divided by an estimation of the characteristic stiffness, the K_1 taken from the *ex vivo* characterization experiment from Table I, to finally obtain gf. t1 and t2 show then a relative fixation (28% and 43%), much higher than t3 and t4 (5% and 4%), what it really happens in the porcine abdominal cavity. Nevertheless, t1, the diaphragmatic crus, is a very fixed tissue which is not reflected in obtained data. This assessment of the grade of fixation has to be regarded as a very rough approximation due to the different sources of imprecision and the assumptions taken.

Finally, and due to the low resolution in the human perception of tissue consistency and the high variability in biomechanical experimentation, it seems to be appropriate to regard this model under a fuzzy logic point of view. In this manner, tissue stiffness and the degree of fixation could be classified in a discrete number of categories. A first proposal could be to categorize tissue stiffness as high, corresponding to muscular tissues ($K \approx 10$ N/cm), medium ($K \approx 5$ N/cm), and low ($K \approx 1$ N/cm), corresponding to fat tissues, and to classify the grade of fixation as high (gf $\approx 50\%$), medium (gf $\approx 20\%$), or low ($gf \approx 5\%$).

B. Defining AR Applications

A secondary objective of present study is to find some fundaments for augmented reality applications. The idea is to enhance the limited capabilities of surgeons, and the first step is to define those *perceptual* and *utile boundaries*. Proposed methodology has assessed the *perceptual boundary* of pulling forces, what has revealed to be quite rough. One interesting starting hypothesis is that "an AR system that delivers effectively information of pulling forces improves surgical safety and performance." This could be delivered with a sensory substitution system, a graphical display superimposed in the corner of the laparoscopic monitor. Color codes could even inform about the risk of damage to tissues being manipulated.

Nevertheless there are some doubts about the suitability of such system. The main one is to estimate the added value of enhancing pulling force perception. It might be the avoidance of tissue damages, but it seems that laparoscopic surgery has very few tissue tearings caused by pulling. In fact, results of present study has shown how analyzed tissues are quite resistant, they are released in an *ex vivo* condition before being torn in most of cases (t1, t2, and t3), and only a delicate epiplon reaches a tearing (t4). The answer to this point is that in laparoscopic surgery there are actually tearings and damages, and they are caused by excessive forces. These forces might not belong to a "pure" tissue pulling holding a full grasp, the experimental condition studied, whereas to other gestures like the dissection. Future work should be focused on the analysis of laparoscopic procedures in order to define those situations in which there are tearing risks, and in which such AR system could make sense.

A second important criticism is the hypothesis that "visual information of tissues being deformed actually delivers to surgeons enough information in order to prevent damages." Our former results have revealed how this visual information is not enough to provide a good force estimation [8], but experienced surgeons might use it effectively in order to prevent tissue tearing. In fact, tissue damage in the majority of cases occurs under a condition of no vision (blind insertion and movements of tools). Nevertheless, at least novice surgeons would need to learn how to interpret visual cues, and an AR system would help them. Moreover, the damage done during blind movements could be avoided with such system. And there is not always enough visual information to avoid damage, like in pathological conditions of tissues like an aberrant inflammation, and this could be improved. In conclusion, we believe that an AR system makes sense for improving tissue safety, it can be an interesting complementary source of information for the surgeon. This is an interesting field for future research and development.

VI. Conclusion

The *perceptual fidelity boundary* of laparoscopic tissue pulling has been assessed. Surgeons are able to differentiate tissues and perceive somesthesic information despite the presence of interfering trocar frictions of similar magnitude. The most important factors in this perception are the kind of tissue, the degree of fixation, the amount of tissue grasped, and the organ mass. These results are a clear requirement analysis for the force feedback algorithm of a virtual reality laparoscopic simulator. Finally, a rationale has been proposed for future AR applications to provide a "supersensing" of pulling forces to a surgeon.

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Pablo Lamata was born in Soria, Spain, in 1979. He received joint B.S. and M.S. degrees in telecommunications engineering from Universidad de Zaragoza, Zaragoza, Spain, in 2002 and the Dr.Eng. degree in biomedical engineering from the Universidad Politécnica de Madrid-UPM, Madrid, Spain, in 2006.

He is currently a Marie Curie Experienced Researcher in Siemens Molecular Imaging, Oxford, U.K. He works within the ARIS∗ER consortium (www.ariser.info). He was also a Visiting Researcher at the Interventional Center, Rikshospitalet (Oslo, Norway), a Visiting Researcher at the Department of Biosurgery and Surgical Technology, Imperial College (London, U.K.), and Technical Manager at Integrating the Healthcare Enterprise Spain (Madrid). His research interests include surgery of the future, driven by technical advances in virtual or augmented reality, robotics, and computer-assisted systems.

Dr. Lamata is member of the Sociedad Española de Ingeniería Biomédica (SEIB).

Enrique J. Gómez (S'83–M'85–SM'06) was born in Madrid, Spain, in 1960. He received the M.Eng. degree in telecommunications engineering and the Dr. Eng. in biomedical engineering from Universidad Politécnica de Madrid, Madrid, Spain, in 1987.

He is a Professor (Hab.) of biomedical engineering at the Universidad Politécnica de Madrid. He has been a Visiting Fellow at City University (London, U.K.) and Visiting Professor at Patras University (Patras, Greece), Technical University of Szczecin (Szczecin, Poland), and University of Athens (Athens, Greece). He belongs to the Spanish CIBER-BBN Networking Research Center, Barcelona, Spain. His research interests include telemedical artificial pancreas and virtual surgery simulation and planning. He has published 260 publications on scientific journal papers and conference proceedings in related fields and directed 39 national and international research projects.

Prof. Gómez is the Treasurer of the European Alliance for Medical and Biological Engineering and Sciences (EAMBES) society and Secretary General of Spanish society for Biomedical Engineering (SEIB). He serves as an Associate Editor of the IEEE Transactions on Information Technology in Biomedicine.

Félix Lamata Hernández was born in La Rioja, Spain, in 1954. He has a six-year medical studies degree and the Ph.D. degree in surgery from the Universidad de Zaragoza, Zaragoza, Spain, in 1978 and 1987, respectively.

In 1982, he made a residency in surgery at the Surgical Service of the Hospital Clínico Universitario, Zaragoza, where he has worked since then. He is also a clinical lecturer at the Medical School of the Universidad de Zaragoza, where he leads a Ph.D. course about methodology in scientific investigation. His research interests and professional activities include laparoscopy, liver transplant, and unit breast cancer.

Dr Lamata is member of the Sociedad Española de Cirugía (SEC), Sociedad Española de Investigaciones Quirúrgicas (SEIQ), Sociedad Aragonesa de Patologíao Digestiva (SAPD), and Sociedad Aragonesa de Cirugía (SAC).

Alfonso Oltra Pastor was born in Alcoy, Alicante, Spain, in 1975. He received the B.S. degree in mechanical engineering from the Universidad Politécnica de Valencia, Valencia, Spain, in 2000.

He is responsible of Workplace Health Department at the Instituto de Biomecánica de Valencia. He has been collaborating during last six years in projects related to orthopedic implants and surgical instruments with the Department of Health Technologies. He has wide experience in developing and coordinating national and international RTD projects.

Francisco Miguel Sánchez-Margallo was born in Albalá, Cáceres, Spain, in 1970. He received the B.S. and Ph.D. degrees in veterinary science from the University of Extremadura, Cáceres, Spain, in 1992 and 1999, respectively.

He is the Scientific Director at the Minimally Invasive Surgery Center, Cáceres. He is Professor and organizer of National and International Courses for the practical training of surgeons and health professors. He is Director of the Quality System (Norm UNE EN ISO 9001:2000) at the Minimally Invasive Surgery Center. He has participated in 38 research projects financed by public entities and by companies. He has made a Postgraduate stay in the Telemedicine Center of the Brody School of Medicine, East Carolina University, NC. He is author or coauthor of 21 journal publications, two books and 25 book chapters and several international and national conference and diffusion articles related to the minimally invasive surgery and surgery, and he is author of two utility models.

Dr. Sánchez-Margallo has won different national and international research prizes like the Spanish Royal Academy of Doctors (2001).

Francisco del Pozo Guerrero (SM'04) was born in Madrid, Spain, in 1945. He received a degree in telecommunications engineering in 1969 and the Ph.D. degree in 1979, both from the Universidad Politécnica of Madrid (UPM), Madrid, Spain.

He was a Research Fellow in the Physics Department, Imperial College, London, U.K.; Neurobiology Department, University of Yale, New Haven, CT; Department of Laboratory Medicine and Pathology, University of Minnesota, Minneapolis; and Biophysics and Physiology Department, University of New York. He was an Invited Professor of several U.S. and E.U. Universities. He was a Full Professor (1986) at UPM. He was a Founder (1985) and Director of the Bioengineering and Telemedicina Department, UPM. He was a Scientific Advisor of main medical and telecommunication companies and health care institutions. He was Founder and Chief Editor of the journal *International Telemedicine*. He was a Board Member of several scientific journals and President of the Sociedad Española de Telemedicina (SET). He directed more than 400 scientific papers and 20 Ph.D. theses. He was a main researcher of more than 40 E.U.-funded research projects, 25 national research projects, and 25 contracts with industrial companies. He was a founder and coordinator of M.S. programs and a Ph.D. program on biomedical engineering.