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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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 grasping 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.

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 (Vpp) and maximum temporal slope (m). It has to be regarded that Vpp is the sum of the tissue reaction force (Ftissue) and two times the trocar friction (Ftrocchar), since a complete pulling/pushing cycle adds Ftrocchar in extractions and subtracts Ftrocchar in insertions. Therefore, the pulling interaction force (Fpull) that a surgeon perceives, the addition of Ftissue and Ftrocchar in the extraction of a grasper, is assessed as the peak to peak value (Vpp) of each cycle minus the trocar friction as shown as follows:

\[ F_{\text{pull}} = F_{\text{tissue}} + 2F_{\text{trocchar}} = V_{\text{pp}} - F_{\text{trocchar}} \]
The device is also used to assess $F_{\text{trocinfo}}$. 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. $F_{\text{trocinfo}}$ 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 extensimetric 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 ($F_{\text{grip}}$) 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 ($F$). $F_{\text{grip}}$ 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.

Results are analyzed in order to determine if grasping force ($F_{\text{grip}}$) 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 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

<table>
<thead>
<tr>
<th>Sample</th>
<th>Object</th>
<th>Subjective perception of tissue consistency ($n = 29$)</th>
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<tbody>
<tr>
<td></td>
<td>Perception (0 to 10)</td>
<td>$8.5 \pm 0.9$</td>
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<tr>
<td></td>
<td>$V_{wp}$ (N)</td>
<td>$5.8 \pm 1.2$</td>
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<tr>
<td></td>
<td>$m$ (N/s)</td>
<td>$7.4 \pm 1.9$</td>
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<tr>
<td></td>
<td>$K_1$ (N/mm)$^*$</td>
<td>$1.23 \pm 0.80$</td>
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<tr>
<td></td>
<td>$K_1$ (N/mm)$^{**}$</td>
<td>$0.43 \pm 0.33$</td>
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<tr>
<td></td>
<td>$K_1$ (N/mm)$^{***}$</td>
<td>$0.16 \pm 0.16$</td>
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<td></td>
<td>$K_2$ (N/mm)$^*$</td>
<td>$3.3 \pm 0.6$</td>
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<td></td>
<td>$d_p$ (mm)$^*$</td>
<td>$4.02 \pm 0.00$</td>
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<td></td>
<td>$F_p$ (N)$^*$</td>
<td>$6.25 \pm 1.52$</td>
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A logarithmic regression is calculated as indicated in (1), etc. A grasp release in t1, t2, and t3, is not a determining factor in the condition, and a decrease of 42% changing is and is

Finally, the biomechanical characterization study assesses the stiffness (K1 and K2) and point of release or tearing (dp and Fp)

of tissue samples, showing a high variability in these values (see Table I). The Krustal–Wallis of K independent samples reveals how grasping force (Fgrasp) 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 tip” BS condition. Finally, the peak point (Fp, dp) 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, 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-
forces with $t_3$ and $t_4$ are similar to trocar friction, sur-
genons were able to distinguish between them. This leads to the
ception compared to $t_4$).

This apparent contradiction is prob-
ably due to the inertial mass that is not registered in force pro-
m
tments add the boundary conditions of the abdominal
mmence should not be relevant, even more with the low resolution
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 require-
ments for surgical simulation. The ex vivo experiment provides
the characteristic isolated tissue stiffness, and the in vivo mea-
surements add the boundary conditions of the abdominal fixa-
tion. 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 loga-

rithmic law (see Fig. 5), something common to many sensorial
human capabilities and related with the concept of the just no-
ticeable difference (JND). Nevertheless, perception differences
between $t_4$ and $t_3$ (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
troc friction (0.7 N, a good value for friction considering that
this can be up to 3 N [6]). This apparent contradiction is prob-
due to the inertial mass that is not registered in force pro-
m
tures as commented before ($t_3$ is the stomach held by the fundus,
and its inertia to changes in velocity could be a difference in its
perception compared to $t_4$).

The surprising aspect is that, despite the fact that interaction
forces with $t_3$ and $t_4$ are similar to trocar friction, sur-
geons were able to distinguish between them. This leads to the
hypothesis that “surgeons are able to differentiate tissues and
perceive somesthetic information despite the presence of inter-
fering trocar friction.” It seems that surgeons learn to distin-
guish 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 somesthetic
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 tis-
ues have been characterized with their peak value and its max-
imum 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 inter-
esting result has been the different tear and release thresholds.
The ex vivo trials in which tissue portions were stretched fin-
ished with the release of the grasper or with the tearing of the
tissue, determining the peak force ($F_p$, see Fig. 3). $t_4$ has found
a tear threshold (2.13 N), and the other tissues ($t_1$–$t_3$) have found
their correspondent release thresholds (see Table I). One of the
reasons why tissues are released instead of torn is the low effi-
cient transmission of grasping forces between handle and tool

V. MODELING FORCE PERCEPTION

Results of former experiments are interpreted and general-
zied with the construction of a model that gathers the main
parameters that influence the perception of pulling forces. De-
spite 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 infor-
mation. The grasping force when holding the tissue with the
gasper 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

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<tr>
<th>Is $F_{group}$ a determining factor?</th>
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<th>Is BS a determining factor?</th>
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<td>$t_1$</td>
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peak-to-peak force values. For example, t3 is stiffer than t2, but t2 produced bigger interaction forces than t3 (see Table 1). 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 $K' = gf \cdot K(BS)$

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

(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 virtual reality 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 experimental data ($K' = gf \cdot K$). 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 1) 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 fundamentals 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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