Low-Cost Quantitative Tool-Tissue Applied Pressure Indication Method for Surgical Training and Assessment in Reality-Based Physical Models

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Abstract. We present a method of quantitatively measuring the pressure distribution applied to synthetic tissues by surgical tools via dye-impregnated microcapsules that rupture at specified pressures. A method utilizing pre-made indicator sheets is evaluated by force applications on synthetic bowel, and methods for creating paint-on indicator slurries were explored. A high spatial resolution of pressure intensity is demonstrated (0.1mm) and preliminary results merit further study.

Keywords. Surgical training, pressure indication, skill evaluation, forces on tissue, microcapsules

Introduction

One goal of surgical technical skill training is to instill "respect for tissue," yet this lacks a quantitative basis. In [1], De indicated that grasper-induced tissue stress injury may cause scar tissue formation, bleeding, adhesions, loss of bowel motility, severe injuries such as perforation or hemorrhage, or less severe ileus in organs such as liver, small bowel, and ureter. While the skill of appropriate tissue handling with instruments is clinically important, prior work [2-5] or present practices may not adequately address it, particularly in the context of training and technical skill evaluation via objective, quantitative means. Virtual Reality (VR) simulation can potentially address this issue but it suffers from considerable expense and accurate tissue modeling required. Our method can be used to inform accurate virtual models.

Prior work by Brown et al. [6] and Rosen et al. [7] provided a way to instrument laparoscopic tools to measure tool-tissue force interaction and found differences in force use among differing levels of surgical skill. De furthered this work by correlating tissue damage markers and applied, measured forces as well as quantitative tissue models of live porcine models. Roan furthered this work by improving the tool into a robust data collection platform capable of real-time feedback to make *in vivo* measurements of force, deformation, and additional properties for live porcine models [8]. However, the instrumentation costs involved in such prior work is prohibitively

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high for its use in widespread training and evaluation. This motivates a low-cost approach that can provide quantitative accuracy yet be amenable to inexpensive widespread use in surgical training and assessment of appropriate tissue handling.

We propose such a method for reality-based training (i.e., the use of real tools in physical tissue phantoms or porcine training models) where an accurate, quantifiable indicator of tissue damage can be inexpensively deployed at any physical tool-tissue interface. Our method utilizes dye-impregnated microcapsules that burst at a tunable pressure resulting from an applied force to provide a continuous measure of pressure-related damage. We herein compare two microcapsule deployment techniques: indicator sheets and indicator slurries to determine their relative feasibility as markers for tool-tissue pressure indication for use in surgical training and skill assessment.

1. Methods & Materials

1.1. Indicator Sheet Calibration and Pressure Indication Experiments with Fixed Weights and MSEG

A polyester-based Prescale pressure sensing film (4LW, Fujifilm Holdings Corp, Tokyo, Japan) microcapsule indicator was used. Color intensity calibration of Prescale was performed. The double-layered pressure sensing films were placed on top of a flat glass base. A 0.25inx0.952in gauge block (614212, Mitutoyo America Corp, Aurora, IL) was stacked on top of the pressure sensing films (test site) and standardized fixed weights were subsequently applied. The weights were applied to five different test sites, linearly separated by 1.5cm. The applied weights ranged from 200g to 1000g at increments of 200g for each test site. We repeated the same experiment, adding a single-layered synthetic bowel tissue made from silicon rubber (LGI-10, Simulab Corporation, Seattle, WA) between the glass piece and the pressure sensing films. The experiment test bed of the calibration process and pressure indication experiment with bowel tissue is shown in Figure 1a.

The Mechanical Smart Endoscopic Grasper (MSEG) developed by Roan et al. [8] was used with identical settings and calibration established in [1,8]. The device was used to apply and measure constant single-grasps to synthetic bowel tissue with no overshoot. The test bed consisted of suspending the bowel tissue from two pedestals 3cm apart, placing the Prescale on top of the tissue, and applying a constant, measured force level for about 2 minutes to each test site (linearly separated by 2cm). The target force levels ranged from 1.5 Newton (N) to 3.5N at increments of 0.25N. An image of the test bed before any grasps were executed appears in Figure 1b.

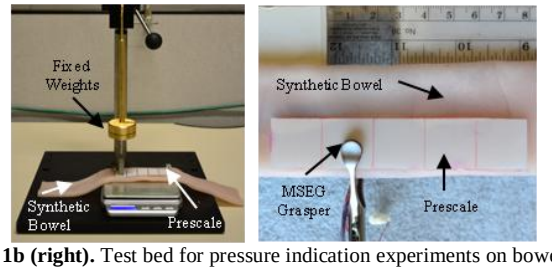

Figure 1a (left) & 1b (right). Test bed for pressure indication experiments on bowel tissue with fixed weights (left) and with MSEG (right).

After at least 20 minutes had elapsed, photos of the indicator sheets were taken with a digital camera (D3100, Nikon Corp, Tokyo, Japan) under standard office lighting conditions. The resulting files were processed with ImageJ and MATLAB into a 258x882pixels (7.5x25.64mm) 8-bit image individually to quantify the color intensity in different regions via the colormap tool. The intensity was linearly normalized to be between 0 and 1.

1.2. Indicator Slurry Approach

In an effort to directly apply indicator slurries to synthetic tissue, eight industry vendors were approached though obtaining microcapsules in slurries were not possible at this time. With no viable options commercially available, we pursued alternatives for the custom application of indicator slurries to synthetic tissue. Firstly, we attempted to synthesize alginate capsules using common culinary methods [9] around an indicator liquid that would burst and leak their contents when appropriate force was exerted. Secondly, we attempted to extract the microcapsules from the Prescale into slurries and directly apply them to synthetic tissue.

Analysis of the related patent [10] suggested that the microcapsules are held to the indicator sheets in a matrix consisting of poly(vinyl alcohol), carboxy-modified SBR latex, and starch powder which is applied as an aqueous solution. With this in mind, the Prescale, consisting of a donor and a developer sheet, was cut into 1cm squares then placed into a water bath and slowly heated to ~60° C and held there for 5 minutes before being cooled to room temperature. The solution was drawn into a 3mL syringe. The syringe was attached to a 25mm diameter 0.2μm polytetrafluoroethylene (PTFE) syringe filter (Scientific Strategies, Yukon, OK) using a Luer lock mechanism. The slurry was then forced through the filter using a syringe pump to provide a constant rate of filtration. The filter was extracted and allowed to air dry. A developer sheet was applied to the filter sheet and force was applied. To demonstrate the effectiveness of the processing, donor sheets were dipped into the solution and allowed to dry then applied to developer sheets with force.

To create slurries containing microcapsule donors and developers, eight 1cm squares of both donor and developer sheets were placed in 30mL deionized water, heated to ~60°C, and allowed to soak for at least 20 minutes. This solution was run through a filter following the same procedure described above.

2. Results

Figure 2 shows the digitally extracted colormap distribution of the pressure gradient from the Prescale. Table 1 shows the resulting quantities. The mean intensity was calculated over all pixel values in each test site image, and the affected area was computed by summing all pixel areas that exhibited values above the baseline threshold of no applied pressure.

Our work on alginate microcapsules faced three barriers. First, the alginate capsules formed were unfavorably flexible, and deformed rather than popped resulting in inconsistent pressure readings. Second, the resolution was limited by the excessive size of the capsules. Third, the capsules failed to retain water when left exposed.

Unlike the alginate capsules, the slurry derived from the Prescale still functioned after drying and showed promise of calibration and resolution similar to the unmodified

Prescale. When the PTFE filters used with the microcapsule slurry were removed and force applied in the presence of a developer sheet, indicator dye was observed sporadically on the filters. Developer sheets dipped in the slurry did not result in observable color change indicating minimal microcapsule breaking during processing though already processed donor sheets applied to developer sheets with pressure resulted in color change demonstrating microcapsule removal was not complete. When the PTFE filters used with the combined donor-developer solution were removed, indicator dye was visible prior to additional pressure being applied and was likely due to the fluid pressure of the syringe; however, applying additional pressure did increase the degree that the indicator dye was seen.

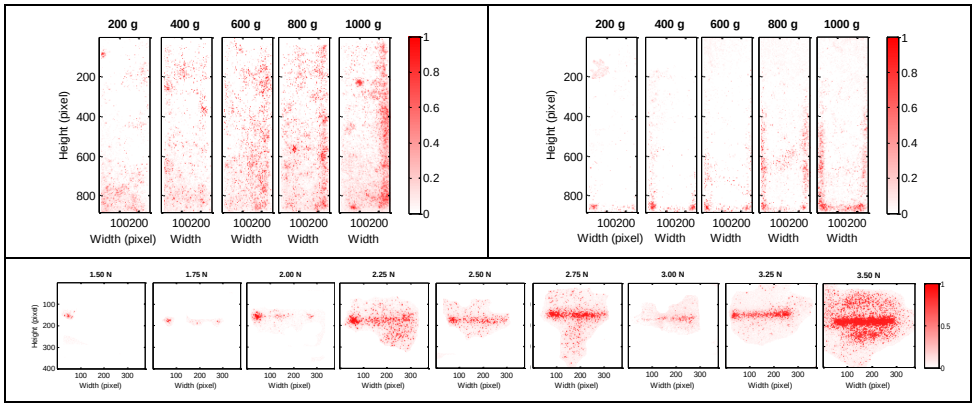

Figure 2a (left), 2b (right), & 2c (bottom). Pressure gradient colormap of indicator sheet calibration (left), pressure indication experiment with fixed weights (right), and with MSEG (bottom).

Table 1. Normalized Mean Intensity and Calculated Area of Colored Pixels for Calibration and Pressure Indication Experiment with Fixed Weights and MSEG

Fixed Weights (g)	**Calibration**		**Pressure Indication Experiment**	
	Mean Intensity	**Affected Area (mm^2)**	**Mean Intensity**	**Affected Area (mm^2)**
200	0.0076664	58.9248	0.0015745	15.5763
400	0.0115272	81.2633	0.0030090	23.0213
600	0.0183892	101.1590	0.0036755	32.4979
800	0.0206257	120.4460	0.0118303	119.6830
1000	0.0335509	143.2900	0.0139008	125.3660
Pearson's R	0.9661 *(p<0.01)*	0.9996 *(p<0.00001)*	0.9387 *(p<0.02)*	0.9175 *(p<0.03)*
Spearman's ρ	1 *(p<0.02)*	1 *(p<0.02)*	1 *(p<0.02)*	1 *(p<0.02)*
MSEG	**Pressure Indication Experiment**			
	Mean Intensity		**Affected Area (mm^2)**	
Pearson's R	0.71 *(p<0.03)*		0.87 *(p<0.003)*	
Spearman's ρ	0.78 *(p<0.01)*		0.88 *(p<0.003)*	

3. Conclusion and Discussions

We expected to see a monotonic increase in overall intensity for each test in the indicator sheet (Figure 2). While there is an overall trend of increase (Spearman's ρ = *1* and *0.78* in Table 1), there are several deviations from a purely monotonically

increasing trend. The patterns in Figure 2 show the pressure distribution in much finer spatial resolution (0.1mm according to the manufacturer) than the single grasper force measurement provided by the MSEG, revealing that only the first row of grasper jaw "teeth" engage the tissue a high force due to the angle of incidence. This illustrates that even if the MSEG force sensor was accurately calibrated, the computation of applied pressure distribution may be inaccurate if done with simple assumptions about grasper area, angle of engagement, and tool-tissue orientation. We suspected the force levels indicated by the MSEG were less accurate than those derived from the indicator sheet approach. Our claim was verified by the data obtained from the pressure indication experiment with fixed weights, showing Spearman's $\rho = 1$, a higher correlation than for the MSEG $\rho = 0.78$.

The goal of creating indicator slurries capable of direct application to synthetic tissue was to minimize the changes to mechanical behavior when indicator sheets were attached. Our results indicate successful extraction of viable microcapsules but further work is required to apply the active slurry to tissue successfully.

Limitations of the microcapsule approach include time and repeatability requiring a readily replaceable and disposable solution. We conclude that the microcapsule approach may provide an inexpensive, quantitative method of measuring surgical tool-tissue pressure distribution at a high spatial resolution and that this approach merits further study.

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