Small bowel anastomosis simulation in residency training

Molly Scott[1], Andrea Doll[1], Ryan Serbin[1], Tracy Puccinelli[1], and Calvin Kwan[2]

[1]University of Wisconsin-Madison College of Engineering, Department of Biomedical Engineering, 1415 Engineering Drive, Madison, WI 53706, USA
[2]University of Wisconsin School of Medicine and Public Health, Department of Surgery, 600 Highland Ave, Madison, WI 53792, USA

Emails: acscott3@wisc.edu, ajdoll@wisc.edu, rserbin@wisc.edu

Corresponding Author:
Calvin Kwan, BS
University of Wisconsin School of Medicine and Public Health, Department of Surgery
600 Highland Ave, Madison, WI 53792
(608) 262-5241
Email: kwan@surgery.wisc.edu

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Abstract

Background: In the last few decades, residency programs and medical schools have used animal tissue to teach surgical procedures. Animal tissue has become increasingly costly and unavailable, and currently there is a demand for more realistic models that accurately replicate the *human anatomy.* This project focuses on creating an affordable, accurate synthetic small bowel on which residents and surgeons can practice as well as be assessed on techniques such as resection and anastomosis. Currently, there are three human synthetic small bowel products on the market, but they offer no increased human authenticity or anatomical complexity that promote their use over animal tissue. **Methods:** Therefore, to meet this demand, a novel synthetic small bowel was created using an innovative fabrication protocol called "The Nesting Dolls Technique." This product uses a cotton fiber mesh as a scaffolding matrix, cellulose fiber sheets, and Smooth-On products to model the surgically-identifiable small bowel layers. Medical personnel performed a surgical simulation on the prototype and evaluated its performance. **Results:** The MTS testing proved that compared to the average maximum stress of the first generation small bowel model (0.31 MPa), the second generation small bowel model (0.47 MPa) better mimics that of human small bowel tissue (0.9 MPa). Additionally, considering that the elongation at failure of human small bowel is 162%, the second generation model has a more accurate elongation to failure (196%) compared to the first generation model (232.5%).[13, 16] Qualitatively, the survey administered to residents proved that the model accurately showed their skills in decision making and completing the anastomosis procedure, and agreed that this model is beneficial for education and maintenance of skills. **Conclusion:** Overall, the finished product offers more simulation advantages than the current products on the market with its high degree of anatomical and mechanical accuracy, ease of fabrication, and overall decrease in product cost.

Introduction

The educational approach to surgical training has changed significantly over the past few decades. While apprenticeship used to be the sole model of training, students are now also acquiring professional training by utilizing surgical skills laboratories.[1] Animal tissue simulations are the current method and are very useful because of their genuine anatomical attributes, but samples can be costly, unavailable, and short-lived.[2] The use of and demand for animal tissue has therefore drastically increased within the surgical-training field to assess various surgical techniques. Due to a shortage of adequate material to practice and to learn surgical procedures, it is of great concern to find a realistic alternative. The simulation of small intestine gastrointestinal procedures, particularly resection and anastomosis, is of particular interest to this project.

Globally, penetrating abdominal trauma results principally from military actions and wars, with

69% resulting from gunshots or shotgun wounds, and the remaining 31% from stab wounds. In penetrating abdominal wounds, the small bowel has the highest incidence of perforation at 50%, followed by the large intestine at 40% incidence.[5] Intestinal anastomosis procedures are regularly done on civilians as well as soldiers to correct for numerous problems, such as malignancies (i.e. cancers) and benign conditions (i.e. polyps, infections, inflammatory bowel disease, and Crohn's Disease).[6] Currently, it is common to use horse and rodent bowel tissue as practice for these surgical procedures.[3] With medical error being the third leading cause of death in the United States in 2013, residents and tenured surgeons cannot afford to translate animal tissue practice incorrectly to surgical procedures on humans.[4]

However, regardless of the underlying cause that prompts the need of intestinal anastomosis, the same complications can ensue. Postoperative complications include anastomotic leaks, bleeding, wound infections, and anastomotic stricture.[6] Practice and familiarity with different anastomotic scenarios are crucial to protect the long term safety and longevity of the patient, with patients showing four times the risk of mortality should they experience an anastomotic leak.[7] Practice and familiarity with the anastomosis procedure can ensure that complications such as leaks do not arise, decreasing the mortality rate of these procedures.

To decrease medical error and increase surgical precision, synthetic small bowel models need to be developed to account and replace the animal tissue demand. Current products that model the small bowel lack the proper shape or texture of human bowel tissue, using materials such as fabric.[8,9] The current models do not differentiate between the distinct layers of the small intestine nor the unique mechanical properties. There are four distinct layers of the small bowel, however, only the mucosa and the muscularis layers are mechanically and physically differentiable to medical personnel during a procedure. Distinction between these layers guide a surgeon through a two-layer hand-sewn anastomosis procedure via proprioceptive feedback. Therefore, it is necessary to incorporate these two layers in a model to mimic the realistic operating environment with human small bowel tissue. In addition to the lack of accuracy, the synthetic models are expensive, costing up to $375 per model, and cannot be reused.[9] Thus, a more anatomically and mechanically accurate, reusable, and cheaper alternative is in demand to provide a tool on which new surgical students and tenured surgeons alike can learn and maintain their skills.

Herein, the usefulness and efficacy of the synthetic small bowel tissue model to test residents' knowledge and skill of bowel repair, resection, and anastomosis is discussed. Furthermore, the mucosa and muscularis tissue layers need to be incorporated to accurately model small bowel. The mucosa has little structural integrity and forms the inner layer of the lumen. It is made up of intricate folds to increase the surface area of the gut to enhance the absorption of nutrients. The muscularis is the thickest layer of the small intestine and is the only one that can be seen clearly with the naked eye. The muscularis provides the structural and mechanical attributes of the small intestine. The small bowel tissue has a maximum stress of 0.9 MPa and an elongation to failure of

162%. Overall, the four layers of the small bowel measure 1 mm in thickness, and the inner hollow lumen of the small intestine is ~2.5 cm.

In addition to the small bowel itself, the incorporation of the mesentery is demanded to further increase the anatomical accuracy of this model. The mesentery connects the gastrointestinal tract to the abdominal wall and carries blood and lymphatic fluid between the intestine and the rest of the body.[10] The prototype does not need to include the fluidic aspect of the mesentery (blood and lymph vessels), but should include a material to model the general thickness, aesthetic, and mechanical properties of the mesentery. The mesentery is primarily composed of connective tissue like adipose tissue. *Qualitative* properties of adipose will be modeled according to current synthetic materials currently in use, particularly those in use to model the fat layer in the Smooth-On tutorial to make a synthetic suture pad.[11]The entire model should then be coated in a semblance of peritoneal fluid to give the slick nature of the abdominal cavity.

Materials and Methods

Small Bowel Fabrication

The synthetic small bowel was made from the Smooth-On product Dragon Skin® FX Pro, a silicone rubber developed by Smooth-On. In this semester's next generation model, Smooth-On Slacker® was added to achieve more realistic mechanical properties. The model's innermost layer was a dyed cellulose fiber sheet from Uline (S-13728) to model the mucosa and reinforced with a one-ply woven organic cotton matrix to replicate the strength of *in vivo* small bowel.[12,13] Smooth-On Silc Pig® colors "Blood" (PMS 7421C) and "Flesh" (PMS 488C) were added to the silicone to aesthetically resemble the small bowel.[14]

The cellulose fiber sheet and organic cotton fiber matrix were wrapped sequentially around a straight polyvinyl chloride (PVC) pipe with a diameter of 1.27cm. The silicone is then applied externally to the cotton matrix around the pipe and enclosed by another straight PVC pipe with a diameter of 2.54cm that has been cut in half lengthwise. The difference in the two PVC diameters determines the thickness of the silicone layer. An excess portion of uncoated cotton fiber matrix extends out of the mold longitudinally to create a sheet for the mesentery scaffold. After the silicone cures, the model is removed from the mold. To incorporate the mesentery, Smooth-On EcoFlex® Gel is dyed to the appropriate yellow color of adipose and applied to the non-coated cotton fiber sheet extending from the model. After the mesentery cures, a surgical lubricant is applied to the external silicone surface to reduce the coefficient of static friction and to represent the peritoneal fluid in the abdominal cavity. The fabrication process is laid out in a stepwise fashion in **Figure 1.**

MTS Testing

Mechanical testing of the synthetic small bowel was performed in the Biomedical Engineering Tissues Lab at UW-Madison. The silicone sample was placed in the MTS Criterion C43.104 equipped with a 2,248kg load cell, calibrated with a voltmeter (**Figure 2**). The raw data was collected by Test Suite software, and then analyzed with MATLAB R2015a. Three samples from the first generation prototype and three samples from the second generation prototype were tested. The differentiation between generations of prototypes is the incorporation of Smooth-On Slacker to the DragonSkin FX-PRO silicone mixture in the second generation.

Simulation Evaluation Questionnaire

All simulation exercises were conducted in April 2017 at University of Wisconsin Hospital (UW Hospital) in Madison, WI through the residency surgical training program. The methodology was institutionally approved under the scope of the Simulation Lab at UW Hospital.

Initially, the synthetic model was assessed by Dr. Jay Nathwani, a 5th year surgical resident in the Department of Surgery at UW-Health. He assessed the model by performing a resection and anastomosis on the prototype. The three criteria used to evaluate the completion of a successful anastomosis were: a) the diameter of the bowel should not be reduced by 50% or more, b) the sutures should not be caught on the back wall of the bowel and should not rip the synthetic tissue, and c) there should not be any air or fluid escaping from the incision line. Following preliminary evaluations, surgical residents in the medical program or affiliated with the University of Wisconsin, School of Medicine and Public Health or UW Hospital were invited to participate in a simulation exercise that included repair, resection, and two-layer hand-sewn anastomosis of the updated, second generation synthetic small bowel model.

A demographic survey of the residents was initially administered. All participants indicated sex, current position, specialty, years in training, number of bowel repairs performed (0, 1-5, 6-10, 11-15, 16-20, >20), currently teaching anastomosis procedures (Y/N) and experience using synthetic models (Y/N). The participant was given a synthetic small bowel that had been perforated to resemble a gunshot wound (in a basin with artificial blood) and tasked with completing a resection and anastomosis to repair the bowel. All necessary surgical instruments were provided including an open tray and sutures. The participants completed the procedure individually and were given 15 minutes to complete the simulation.[15] **Figure 3** shows a subject performing a resection and anastomosis simulation and the "repaired" small bowel model. Following the simulation, the participants were given a survey that evaluated various performance and aesthetic characteristics of the product, as well as its marketability in the medical simulation market.

Multivariate Analysis

After completing the simulation procedure, the participants provided feedback by taking a post-assessment survey, which included whether or not the model accurately resembled a human small bowel, procedural accuracy to that of the actual operating room, surgical accuracy on how the small bowel behaved upon suturing and tightening, and post-procedure confidence and satisfaction with the synthetic small bowel. In addition, the survey included marketability or how this model compares to other product and if the model was a useful tool to teach and anastomosis procedure).The survey was ranked on a 5-point Likert scale (1=highly inaccurate, 3=average, 5=highly accurate) and additional comments were submitted by the participants.

Results

MTS Testing Results

After the tensile testing was performed by a MTS machine, the data was analyzed through MATLAB R2015a to determine the maximum stress and the elongation at break for both generations of prototypes. Results were then averaged and recorded in Excel. **Table 1** shows the average maximum stress for first generation model (without Slacker) and the second generation model (with Slacker) (0.31 and 0.47 MPa, respectively). **Table 2** contains the data comparing the first and second generation models' average elongation to failure (233% vs. 196%, respectively).

Simulation Evaluation Questionnaire Results

Preliminary Resident Feedback

Dr. Nathwani, a surgical resident at UW-Hospital who was a reference for the qualitative nature of the surgery, was presented with the first generation prototype of the small bowel. During and following the anastomosis simulation on the synthetic model, he gave verbal comments and critiques, so we could not make the transition between the qualitative survey to a quantified "score" of realism, as was initially planned. His comments are listed below in **Table 3.** While Dr. Nathwani informed us that there is still room for improvement in the anatomical accuracy of the mucosa, he was very impressed in how our model accurately appeared and felt like actual human bowel. He ran some stitches through the silicone and cotton fiber matrix layer and noted that when pulled to tension, the string did not rip through the silicone, a feature that is crucial to model correctly to provide an accurate simulation of bowel anastomosis on real human small bowel (**Figure 3**). Overall, Dr. Nathwani said that, when paired with the mesentery, he could easily look at the prototype and identify it as a human small bowel (**Figure 3**).

Multivariate Analysis

The simulation and resulting survey was administered to three participants. Participant A responded that this simulation could be used to highlight strengths and weaknesses in their technical skills (4-Likert Scale). However, participant A also reported a 2 on the Likert scale in terms of anatomical accuracy, surgical environment, and performance.

Participant B expressed the importance and relevance for use of this simulation to enhance surgical and technical skills (5-Likert Scale). In addition, participant B reported a 4 on the Likert scale in terms of anatomical accuracy of the small bowel model compared to a human bowel. Specifically, the color, feel and overall look of the model represent a human bowel accurately. Minor improvements include making the surgical environment more realistic (2-Likert Scale) and the shape of the bowel could be improved (3-Likert Scale).

Participant C also emphasized that this simulation could be used to highlight strengths and weaknesses in their technical skills (5-Likert Scale). This participant also strongly agreed that this simulation made them more confident in performing the anastomosis procedure (5-Likert). Additionally, they think that this model is a better substitute than other synthetic small bowel materials they have used for this purpose (5-Likert Scale). However, the participant also stated that the product's feel could improve (2-Likert Scale) as well as its response to suturing tightly (3-Likert Scale).

The averages from the three categories of survey questions (physical/aesthetic accuracy, surgical accuracy, and marketability) were calculated in Excel, resulting in a median of 3. Results can be found in **Table 4**.

Discussion

The ultimate tensile strength, or maximum stress, is the maximum stress a sample can withstand while being stretched or pulled until fracture.[16] See **Figure 4**, a bar graph that compares the average maximum stress for the two generations of model and compares them to the maximum stress of human small bowel. The second generation model, which incorporated Slacker, had an average maximum stress of 0.47 MPa compared to the first generation's maximum stress of 0.31 MPa. The use of the Slacker and the cellulose fibers reinforced the cotton matrix, increasing the maximum stress that the model was able to withstand prior to tearing apart. The second generation on average has a closer maximum stress value to the desired stress of 0.9 MPa, the true maximum stress of human small bowel.[17]

The elongation to failure or strain is the percentage that the bowel stretched from its original length at failure.[18] See **Figure 5**, a bar graph that compares the average elongation to failure for the two generations of model and compares them to the elongation to failure of human small bowel. The second generation model, which incorporated Slacker, failed at an average elongation of 196% compared to the first generation model failing at 233%. Therefore, the second generation model better mimics the desired 163% elongation to failure value of small bowel.[13]It can be concluded that adding the Slacker to silicone decreased the elongation to failure for the second generation model to better mimic the mechanical properties of human small bowel.

While these two mechanical attributes are very mechanical in nature, they are relevant in their qualitative use as an assessment technique for the anastomosis procedure. Following the two-layer handsewn anastomosis, the teacher checks the sutures' placement and tightness by pulling on both ends of the small bowel. The stitches tear if placed too close to the resected area or, in simulation purposes, if the underlying material is not strong enough.[19] By ensuring that the mechanical properties of the maximum stress and elongation to failure are comparable, the suture strength will behave comparably to that of *in vivo* human small bowel tissue.

The results from the three residents' survey responses were analyzed using the corresponding Likert scale (1= highly inaccurate, 5= highly accurate). **Figure 6** shows a bar graph depicting the average aesthetic & physical accuracy scores, surgical accuracy, and marketability scores. Overall the second generation model scores in the average accuracy across all the categories that were assessed. The quantitative analysis of the survey proves this is a fair model for simulation of small bowel surgeries and the qualitative responses/comments of the subjects were positive. Subjects stated that the model "is a better substitute than other small bowel materials that I have used" and that it "could be used to highlight strengths and weaknesses in my technical skills." Because the second generation introduced Slacker, this increased the tackiness of the material providing a more realistic tissue feel.[20]Looking forward, this product needs to be offered to more subjects for surgical simulation to get more statistically significant results.

Additionally, the materials to fabricate each synthetic bowel model only cost $5.03. An additional $7.12 was used for the fabrication equipment such as the PVC nested pipes, silicone mixing materials, clamps, etc. This price of physical equipment was not included in the price per prototype, as the cost of equipment can be distributed over the creation of hundreds of prototypes. This final product is far less expensive than other models on the market, which can cost upwards of $300, dry out, and are not reusable. Following an anastomosis procedure, the sutures can be removed and the model used over again for another surgeon or for more practice. This small bowel model drastically cuts cost while maintaining its efficacy in providing residents and surgeons a realistic small bowel equivalent on which to practice life-saving procedures.

Conclusion

Overall, the second generation model that incorporates Slacker mimics the mechanical properties of human small bowel more accurately than the first generation model in both maximum stress and elongation at failure. The survey results from the surgical residents confirms the model's advantages over the current products on the market with its high degree of anatomical and mechanical accuracy, ease of fabrication (and thus, real-time availability), and overall decrease in product cost.

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Tables:

Table 1:

	Average Max. Stress (MPa)	Std. Deviation (MPa)
Samples without Slacker	0.3100	0.059
Samples with Slacker	0.4694	0.078

Table 2:

	Average Elongation at Failure (%)	Std. Deviation (%)
Samples without Slacker	232.53	101.92
Samples with Slacker	195.66	105.45

Table 3:

Question	Answer
Pigmentation?	Darker pink
Structural Integrity?	Pulls apart like mucosa
Tensile strength?	Feels just like bowel
Handling?	Needs to be more slippery
Surgery performance?	Feels a lot like tissue
Inner texture?	Needs improvement

Table 4: The Mean and Standard Deviations for the following categories from survey responses: Aesthetics & Physical Accuracy, Surgical Accuracy, and Marketability

	Aesthetic & Physical Accuracy	Surgical Accuracy	Marketability
Mean	3.20	3.08	3.57
Standard Deviation	0.77	1.38	1.09

List of Figure Legends:

Table 1: The maximum stress was determined using the Data Cursor on the graph determined in MatLab R2015a from the MTS data collection. Three samples from each generation of prototype were averaged. The standard deviation of the sample size was then found using formula on Excel.

Table 2: The elongation to failure was determined using the Data Cursor on the graph determined in MatLab R2015a from the MTS data collection. Three samples from each generation of prototype were ~~averaged~~. The standard deviation of the sample size was then found using formula on Excel.

Table 3: Dr. Nathwani's verbal comments on the anatomical accuracy of this first generation of small bowel prototype (without Slacker, but included mesentery).

Table 4: Average Likert scores (1= highly inaccurate, 5=highly accurate) across the three categories of questions across the three surveys obtained from the anastomosis simulations.

Figure 1: A schematic showing the steps of how the second generation prototype was fabricated. Labels A-H are noted in each photo's upper right corner. A) Fabricating cellulose sheath B) Placing preformed sheath on inner PVC mold C) Wrapping inner tube from (B) in cotton matrix D) Coloring DragonSkin/Slacker and EcoFlex Gel for small bowel and mesentery E) Spreading Smooth-On from (D) onto wrapped pipe from (C) F) Securing pipe/cotton matrix/silicone complex in outer mold G) Pouring yellow EcoFlex Gel onto cotton matrix to form mesentery H) Adding vasculature to the mesentery.

Figure 2: A) MTS testing performed on a small bowel synthetic model. B) Close-up of sample beginning to elongate. The raw data was collected from Test Suite software and further analyzed with MATLAB R2015a.

Figure 3: A) Dr. Nathwani running a stitch through the synthetic small bowel prototype. B) the synthetic small bowel post-resection and anastomosis simulation.

Figure 4: bar graph depicting the average maximum stress values for the two generations of models and compares them to the elongation to failure of human small bowel.[16]

Figure 5: bar graph depicting the average elongation to failure for the two generations of models and compares them to the elongation to failure of human small bowel.[16]

Figure 6: bar graph depicting the average aesthetic & physical accuracy scores, surgical accuracy, and marketability scores from the survey questionnaires following the simulation of a resection/anastomosis procedure. (n=3)

Figures:

Figure 1:

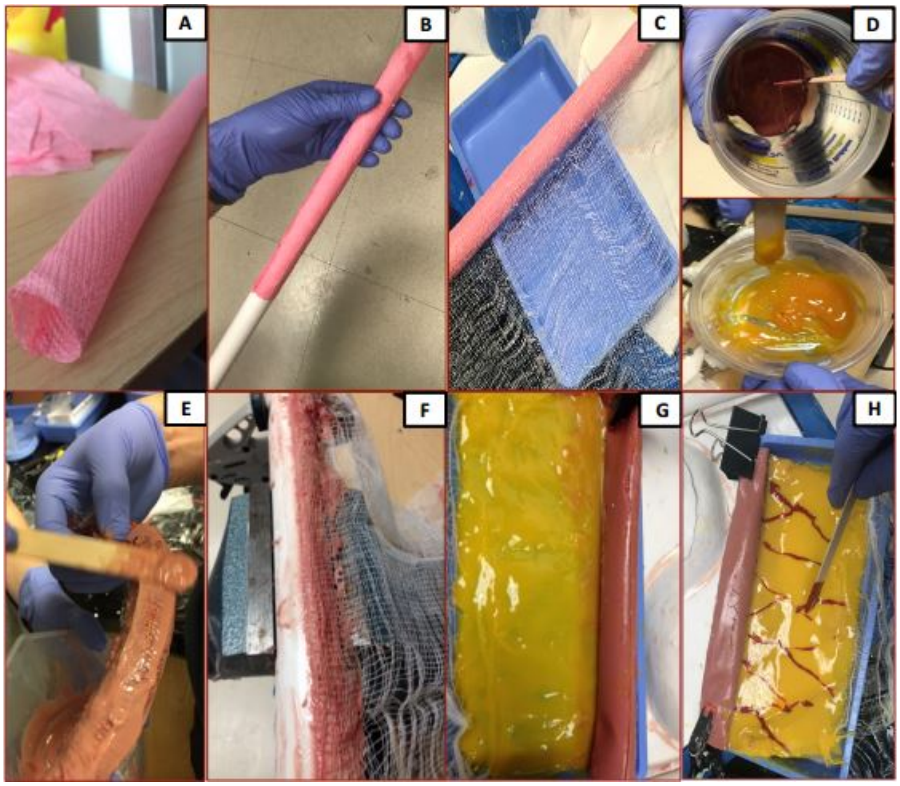


Figure 2:

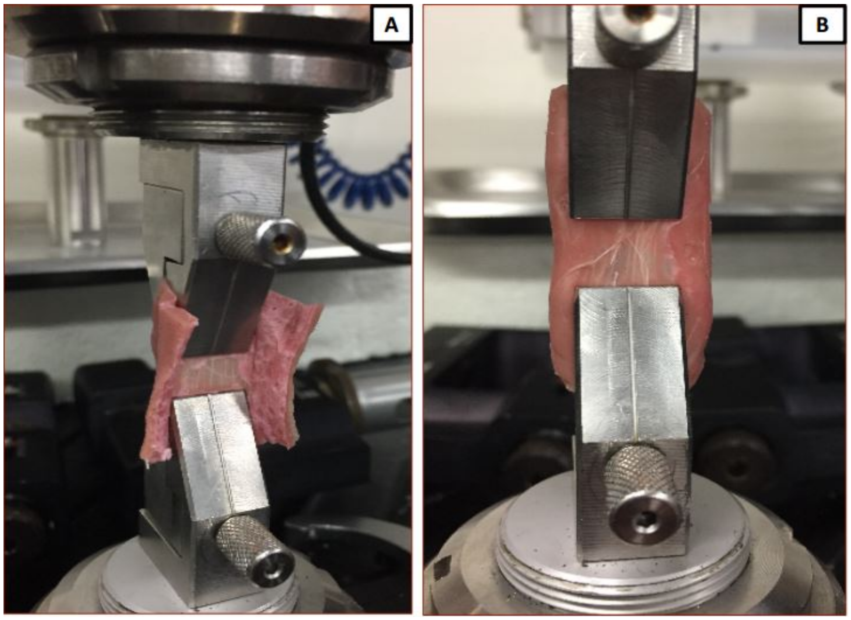
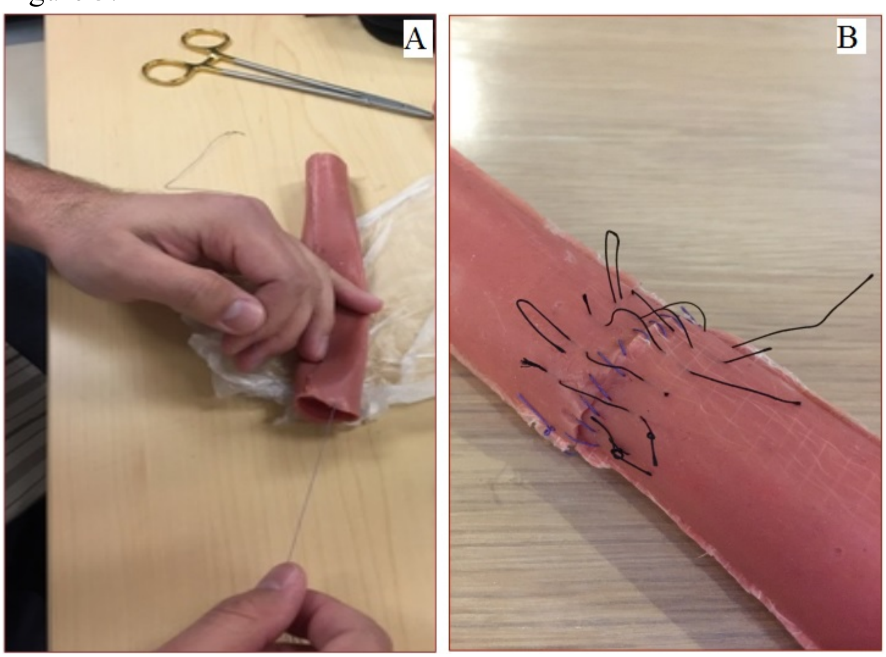


Figure 3:



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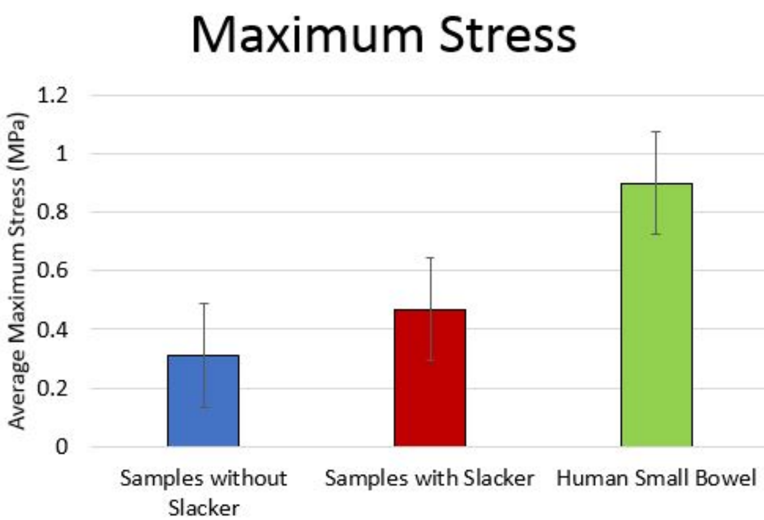


Figure 5:

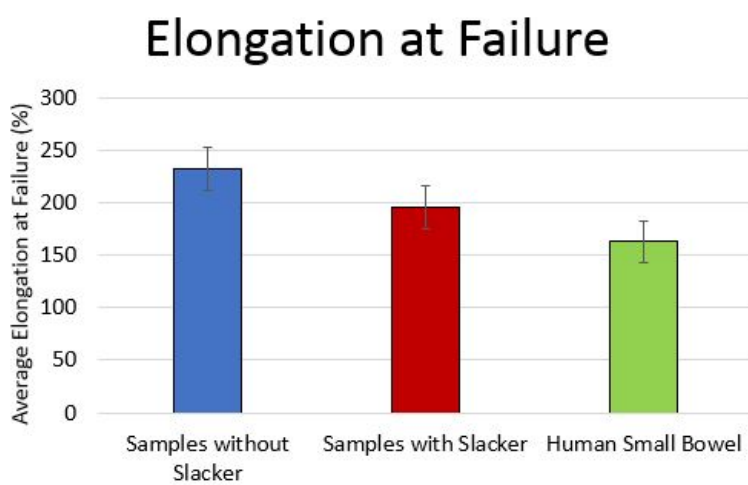
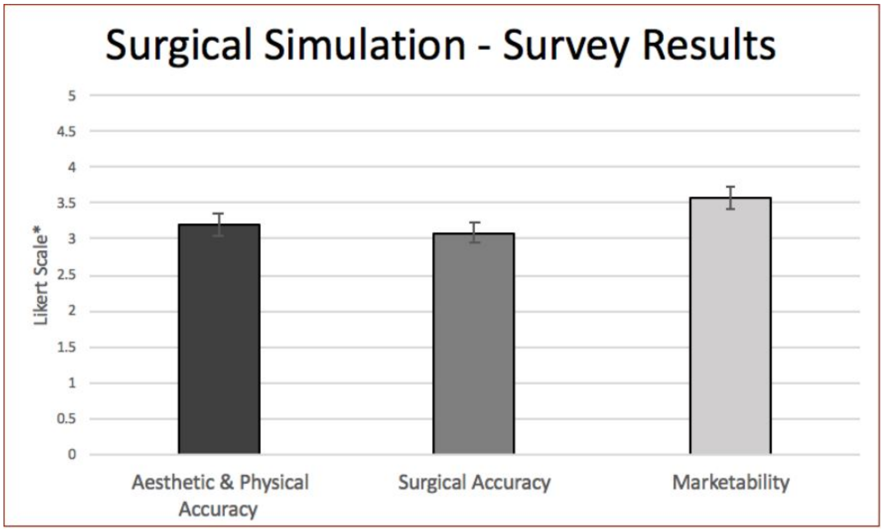


Figure 6:



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Appendix:

Participant Number

UNIVERSITY OF WISCONSIN SMALL BOWEL SURVEY

Completion of this survey constitutes your consent to participate and gives us permission to use the survey entries and simulation data for research purposes.

BACKGROUND INFORMATION

Directions: Select the option that ***best*** describes you.

1) **Current Position:**

Physician	
PA	
Medical Student	
Resident	
Other (please specify)	

If Resident / Medical Student…

2) **Intended specialty** ____

3) **Year in training** ____

If Physician, Nurse, PA or Other

2) **Specialty** ____

3) **Years of practice** ____

4) **Number of Primary Repairs Performed Per Month**

None	
1-5	
6-10	
11-15	
16-20	
> 20	

5) **Sex:**

Male	
Female	
Prefer not to answer	

		No	**Ye s**
6)	**Do you *currently* teach students or residents how to perform double layer anastomosis**	☐	☐

		No	**Ye**
7)	**Have you *previously* used synthetic models for…**		

s

Teaching?	☐	☐
Learning?	☐	☐

Directions: Rank the following statements before performing double layer anastomosis	**Highly inaccurate**	**Inaccurate**	**Average**	**Accurate**	**Highly accurate**
1. Generally, this product models the look of human small bowel	☐	☐	☐	☐	☐
2. Specifically, this product models the *color* of human small bowel.	☐	☐	☐	☐	☐
3. Specifically, this product models the *shape* of human small bowel.	☐	☐	☐	☐	☐
4. This model *feels* like human small bowel when I hold it.	☐	☐	☐	☐	☐
5. This model is a good representative model for primary anastomosis simulation	☐	☐	☐	☐	☐
5. I am comfortable with performing the primary anastomosis procedure	☐	☐	☐	☐	☐

Additional Comments/suggestions (If answered inaccurate or average, please give clarification on what is lacking):

Directions: Answer the following questions about the procedure	Highly inaccurate	Inaccurate	Average	Accurate	Highly accurate
1. The needle penetrates the model similarly to small bowel	☐	☐	☐	☐	☐
2. When the suture is tightened, the model does not tear	☐	☐	☐	☐	☐
3. The suture can be tightened appropriately	☐	☐	☐	☐	☐
4. When the suture is pulled taut, the material responds like small bowel	☐	☐	☐	☐	☐

Additional Comments/suggestions:

____

____

____

____

Directions: After performing double layer anastomosis...	Highly inaccurate	Inaccurate	Average	Accurate	Highly accurate
1. Overall this synthetic small bowel realistically mimics human intestinal tissue.	☐	☐	☐	☐	☐
2. Overall this synthetic small bowel is a good resource in practicing the anastomosis technique.	☐	☐	☐	☐	☐
3. This model has the potential to model different intestinal trauma.	☐	☐	☐	☐	☐
4. I am more confident in performing the anastomosis procedure.	☐	☐	☐	☐	☐
5. This small bowel model is a better substitute than other synthetic small bowel materials that I have used.	☐	☐	☐	☐	☐
6. Simulation is a valuable tool for clinical skills and knowledge.	☐	☐	☐	☐	☐
7. I would benefit from annual simulation courses.	☐	☐	☐	☐	☐

8. Simulation is a valuable tool in my training as a medical professional.	☐	☐	☐	☐	☐
9. This simulation could be used to highlight strengths in my technical skills.	☐	☐	☐	☐	☐
10. This simulation could be used to highlight weaknesses in my technical skills.	☐	☐	☐	☐	☐
11. The surgical environment was realistic.	☐	☐	☐	☐	☐
12. I behaved in the same way as I do/would in a real operation.	☐	☐	☐	☐	☐
13. The time I took to complete the anastomosis simulation was comparable to the real time in the operating room.	☐	☐	☐	☐	☐
14. The steps involved in the surgical procedure closely approximated a real surgery.	☐	☐	☐	☐	☐
15. I would recommend this simulation to people who are interested in developing/refining their anastomosis skills.	☐	☐	☐	☐	☐
16. I would have liked this small bowel simulation at my disposal during my residency/schooling.	☐	☐	☐	☐	☐
17. I would purchase this small bowel model.	☐	☐	☐	☐	☐

Additional comments/suggestions: