Medical Simulators for Developing Countries Via Low-Cost Two-Dimensional Position Tracking[1]

Robin Walz
Department of Mechanical Engineering,
University of Minnesota,
111 Church Street SE,
Minneapolis, MN 55455

Zachary Meier
Department of Mechanical Engineering,
University of Minnesota,
111 Church Street SE,
Minneapolis, MN 55455

Michael Winek
Department of Mechanical Engineering,
University of Minnesota,
111 Church Street SE,
Minneapolis, MN 55455

Timothy M. Kowalewski
Department of Mechanical Engineering,
University of Minnesota,
111 Church Street SE,
Minneapolis, MN 55455

1 Background

Mortality rates are unnecessarily high in developing countries due to lack of medical training or available procedures. For example, maternal deaths were estimated at 287,000 in 2010 of which 99% happened in developing countries [1]. Many of these deaths could be avoided if the physicians and nurses had a way to train and practice life-saving medical procedures like Cesarean sections or tracheotomies without risking harm to patients. A way to do this would be to have surgical simulators that they could train on. While the medical profession in the developed world has shifted to simulation-based training [2], current procedural simulators range from $500 to $300,000 [3], which is not an option for most hospitals or care providers in developing countries.

We propose an open-source ultralow-cost (less than $10 USD) medical procedure simulator platform that would be made of materials available in developing countries so that they could be locally made yet provide a means to accurately train and assess skill acquisition in medical procedures. Two enabling technologies may satisfy these requirements: low-cost bioplastics to simulate tissue and two-dimensional surface potentiometers to electronically track surgical tools on tissue. The goal of this research is to assess the feasibility of such simulators by evaluating the feasibility of these two technologies for low-cost medical simulators in the developing world.

2 Methods

The first part of the project consisted of developing an artificial tissue that would be made of inexpensive, locally available mate-
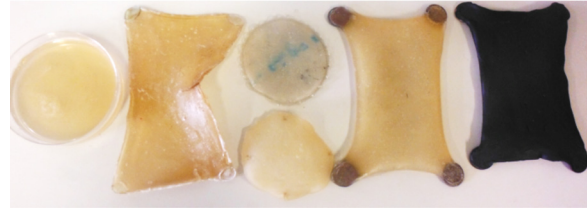
Fig. 1 Bioplastic samples (left to right: gelatine (wet), gelatine (dry), starch (top) and fautex (bottom), fautex, and fautex with graphite powder)

rials, and that would provide some conductivity in order to use as a two-dimensional potentiometer to track a typical tool (e.g., scalpel or needle) interacting with tissue. Our idea was to use bioplastics based on prior work from Azwar [4], Gaspar et al. [5], and Yunos [6], as the ingredients are ubiquitously available and very inexpensive in addition to being recyclable, environmentally sound, and safe. We looked at two different bases for our recipes: starch and gelatine. We experimented by varying the proportions of the ingredients and trying to add additional ingredients like vinegar, salt, or graphite (pure graphic powder, General's Pencil Co., Redwood City, CA, and powdered graphite lubricant, Hillman Group, Cincinnati, OH) in order to obtain the mechanical properties desired that would replicate skin tissue as best as possible. The last recipe involved low-cost construction silicone sealant (premium waterproof silicone, Momentive Performance Materials Inc., Columbus, OH)–derived plastic (Fig. 1).

The typical recipes are as follows: gelatine (3 g glycerin, 12 g gelatine, 60 ml water); starch (ratio by volume: 3 tapioca starch, 12 water, 1 glycerin, 1 vinegar); fautex (250 ml water, 23 g starch, 7 g gelatine, 40 g vinegar, 60 g glycerin); silicone (ratio by volume: 1 silicone, 3 graphite lubricant, 1/4 starch) (Fig. 2).

A two-dimensional potentiometer would enable an inexpensive microcontroller (<$4 USD) to track the position of a surgical tool in our synthetic tissue. This required a polymer with overall resistance of 100 Ω to 1 MΩ. Two types of conduction mechanisms were tested: one due to the salt and water in the bioplastics (ionic conduction), and the other due to the carbon present in the plastic from the graphite powder. We also tried various probe arrays. Our starting method was a 2 bar method that created a one-dimensional potentiometer. We evaluated two four-point probe methods for two-dimensional potentiometry. The first grounded our moving probe (scalpel) and voltage and ground was alternately applied through known resistors at each corner of the sample, then measured the voltage at each corner. The second method is shown in the schematic below, where we apply a voltage at two corners and ground the other two, while measuring the voltage of the moving probe. We then switch voltage assignments through all permutations at high frequency in order to get measurements in both the x and y directions. In all probe strategies, the contact resistance between the pad (pennies were used) and potentiometer material is not negligible.
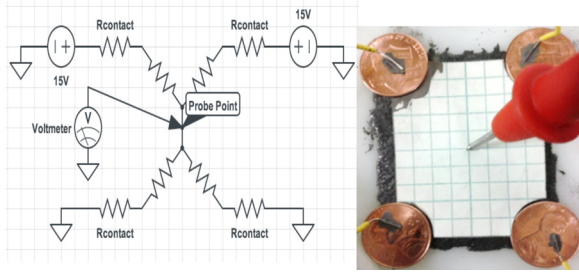

(a)   (b)
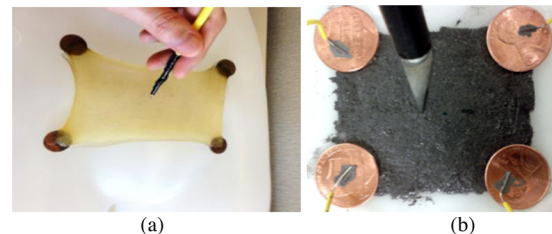
Fig. 2 (*a*) Low-cost simulator concept: re-usable, flexible bioplastic insert on mannequin tracks incision accuracy in C-section trainer. (*b*) Silicone and graphite plastic tracking tool position in 2D during incision test.
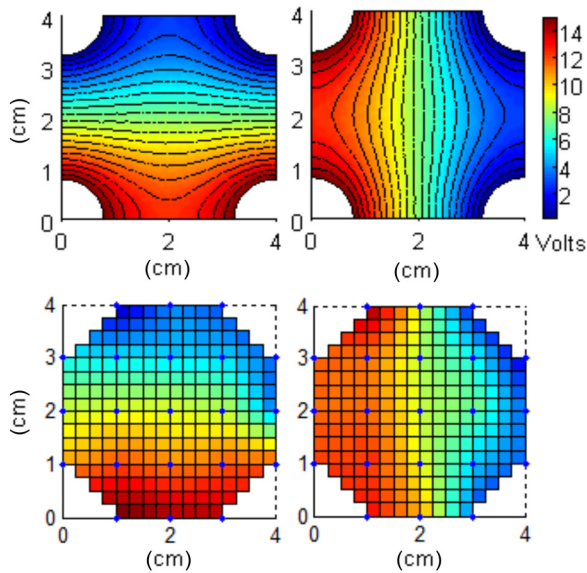
Fig. 3 Schematic of the four-point probe for a single permutation of switching pad voltage schemes (left) and method of testing voltage to grid of finite spacing (right)

Fig. 4 (top) Simulation results for spatial voltage distribution on two permutations of voltage input; and (bottom) corresponding data (dots) and extrapolation (color map) from silicone + - graphite polymer sheet

We adopted a finite element model of diffusion in dc conduction for two-dimensional media to model the expected mapping of 2D position to voltage measurements. We employed MATLAB's (MathWorks Natick, MA) partial differential equation toolbox to numerically compute this with the conditions

$$-\nabla \cdot (\sigma \nabla(V)) = q, \quad E = \nabla(V)$$

where conductivity $\sigma = 1$, $V = 15\,\mathrm{V}$, a mesh of $n = 2469$ nodes, and dimensions to match potentiometer shape.

To evaluate whether design candidates met the feasibility criterion, we employed the following scale: (+) favorable/acceptable: close to what we want (0) marginal: not ideal but will still operate, and (−) not acceptable: could prevent the design from being operational depending on how critical the criterion is (Fig. 3).

3 Results

Tables 1–3 present the results for the different materials, methods, and prototypes researched (Fig. 4).

4 Interpretation

We explored a variety of recipes for artificial tissues that exhibited mechanical properties comparable to human skin as well as relatively low electrical resistance. These bioplastics proved desir-

Table 1 Bioplastic recipe comparison

Recipe base	Cost	Time to make	Stretchable properties	Optical properties	Electrical properties	Reusable	Shelf life
Gelatine bioplastic	+	+	+	+	−	+	−
Starch bioplastic	+	−	+	−	−	−	+
Fautex	+	+	+	+	−	+	+
Paper + graphite	+	+	−	−	+	−	+
Silicone sealant	+	+	+	−	+	−	+

Table 2 Electrical conduction mechanisms

Conduction mechanism	Optically transparent	DC potentiometer	Messy	Compatible w/electrodes
Ionic	+	−	+	−
Electronic	−	+	−	+
Combined	−	−	−	−

Table 3 Probe array methods

Probe arrays	Reliability of measurements	Complexity of setup	Complexity of use	Capable of 2D
Four points with probe as voltmeter	+	0	0	+
Four points with probe as ground	−	0	0	+
2 bar	+	+	+	−

able in terms of simplicity to make, recyclability, and availability and cost of ingredients. However, they failed to provide accurate potentiometer measurements due to their ionic conduction. Ionic conduction rendered the sample's conductivity nonhomogeneous, making it impossible to track a tool accurately with a potentiometer system. Therefore, our best solution for accurate tracking was the silicone-sealant-based recipe that includes a large proportion of graphite, but no water, and, therefore, no ionic conduction. The type of graphite used was found to be crucial. The graphite used must have larger flakes (approx. 200 μm width, <50 μm thickness) such as the graphite lubricant used for this experiment. Finer graphite lubricants, carbon black, or granular graphite powder will not work. Any clear silicon sealant can be used for this recipe, and it is a product that is available in developing countries at a cheap price (around $5–$10 per tube). However, even though graphite lubricant is available in most places around the world, the specific kind needed may not be.

The voltage measurements from the silicone graphite sample are close to the simulated values from a homogeneous potentiometer even though our sample was not perfectly flat or uniform. Moreover, the inner area (center $2\,\mathrm{cm} \times 2\,\mathrm{cm}$) appears quite consistent, suggesting this may be a viable method to track tools accurately if the targets are located in such a region.

We discovered no single biopolymer that could meet all of our requirements. However, we produced stovetop biopolymers that were favorable in most regards except electrical. If these can be used to model the bulk of tissues and a very thin layer of silicone-sealant-derived compound provides sensing, then the low-cost simulator for global health applications may be feasible.

Future work will include developing a polynomial model of position based on voltage readings for low-throughput processing and investigation of potentiometric methods for ionic conduction via capacitive coupling to obviate ionic conduction artifacts.

References

[1] WHO, 2012, "Maternal Mortality," World Health Organization, Geneva, Switzerland, http://www.who.int/mediacentre/factsheets/fs348/en/

[2] Kunkler, K., 2006, "The Role of Medical Simulation: An Overview," Int. J. Med. Rob. Comput. Assist. Surg., 2(3), pp. 203–210.

[3] SIMULAB Corporation, 2014, www.simulab.com

[4] Azwar, E., and Hakkarainen, M., 2012, "Tuning the Mechanical Properties of Tapioca Starch by Plasticizers, Inorganic Fillers and Agrowaste-Based Fillers," ISRN Polymer Science, 2012, p. 463298.

[5] Gaspar, M., Benko, Z., Dogossy, G., Reczey, K., and Czigany, T., 2005, "Reducing Water Absorption in Compostable Starch-Based Plastics," Poly. Degrad. Stab., 90(3), pp. 563–569.

[6] Yunos, M. Z. B., and Rahman, W. A. W. A., 2011, "Effect of Glycerol on Performance Rice Straw/Starch Based Polymer," J. Appl. Sci., 11(13), pp. 2456–2459.