Dynamic Tissues for Responsive Moulage in Infected Wound Training

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Abstract

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Trainings for military medics are shifting focus as the nature of combat changes, requiring new training modules for long term care including the recognition and treatment of infected wounds. This paper proposes a morphing moulage design for infected wound training simulations. The medical simulation industry is rapidly growing as it replaces old textbooks and animal models and improves existing medical training with the increased inclusion of more hands-on practical skill learning. Creation of high-fidelity simulators is an emerging field of study that has shown that the inclusion of moulage significantly improves engagement and learning in these simulations. To further improve the moulage, I have developed a dynamic moulage to represent an infected wound that is capable of changing appearance in response to actions taken during a simulation.

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Acknowledgments

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Dedication

This work is dedicated to everyone who helped make it happen. I could not have finished this project and achieved what I have without the support of my family, including my fiancé Baylor Blair and my parents, and my friends. Baylor has been supportive, always willing to read through drafts and offer his feedback in addition to listening to all my complaints patiently. I would also like to dedicate this to my cat Marceline and my childhood cats Spirit and Squeek who kept me sane through countless finals weeks and were always there for me. This work is also dedicated to my mentor Alex Gong without whom this project would likely have not been possible. His endless support and assistance even when nothing was working was invaluable.

Introduction

Medical Motivation

Global military engagements have shifted from the traditional battlefield and defined theaters of operation to small units deployed in various, often remote locations [1]. This has in turn also caused a shift in how the United States treats soldiers wounded in the field. With this lack of a shared deployment location, the "Golden Hour" system where injured soldiers would be airlifted out of combat and be on a surgical table within an hour, is impossible to maintain. Now, it is days instead of hours while the troops travel to a safer location where aerial evacuation or trained medical staff are available. This extended time before surgery can be performed creates the need for better trained field medics that can provide all necessary care for seriously injured soldiers before surgery is performed. This has been dubbed prolonged field care (PFC) and has been a serious focus of the Department of Defense for the past few years to ensure the United States' deployed troops receive the highest level of care despite the additional challenges posed by the new form of deployment and combat.

With the quick evacuation times available for injured troops in previous military engagements, the focus of medics used to be lifesaving point of injury trauma care [1]. Long term care, while included in their initial training, was rarely if ever utilized. Because of this, additional training with a focus on these long-term treatments have had to be developed to assist in refreshing skills of current medics and to train new medics with more of a focus on these long-term skills. The skills required of medics include both advanced surgical care and nursing duties, therefore training modules are required for both. The focus of this new training tends to be on the advanced surgical skills required of the medics like administering blood transfusions and placing a chest tube, but just as important in these remote locations are traditional nursing duties. These include wound examination, irrigation, debridement, dressing, and infection prevention and treatment, all of which can cause an injury to turn fatal if not executed properly [2].

Infections can cause delayed healing in the wounds in addition to death in extreme cases [3, 4]. Not catching early signs of an infection also greatly increases the cost of treatment and the likelihood that the infection will become drug resistant. Drug-resistant infections are becoming a larger concern in the medical world due to the difficulty to treat them and their expensive nature [4]. Because of these factors, it is important to teach medics how to identify early signs of infection and how to treat these injuries effectively.

Those in the military are at a higher risk for infections, with one study finding that deployed personnel are at a 4 times higher risk for skin and soft tissue infection (SSTI) than the general public [5]. Out of the military personnel that responded to the study, 5% had experienced at least one SSTI recently. Of those that reported having an infection, 20% of them had to miss work for at least one day due to the infection. Dermatologic conditions accounted for 10% of all disease and non-battle injuries as well. In the military, missing work can have a significant impact on the mission and may mean that the person is not fully operational, which may put themselves and their comrades at risk. While this study focused largely on military personnel not in a fighting arena, they found that many of the factors like crowding, sharing personal items, lack of general hygiene and cleanliness, and frequent skin injuries that contributed to the risk for SSTI's would also be present while deployed. Quick and effective treatment of these infections is important to ensure the comfort and safety of all deployed persons.

Literature Summary

Currently, many training programs use textbooks to teach sight-based skills like recognition of wound infection progression. These depictions are not very accurate as they are not three dimensional or dynamic and only show a single snapshot of a wound. The most promising method for improving the treatment of infected wounds is to incorporate simulation based medical training to expand hands on practice options for learning. Simulation based medical training has a long history of use and is still being researched and improved upon today [6]. There are currently 5 classifications of simulations: verbal, part-task trainer, standardized patients, computer patients, and electronic patients [6]. Part-task trainers are models of individual body parts or systems and focus on particular tasks or afflictions while electronic patients can either be physical manikins or done through virtual reality [6]. These types of simulations can

be very effective for teaching skills in a hands-on manner and are used in many settings including hospitals, schools of medicine, and military training programs [7-11].

While the research on the efficacy of simulators used in an educational setting is not definitive, it is still an emerging field that deserves to be looked into as it may assist in improving skill retention and patient outcomes. One study found that trainings including manikin based simulations significantly improved the students' skills dealing with managing mechanical ventilation [10]. Another found that integrating physical simulations in a graduate level medical training program significantly increased the students final scores and clinical performance [9]. But other studies have found no difference, or their results are inconclusive and they suggest further testing with larger populations [11]. These issues are compounded by the fact that the simulation industry is not federally regulated nor are there agreed upon methods for evaluating the realism. This has resulted in varying quality of simulations and no set of baseline standards, making the results of a simulation very specific to that particular simulation. Overall, more research needs to be done to find more conclusive evidence on the effect of physical simulations like manikins and task-trainers on medical performance and patient outcomes, but early research indicates it may have a positive effect.

Despite the research into efficiency of simulations not being complete, the demand for medical simulators is growing. In 2018, the compound annual growth rate of the medical simulation industry was 15.44%, reaching 2.27 billion in 2019 [12]. More institutions are moving away from using animal models in their training programs testing due to ethical reasons and with cadaver models being prohibitive in availability and cost, new simulators are needed to fill the gap [13]. The military is one of these institutions and their curriculum includes a variety of physical and virtual simulations to train their Forward Surgical Team that are deployed to the front lines [7].

Currently most simulators do not qualify as medical devices and because of this, they are not regulated or held to any form of standard. This has resulted in the simulation industry being inundated with sizable amounts of low accuracy, cheap simulators. To further improve the field of simulation technologies for medical education, new models need to be developed that are dedicated to being high fidelity. Higher fidelity simulators are thought to be more effective at teaching medical skills than lower fidelity models. They have even been shown to be more effective than traditional lecture-based teaching in some cases [9, 10, 14]. Moulage is considered to be the use of make-up and/or special effects techniques to simulate life-like injuries. It enhances the realistic appearance of simulations and helps participants more fully engage in the experience [8, 15]. Engagement in the simulation is a significant determining factor in how much effect the simulation has on learning, with higher engagement levels leading to higher levels of retention [15]. In addition, much of the feedback of current simulation trainings from participants list poor tactile sensation, tissue behavior, and visual error or unrealistic appearance as the main detractors of the simulators [7, 8, 15]. Because of this, moulage is an essential aspect of physical simulators that can contribute to their fidelity.

This project aims to produce a simulation of an infected wound that can be used to train medics in recognizing the signs of infection. This module will utilize novel dynamic moulage to present the symptoms of an infection that is intended to further increase the fidelity of the moulage. In terms of developing this simulation, a number of actuator designs have been researched and published for applications in soft robots that are applicable to creating a model that can swell on command [16-19]. Most involve creating pressure in parts of the system to create swelling in specific directions to achieve movement or force generation. That swelling can be produced by the inclusion of ethanol either mixed with the silicone or encased by it. With the application of heat, the ethanol changes phase to become a gas and expands. This puts pressure on the silicone which then appears to swell. The same principle is applied for wax actuators, but they use the expansion arising from the change from solid to liquid wax [20]. This is typically a smaller, but more forceful expansion than when utilizing ethanol.

Electrical conduction will also be necessary in the simulation model to create the heat to trigger the phase change responsible for the swollen aspect of the design. Basic nichrome wires can be used as resistive heaters to quickly and consistently achieve the desired temperature and are often used in soft actuator applications [18]. The wire would likely have to be custom produced for the specific shape and surface

area needed though. Another option is using a conductive material that can be mixed into silicone to make the silicone itself conductive and able to function as a resistive heater. One of these materials that is relatively cheap and usable in silicone, is carbon black [21].

Methods

Development of Design Specifications

There are a number of elements the simulation model needed to have to accurately represent an infection. An infected wound has edema and this swelling was an important aspect of the model. The time to full expansion in addition to the height and shape of swelling were important aspects to be considered when evaluating the different swelling mechanisms. Finally, the swelling needed to be reversible to allow for feedback within a simulation and reusability.

Another important aspect of the model was its overall appearance. Within the appearance there were two main factors: wound shape and erythema. There needed to be an actual wound that could feasibly be obtained while deployed and then infected. This was important for public health reasons, to ensure the simulation could be recognizable to medical professionals. There also needed to be a color change to represent erythema that involves the transition from a typical skin tone to a reddish color to be accurate to an infection. The color change also needed to be reversible to allow for a dynamic response and reusability.

An additional aspect of the model that was included was the representation of purulence through the active release of pus. This material needed to start the simulation unseen or as part of the wound or scab, and then transition to be seen as pus. The consistency of the material after the transition would ideally be fairly viscous, similar to that of pus as well as being similar in color.

All of these aspects were heat activated and the development of a heating element that can be integrated into a silicone model was additionally required. This element needed to be able to heat up to a target temperature quickly and consistently and be able to provide adequate heat to trigger all of the changes in the model. A number of different considerations were considered for this element with safety being the most important. Users should not be able to burn or shock themselves when interacting with the device.

Including all of the aforementioned aspects into a single model is the final design requirement. Only altogether, do all of these individual aspects accurately represent an infected wound.

While not required, if the model is able to be reusable, that would be ideal so that it can be used in numerous simulations and not just one before it has to be replaced. This would be both ideal economically and environmentally conscious with the cost per model and waste being reduced.

Manufacturability was considered as well when finalizing the design of the model. The ideal, most manufacturable option would be to make all the aspects 3D printable. It would also be acceptable to have only some aspects 3D printable or to have a streamlined set of easy-to-use molds. This would reduce time and complexity to manufacture.

Manufacturing Process

Building onto work done previously during the capstone project, some of the goals for the thesis project was to further improve the design of the model in terms of manufacturability, physiological accuracy, and reusability.

One area of improvement was in the edema element. The amount of swelling seen previously in the ethanol models was too large to be accurate, was difficult to manufacture, and made reusing the model limited. To this end, wax was investigated as an alternative material based on previous usage of the material in wax actuators that achieved small but powerful expansions [20]. Two separate methods for wax expansion were tested with one having the wax encased in a single chamber and the other with liquid wax mixed into the silicone precursors so it was encapsulated in small pockets distributed throughout the silicone. When mixing the wax with the silicone instead of using the chamber design, the

wax was heated until it was a liquid and then it was slowly poured it into part A of the silicone and stirred vigorously until it was well mixed and there were small droplets of cooled wax fully mixed in with the silicone. Part B of the silicone was then added, mixed, and the mixture could be poured like regular silicone. A number of different percentages of wax were tested including 20%, 40%, and 60% wax. The wax used here was basic paraffin wax with a melting point of about 54° C, but other melting points can be purchased to fit users' specific needs.

Another area of improvement was in the purulence element. As the switch to wax had been made for the purpose of edema, melted wax was additionally considered to be the pus. This would be simpler than trying to integrate a custom hydrogel as was initially planned and trialed. A second chamber of wax was placed right below the surface of the wound and a 16-gauge needle coated in Vaseline was used to make a series of holes along the deepest portion of the wound into the wax chamber. When the main wax chamber expanded, it pushed on this smaller chamber and squeezed out the liquid wax which appeared like pus.

Another area of attempted improvement was the heating element. Conductive materials can be mixed with silicone to make a conductive layer that is capable of resistive heating [21]. Carbon black is one such material that is popular for its low price. Using these materials would significantly improve the manufacturability of the model by eliminating the use of the nichrome wire. After mixing silicone with carbon black, the silicone became very difficult to work with, making the manufacturing process complicated. Because of this, the heating element stayed as a hand coiled nichrome wire for the final model.

Another area of improvement was the general manufacturability. While one initial thought was to make every aspect 3D printable, some of the 3D printable materials like the carbon black silicone mixture and wax mixed in with the silicone did not end up being the optimal choice. Instead, the focus became making the manufacturing process for the materials that were chosen as simple and quick as possible with minimal labor. This led to the design of a series of 3D printed molds shown in Fig 1. There were two bases, each with a number of sequential lids that can be used to produce the final model. Each layer of silicone is injected on top of the previous ones to build up the final model. There are two separate molds in this process, one for the reusable bottom half that is responsible for the swelling and heating, and one for the nonreusable top half that is responsible for the color change and purulence. To prepare the molds for use, they must be coated in Vaseline and then the top and bottoms secured together using hot glue. Once this is done, the silicone can be injected.

Figure 1: 3D printed molds used for making the model

The process for manufacturing the bottom half is as follows. Prepare the base mold with the lid for layer one. Prepare 80g of P70 silicone according to the manufacturer's directions, vacuum until the air bubbles are gone, and inject into the prepared mold. Ensure the place holders for the thermocouple and wires are in place before pouring. This layer takes at least 16 hours to set so while it is, wind the wire into the desired coil shape as shown in Fig. 2. Then remove the lid and trim off any excess silicone, remove the placeholders, and place thermocouple and wires. A weight may need to be placed on the wires to keep them in position through the silicone pouring process. Prepare 15g of Gel 25 and hardener in a 1:1:1 ratio and pour over the wires

Figure 2: Shaped nichrome wire taped in place with petri dish placed on top to show its size

and thermocouple. This will hold these pieces in place for the next injection step. Prepare the mold with the next lid and then prepare 55g of Gel 25 with hardener in a 1:1:1 ratio and inject into the mold. Once this has cured fully, the wax can be added. Remove the lid to the mold but leave the silicone in the base to ensure it keeps its desired shape during the wax pouring process. Melt 5g of wax over a hot plate. Place the wax pouring lid on the base mold and pour the liquid wax into the opening until the cavity is full. Any excess that spilled out of the cavity can be removed after the wax has solidified. Then prepare the next mold and 24g of Gel 0020 and inject it. Once this has set, the part can be completely demolded, and excess silicone trimmed off. This process takes approximately 160 minutes of labor spread across multiple days to allow for the silicone to set in between layers.

The process for manufacturing the top half is as follows. Prepare the initial mold and 22g of Gel 0020 to inject. The next step is to pour the wax that will be used for the purulence aspect so heat up 1.0g of wax over a hotplate. Once it is fully melted add a few drops of yellow dye and a pinch of TiO_2 to achieved desired color and opacity. Remove the lid from the mold and pour the fully mixed liquid wax into the cavity until it is full. Let this cool for at least ten minutes before preparing the next mold. Next, measure out 0.5g of the thermochromatic powder and add to 35g of part A of Gel 0020. Additionally add a few drops of skin pigment, one srop of brown pigment, and a large pinch of skin colored flocking. Mix this thuroughly before adding 35g of part B of Gel 0020 and then vacuuming and injecting into the mold. It is important to minimize airbubbles in all layers of the silicone, but especially this top layer. To reduce airbubbles, inject slowly and throughout the injection, hit the mold against a surface to bring air bubbles to the surface. This process took 70 minutes of labor over the course of two days to allow the silicone to fully set between layers. The bottom of this top half and the top of the bottom half are then coated in a thin layer of ecoflex gel mixed with 5g part A, 5g part B, and 6g deadner. This is painted on and when cured is extremly sticky, allowing the two layers to stick together on the model.

To build the circuit for the model, an Arduino mega was used and the circuit is laid out in Fig. 3. The type J thermocouple that was molded into the model was hooked up to a thermocouple amplifier MAX31856. This board was then plugged into the Arduino with the Vin port wired to the Arduino's 5V output and the GND port wired to a GND port on the Arduino. The SCK port was wired to peg 52, SDO port to peg 50, SDI to peg 51, and the CS port to peg 53. A 5V relay was then added to the circuit for heating control. The relay was wired with input from the Arduino from peg 6 and power from the Arduino's 5V peg. The relay additionally had its ground connected to ground on the Arduino. The common peg of the relay output was connected to one side of the coiled heating wire in the model. The other end of the coiled heating wire was connected to the positive port of a 12V power supply. The normally open peg of the relay output was wired to the negative port of the power supply. The Arduino code read the temperature from the thermocouple embedded in the model and then turned the relay on if the temperature was below the set point and then turned it off once the temperature was achieved. If the temperature dropped back below the set point, the relay was then turned back on.

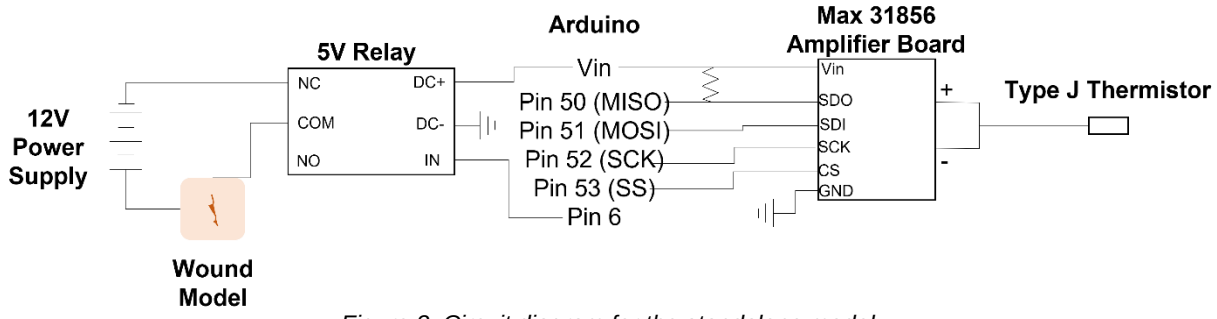

Figure 3: Circuit diagram for the standalone model

The next step was to take the standalone model and integrate it into a manikin. While the wound could theorheticaly be placed anywhere on the manikin there was enough internal space for the base layers and circuitry, the face was selected as it was considered to be the most emotionally compelling location for a wound. To create the new molds, heated clay was spread over the face and allowed to cool to capture the topography of the face. A wound was carved into this clay and then silicone poured over this to create a negative to be used in the new mold for the skin layer. The model needed to be reduced in

size to fit inside the cavity behind the face. To reduce the footprint of the circuit, an Ada Fruit itsy bitsy was used instead of the Arduino mega and the peg numbers were adjusted accordingly. For the model itself, the mold designs were updated and reprinted to be smaller with the width being reduced. The silicone recipes were reduced in volume to reflect the smaller mold sizes, but otherwise remained the same. The recipe for the skin layer did need to be adjusted in terms of pigments used to ensure the skin tone matched that of the already manufactured face being used. Additional code was also written to receive physiological data like core temperature from a biogears simulation. This core temperature was used to inform when the infection should start to develop with the heating process starting when the core temperature reached a certain above normal temperature.

Finally, a survey was conducted using a timelapse video of the benchtop model that was not integrated into a body part. The survey was distributed through email among surgery groups and 15 surgeons responded. The survey began by showing a timelapse video of the benchtop model being heated and then asked a series of questions and had the participants respond using a five-point Likert scale of agreement.

Results

Conductivity and heating testing was done with the carbon black samples using small uniform 4cm by 2cm rectangles of differing concentrations of carbon black with two parallel wires running through them. The carbon black was mixed with gel 0020 which had a longer handling time and was very viscous to try to allow larger amounts of carbon black to be mixed in. The intended concentrations of the rectangles 15%, 20%, and 25% but the 20% carbon black mixture was so viscous that it was very difficult to thoroughly incorporate the carbon black into the silicone and it would be difficult to pour into the mold and so the 25% concentration of carbon black was not made. The heating results for the 15% carbon black rectangle is shown in Fig. 4. After 20 minutes at 10 volts, the surface temperature of the carbon black had increased from about 23 to 32° C and the after 20 minutes at 12 volts, the sample had increased from about 23 to 36° C. The temperature on the surface was not uniform with the corners differing from each other by up to ten degrees and the middle of the rectangle being somewhere in between. It was the temperature of the middle of the model that was recorded and graphed in Fig. 4. The 20% carbon black rectangle was not conductive. One possible reason for this could be how viscous it was leading to air pockets or clumps of carbon black that was not entirely mixed in. Other methods for mixing carbon black into silicone were tested including sonification and mixing the carbon black with ethanol first before mixing it with the silicone. These methods did not improve the viscosity issue enough and the ethanol method required too much ethanol that it interfered with the silicone curing. Both with 10 and 12 V, the temperature of the 15% carbon black sample started to plateau around 10 to 15 minutes into testing. To be usable as a heating element to melt the wax, the desired temperature for this layer would have to be at least 55° C. Because of this, carbon black was deemed to be not the right choice for this application due to the manufacturing difficulties and its inability to produce the amount of heat needed.

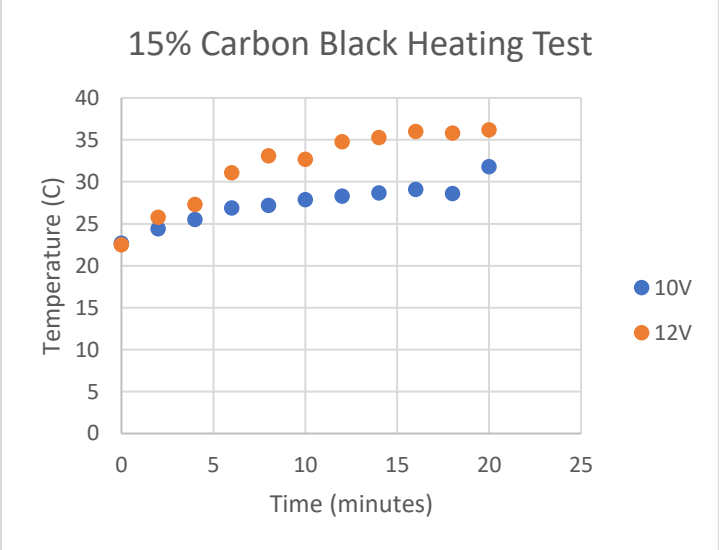

Figure 4: A graph showing the surface temperature of the 15% carbon black test rectangle

Similar issues were encountered when trying to use wax as the phase change material but distributing it throughout the silicone mixture instead of encapsulating it in a chamber. The silicone mixture with 40% and 60% wax were very difficult to mix and pour as it became extremely viscous almost like playdough or wet sand. After curing, the wax fragments were also visible and leaked out of the layer surfaces when

heated. The 20% wax sample was easy to mix and pour and cured well with minimal visual defects. Upon heating there was no noticeable swelling though. This process likely could have been somewhat refined through experimentation in the manufacturing process, but with the encapsulated chamber method working well, this method was abandoned.

When comparing encapsulated ethanol and wax as the phase change material used, ethanol produced a larger deformation as seen in Fig. 5a-b, but had a higher transition temperature around 80° C. While the amount of deformation could be tuned by changing the size of the chamber and therefore also the amount of ethanol, it was also limited in its reusability with the ethanol presumably evaporating out over time. The encapsulated wax chamber produced a smaller deformation as seen in Fig. 5c-d, but had a much lower transition temperature at 54° C. The edema being simulating should not be overly large and so the wax was chosen as the material moving forward as its level of deformation was deemed more physiologically accurate in addition to having a much lower transition temperature that would be safer for users and more similar to a physiological feverish state. The wax was also much easier to work with as it did not need to be injected into a preformed chamber.

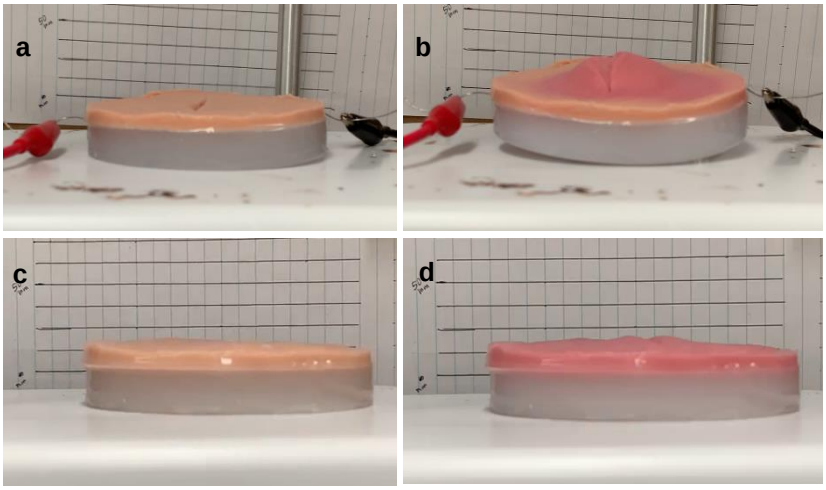

Figure 5: Before (a) and after (b) heating images of a model with a chamber of ethanol as the phase change material as well as a before (c) and after (d) heating images of a model with a chamber of wax

The testing of the nichrome built on that done in my undergraduate capstone and was done while the wire was integrated into a full model. The surface temperature and the internal temperature of the layer right above the wire was recorded during testing and recorded in Fig. 6. To simulate a localized fever, a surface temperature of 99°-104° F or 37°-40° C is ideal. With no electrical regulation of the heating process, the temperature increases in a fairly linear matter, reaching the target internal temperature of at least 55° C needed to melt the wax within 20 minutes.

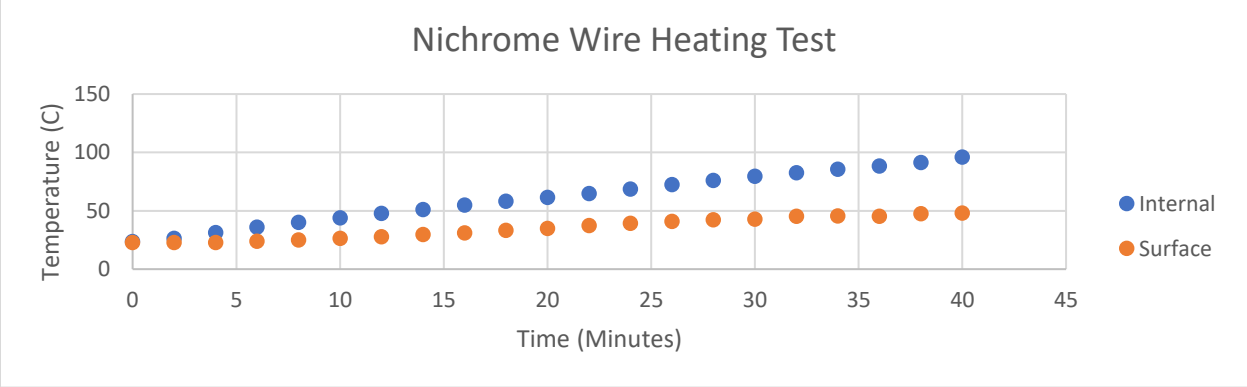

Figure 6: A graph showing the internal and surface temperatures of the model during sustained 12 V power

During the sustained 12V power, the model was monitored for visual changes to attempt to estimate at which temperature the elements began to present and to ensure all elements were present. Fig. 7 shows the model over the course of heating with all elements being present between 60° and 80° C internally. The actual temperature needed to achieve all elements may not need to be as high as seen here due to the time it takes the heat to transfer from the wires to the surface obscuring the actual temperature needed. The edema started around 10 minutes into heating when it would be about 45° C internally. The erythema began to appear around 25 minutes into heating when it would be about 70° C internally and the purulence started soon after. The surface heating is concentrated in the center above the wax chamber with the wound being the hottest.

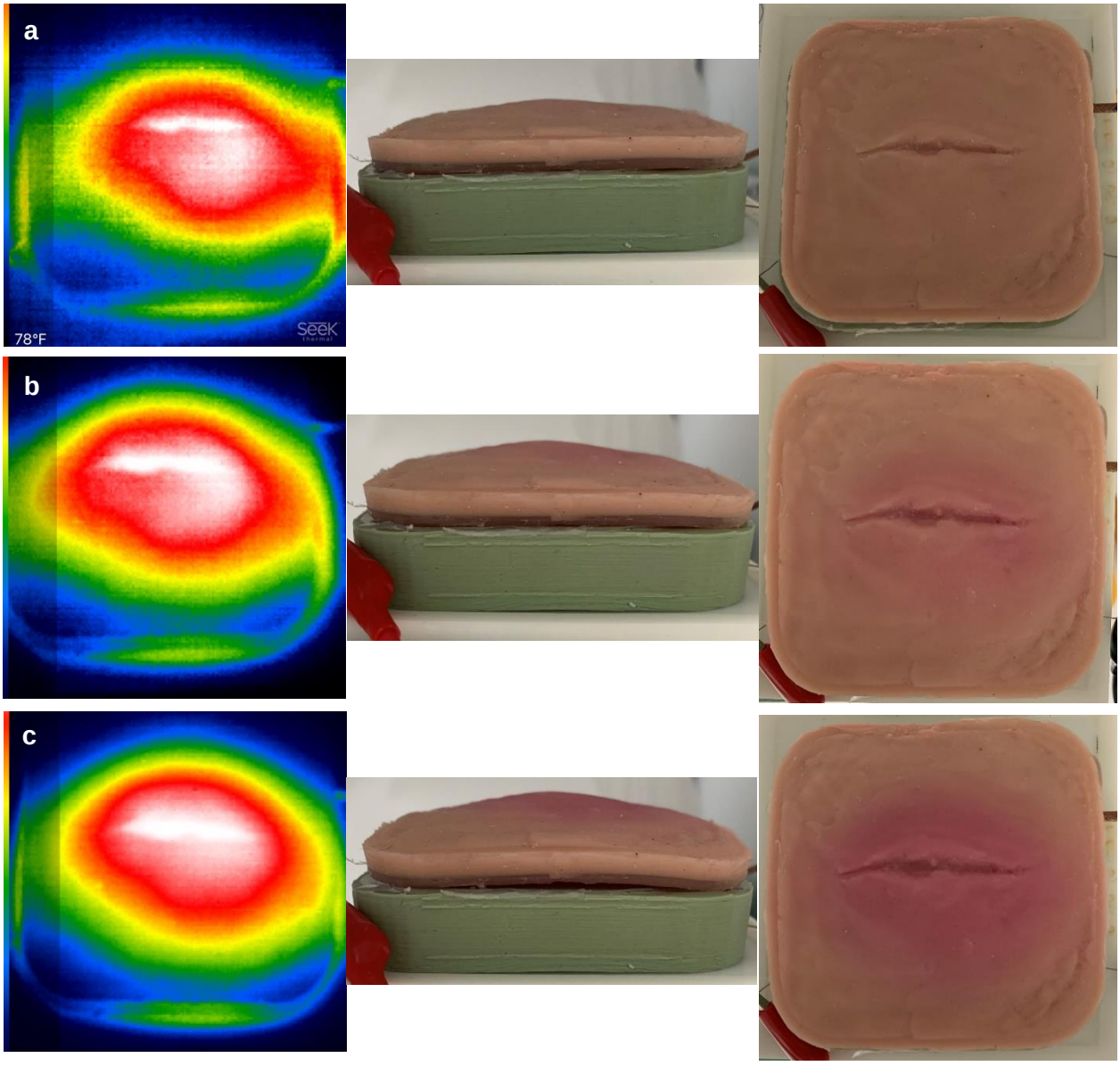

Figure 7: Thermal, side, and top views of the model after (a) 20 minutes of heating at 60° C, (b) 30 minutes of heating at 80° C, and (c) 40 minutes of heating at almost 100° C

With the integration of the thermistor to monitor the internal temperature and the Arduino code to provide feedback, various set temperatures were tested to identify the ideal internal temperature that would produce enough heat to trigger the color change in the skin and the phase changes in the wax for swelling and purulence and also keep the surface temperature within a reasonable, feverish range of 37°-

40° C. Two different temperatures of 60 and 70° C were initially tested for internal targets and the internal and surfaces temperatures as well as the visual status of the model were recorded every ten minutes. These two temperatures were chosen based on observations of the model during continuous heating and when the elements began to present as discussed previously. The surface temperature for the 60° C internal target temperature test plateaued around 37° C and the surface temperature for the 70° C internal target temperature test plateaued around 40° C as seen in Fig. 8. Both of these surface temperatures are acceptable and within our targeted feverish skin range. The 60° C internal target test did not achieve the level of edema, erythema, and purulence that was ideal while the 70° C internal target test did.

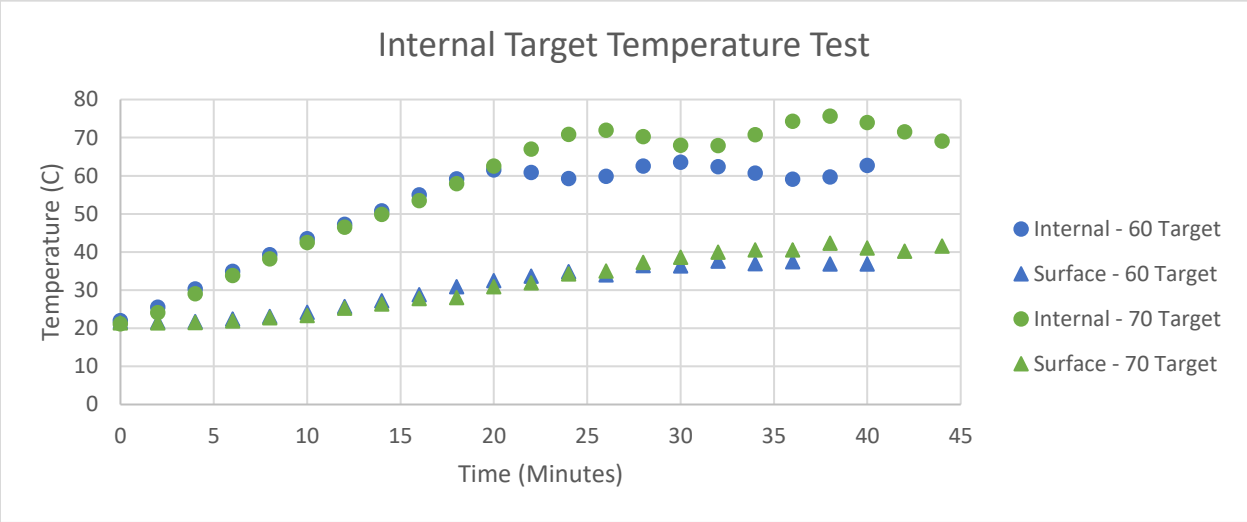

Figure 8: A graph showing the internal and surface temperatures of the model during two internal target temperature tests.

The survey results in response to a video of the model during continuous heating are shown in Fig. 9. When asked to rate how realistically the model portrayed an infected wound, the mean response with a scale of one being not at all realistic and five being very realistic was 4.1 ± 0.7. When asked if they agreed that this module had value for training in the recognition of the signs of infection, the mean response of a scale of one being strongly disagree and five being strongly agree was 4.3 ± 0.9. The final question was how the respondants though the dynamic aspect of the model affected the learning experience and the mean response on a scale of one being makes it worse and a rating of five being that it makes it much better was 4.7 ± 0.6.

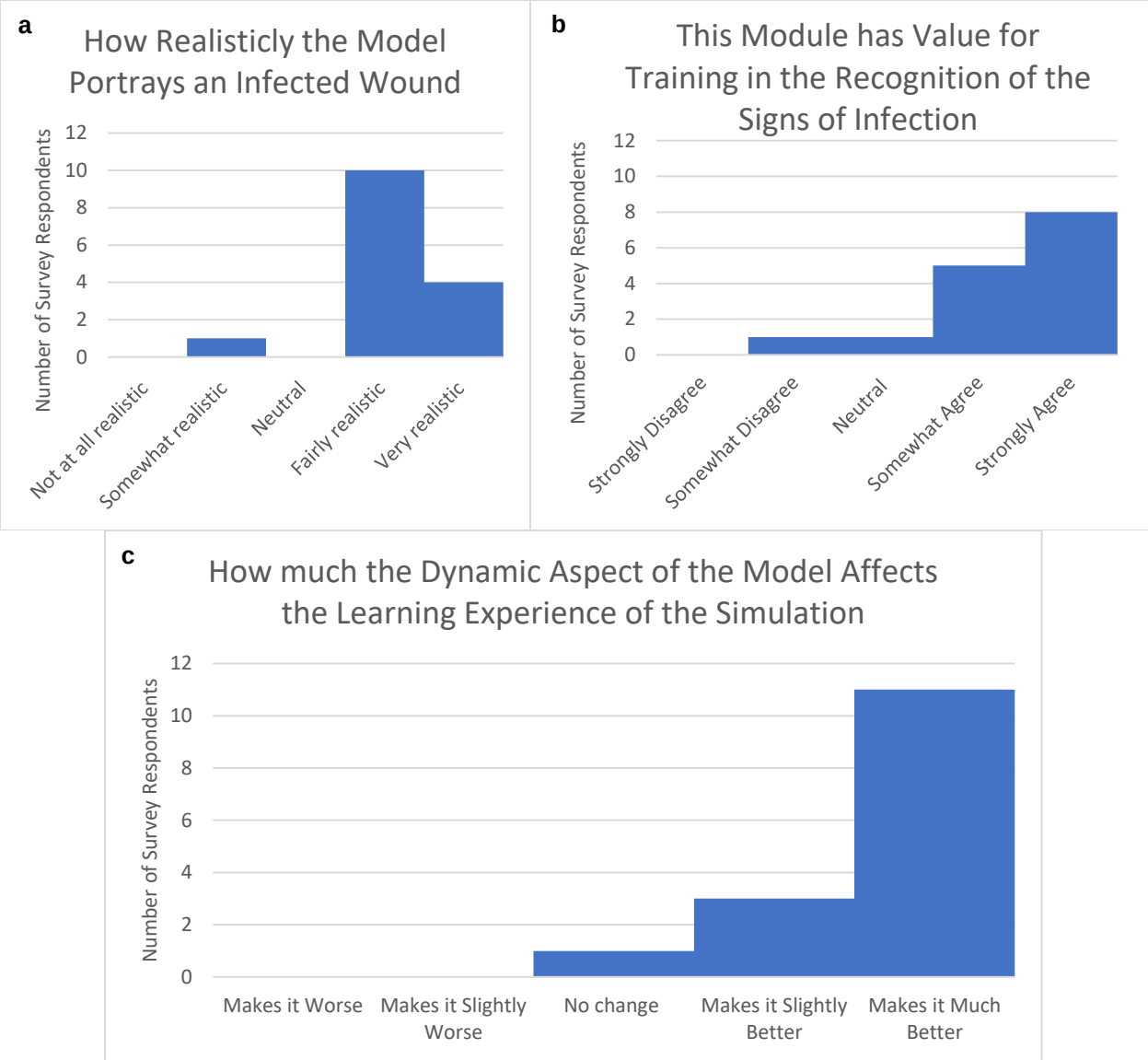

Figure 9: Survey responses to questions one (a), two (b), and three (c)

The integration of the model in a manikin system was done next. This model successfully produced all the intended elements of edema, erythema, fevered skin, and purulence in the new, smaller integrated model. The skin tone of the wound patch matched the face nicely and the activation of the infection process is triggered by the biogears software as shown in Fig: 10. The biogears software is running a simulation of a pateint with a systemic infection and as the fever builds, this triggers the infection model to begin heating that will lead to the development of the edmea, erythema, fevered skin, and purulence around the wound.

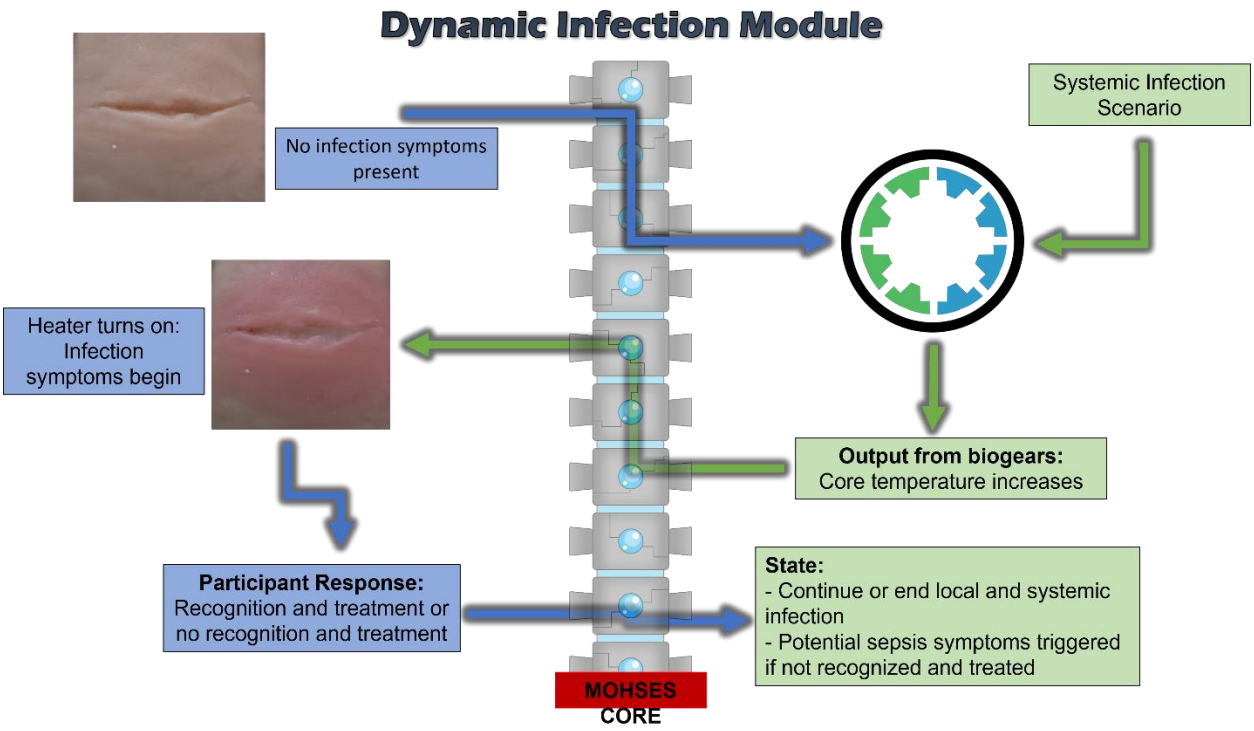

Figure 10: Graphic describing the integration of the dynamic infection module with the MOHSES platform and biogears system

Discussion

This project achieved all of the necessary physical elements to accurately represent an infection. The edema was achieved using the encapsulated wax and produced consistent, uniform moderate swelling once the target internal temperature was achieved. Purulence was produced by a wax mixture and was accurate in appearance. The erythema was also consistent and realistic in appearance once the target internal temperature was achieved. Finally, the heating element worked to evenly heat the module and trigger all of the other elements and warm the surface to between 37-40° C to simulate fevered skin. This was achieved in both a standalone benchtop model and in a model integrated into a manikin face where the activation of the heating process was triggered according to data obtained from a biogears simulation.

This model is the result of improving the previous model developed during capstone. Using wax instead of ethanol as the phase change material was one of the largest improvements. The wax did not produce as much swelling, making the model more physiologically accurate to the amount of swelling that would be seen with an infected wound. The wax also had a lower melting point than the ethanol which reduced the time to induce the swelling and made the model more physiologically accurate by staying closer to actual human body temperatures. This also meant that the model would require less power to operate, making it safer and more efficient. Due to the wax's more forceful expansion, there were issues with directional expansion as the wax tended to expand in all directions instead of just towards the skin. Because of this, the layer of silicone around the wax was changed to gel 25 mixed with hardener and the top layers were all made with gel 00. This helped to direct the majority of the swelling up towards the skin layer. Further testing was also done to explore using alternative, more easily manufactured heating elements, but these did not provide enough heat and also ended up not being as easy to manufacture as previously thought. The purulence was also not present in the previous model and was an improvement made here. The inclusion of an internal thermistor in this version also enabled the model to be integrated into a circuit that controlled the automatic heating process with input set temperatures. This further allowed for the integration of the model into a manikin system like MOHSES that utilizes programs like biogears for use as part of a larger simulation.

When evaluating the model, the surgeons who completed the survey had a positive view on average of the model and agreed that it realistically portrayed an infection and could be useful in training students to recognize the signs of infection. Additionally, the majority of surgeons thought that the dynamic aspect of the model would greatly improve the learning experience during training. This feedback is promising and indicates that this model is realistic and could be used effectively in a training setting. Further studies comparing it to static models and textbooks currently in use could be beneficial to further support these points.

Initially, the intention for the Arduino circuit and code was to integrate a PID control to keep the internal temperature at the target level, but through testing, it was found that the model was quite insulative and when the power was turned off it did not lose heat very quickly meaning that there was not a need for a PID type control that would keep the internal temperature very close to the intended set point throughout use. Maintaining the specific temperature very precisely was also not necessary for heat activation of the various elements. Because the insulative property of the model allowed for some deviation in the internal temperature without altering the appearance of the physiological symptoms and the additional complexity the PID would add, it was decided to not include this aspect.

Throughout the process of making the models, the labor put into making one complete benchtop model is about three and a half hours not including the down time needed to let one silicone layer set fully before the next can be made. The model is largely reusable with only the top layer that takes just one hour to make needing to be replaced as it runs out of wax for the purulence. The 3D printed molds make the manufacturing process much simpler and straightforward with the majority of the labor time comprised of mixing silicone. The construction of the coiled nichrome wire is the most complex task, but is part of the bottom, reusable layer so should only need to be made once per model. With further research and experimentation, this element may also be able to be changed to a more easily manufactured shape or a tool could be made to make the manufacturing less complex.

A model like the one described here that incorporates the aspects of edema, erythema, localized fever, and purulence would greatly improve training modules for military medics. The morphing aspect of the moulage allows for the infection to be dynamic and respond to various simulated scenarios like to dissipate once the trainee has identified the infection and administered the correct treatment or for it to develop over time in response mismanagement of care. The response of the student could be sensed either by a large temperature change in the model itself from applying ice or from a computer input like scanning an antibiotic medication before administering it to the patient. This morphing and the general realism of the appearance of the model also add to the fidelity of the model, increasing participant engagement and knowledge retention.

This technology also establishes a proof of concept that can be applied to other simulation scenarios. Edema and erythema are two elements that are present in a number of medical procedures and conditions. Many different dermatological conditions including those caused by infectious diseases have similar signs and symptoms. The color of the erythema can be easily changed by purchasing other thermochromic powder options. A surgical procedure simulation could use the swelling and color change moulage to signal if a trainee has made a mistake that has irritated surrounding tissue to provide real time feedback on their technique as one example. The model could also be used for simulating post operative care of a surgical wound with the integration of sutures as well. It may also be important to have multiple models with a variety of skin tones eventually for global and cultural considerations. Because some of the signs of infection included in the model may look different on individuals with different skin tones, it is important that medics are prepared to treat everyone. This model can also stand alone as a task trainer specifically for the identification and treatment of infected wounds, or it can be integrated as part of a larger manikin simulation where it can assist in teaching a variety of skills including wound management as well as infection identification and treatment in additional to overall patient care. As shown in this work, the activation of the infection process can be triggered in response to information from a physiology engine like biogears and this could also work the other way around with the infection model providing information to biogears to further activate other steps of the simulation. Hopefully, this technology can help to elevate moulage used in simulations to provide a more accurate and engaging experience for medical trainees that will further contribute to the development of their skills.

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