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TABLE OF CONTENTS

1. INTRODUCTION:

Our primary research objectives are to design, implement, and evaluate a working prototype that enables effective telementoring of a trainee surgeon by a remote mentor. This includes (1) a trainee-site subsystem for augmenting the view of the actual surgical field seamlessly by using a transparent display with illustrations of the current and next steps of the procedure, and (2) a mentor-side patient-size interaction platform with a gesture-based interface.

2. KEYWORDS:

Augmented reality, telementoring, telemedicine, annotation anchoring, transparent display, surgical training, co-presence, simulation, tele-existence.

3. ACCOMPLISHMENTS:

What were the major goals of the project?

Specific Aim 1:
Implement transparent display (03-Mar-2014 – 03-Aug-2015) 100%
Achieve a visual overlay of info. from the mentor (03-Mar-2015 – 03-Mar-2016) 100%
Experimental Design 1: trainee subsystem (03-Apr-2016 – 03-Mar-2017) 100%

Specific Aim 2
Develop a gesture-based interaction system (03-Mar-2014 – 03-Aug-2015) 100%
Experimental Design 2: Gather gesture set (03-Apr-2015 – 03-Mar-2016) 100%
Experimental Design 3: Mentor subsystem (03-Oct-2016 – 03-May-2017) 100%

Phase 2:

Specific Aim 3:
STAR specialization for cric in austere environments (03-Set-2017– 03-Apr-2021) 100%
Experimental Design 4: austere environment validation (03-Mar-2018– 02-Apr-2020) 100%

Specific Aim 4:
STAR specialization for fasciotomy on a cadaveric leg (03-Mar-2018– 02-Apr-2020) 100%
Experimental Design 5: Validate STAR in fasciotomies (03-Mar-2017 – 03-Mar-2018) 100%

What was accomplished under these goals?

<u>Major Activities:</u> Research, develop, and assess a transparent-display augmented-reality system that allows the seamless enhancement of a trainee surgeon's natural view of the surgical field with annotations and illustrations of the current and next steps of the surgical procedure.

Specific Objectives

Task 1.1- Implement transparent display

Subtask 1.1.1: Evaluate tablet computer configuration

<u>Implementation of a head-mounted, augmented reality telementoring platform</u>

Initially, a particular approach to deliver surgical guidance provided by remote mentors to local trainees was used: a tablet-based system. In that system, a tablet was held by a mechanical bracket over the body of a patient and the guidance sent by the mentors appears in the screen of the device as two-dimensional (2D) annotations. Some of the developments done over this system included enhancing the immersive feeling by simulating a transparency effect in the screen of the device and virtually anchoring the created annotation to the body of the patient.
Although the system worked as expected in a controlled condition, as the progress continued it came evident that a tablet-based system introduced some limitations, namely: (i) the system was not easily movable because of the fixed mechanical bracket that held the tablet in place (which is a constraint in an austere condition in which the patient could be in the middle of a battlefield), and (ii) the 2D, flat configuration of the display could not replicate the depth perception feeling that a real three-dimensional (3D) environment has.
Because of these limitations, research was done in enabling another interface to provide the trainee with the mentor guidance. The Microsoft HoloLens was the device selected to this purpose. This head-mounted display (HMD) device allowed the placement of 3D models (referred sometimes as holograms) into the real world 3D space. This was possible because of the acquisition of a low-resolution 3D mesh that represents the space in which the device and the ability to program applications through a cross-platform game engine (Unity). This differed from other HMDs (such as the Google Glass) because the 3D images are placed directly into the field of view of the user, instead of in a small region inside the display. STAR integrated this HoloLens-based trainee to its set of available options to provide the trainee with feedback from the operating room in Phase 2.

For the HoloLens-based Trainee System, modules that replicate some of the functionalities provided by the tablet-based system were created. Some of these modules were: (i) a handler for the transfer of virtual annotations between this system and the Mentor System, (ii) routines to retrieve the annotations information sent by the mentor and draw them into 3D space (either lines or 3D models), and (iii) the implementation of video streaming protocol between Mentor and Trainee systems. Figure 1 shows the illustration of the tools overlaid on the patient's anatomy.

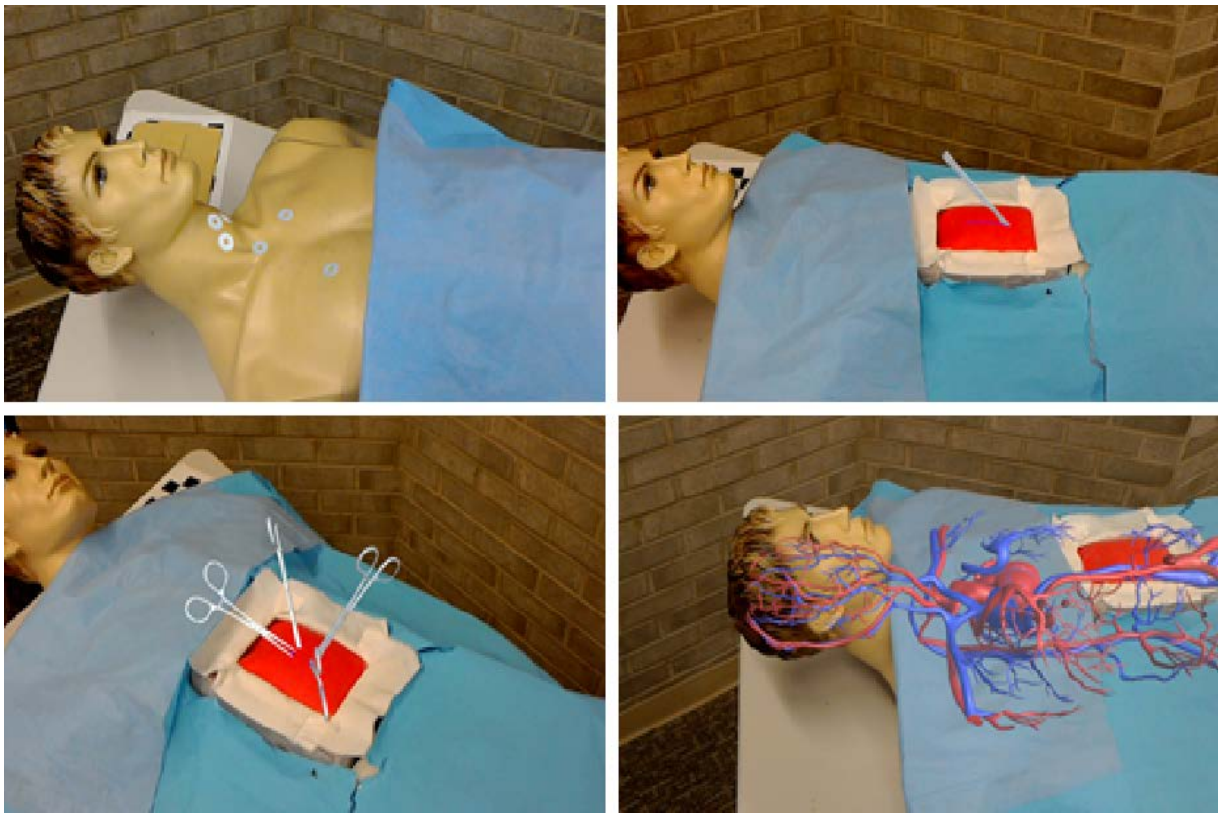

Figure 1. *Augmented reality HMD telementoring system snapshots.*

The development of the video streaming protocol is described. Throughout the development of our system, we have progressively improved the video transmission process. Initially, we sent uncompressed images of the operating field over a socket connection, but we found this to be overly bandwidth intensive. Later, we incorporated MPEG encoding and decoding of frames at both the trainee and mentor sides of the system, so that less data was sent over the network. However, our current approach has still encountered limitations when the trainee and mentor are distant (e.g. between Lafayette, IN and Indianapolis, IN). Network latency has caused video frame delays of ~10 seconds because of incoming data. Moreover, latency can increase over time due to changes in network health, which makes the current approach less usable for real-time surgical telementoring.

Instead, the team implemented a video streaming approach that emphasizes real-time communication. Based on the strength of the network connection, the video resolution or frame rate adapts automatically such that the mentor continues to receive live video from the trainee -- even if the video must be reduced in image quality. Rather than attempt to devise our own approach for this purpose, we instead chose to implement a WebRTC protocol on our trainee and mentor systems. WebRTC (Web Real Time Communication) is an existing standard protocol for peer-to-peer video communication. It is largely supported among Web browsers to allow developers a simple framework that handles adaptive video quality internally.

There are three main components of the WebRTC video streaming system: 1) a signaling server, accessible by both mentor and trainee systems, which is used for initial routing and discoverability between mentor and trainee systems; 2) a video transmitting client on the trainee system that streams video frames; and 3) a video receiving client on the mentor system that decodes video frames and makes them available to the mentor's telementoring interface. In this section of the report, the second subcomponent (a video transmitting client) is discussed.

The implementation of the HoloLens-based trainee system as a Unity application on the Microsoft HoloLens allowed the development of a WebRTC client that runs as a Universal Windows plugin. This plugin connects to the signaling server, negotiates video transmission parameters with the Mentor System, then activates the HoloLens' on-board camera and transmits encoded video data. As bandwidth changes over time due to network conditions, the WebRTC client automatically renegotiates the connection and changes the resolution at which it transmits video frames in order to preserve real-time communication.

Evaluation of a head-mounted, augmented reality telementoring platform

In this subsection, we describe the development of analysis tools to be used in an upcoming user study to measure the accuracy of trainee surgical actions when telementored using the HoloLens as opposed to a traditional telestrator-based system. In 2016, we published a user study ("Medical telementoring using an augmented reality transparent display") that compared the quality of telementored instruction between a tablet-based augmented reality telementoring system and a traditional telestrator-based telementoring system. Participants acted as trainees and completed both a marker placement task and an abdominal incision task while under telementored instruction. We measured time taken to complete the procedure, the number of focus shifts made by the trainee, and the distance between the trainee's marks/incisions on the patient's body and the intended ground truth location based on the mentor's provided annotations.

We conducted a similar user study where instead of a tablet-based telementoring system, we use our new telementoring system that uses the Microsoft HoloLens to display 3D imagery of a mentor's annotations directly onto the trainee's view of the operating field (Figure 2).

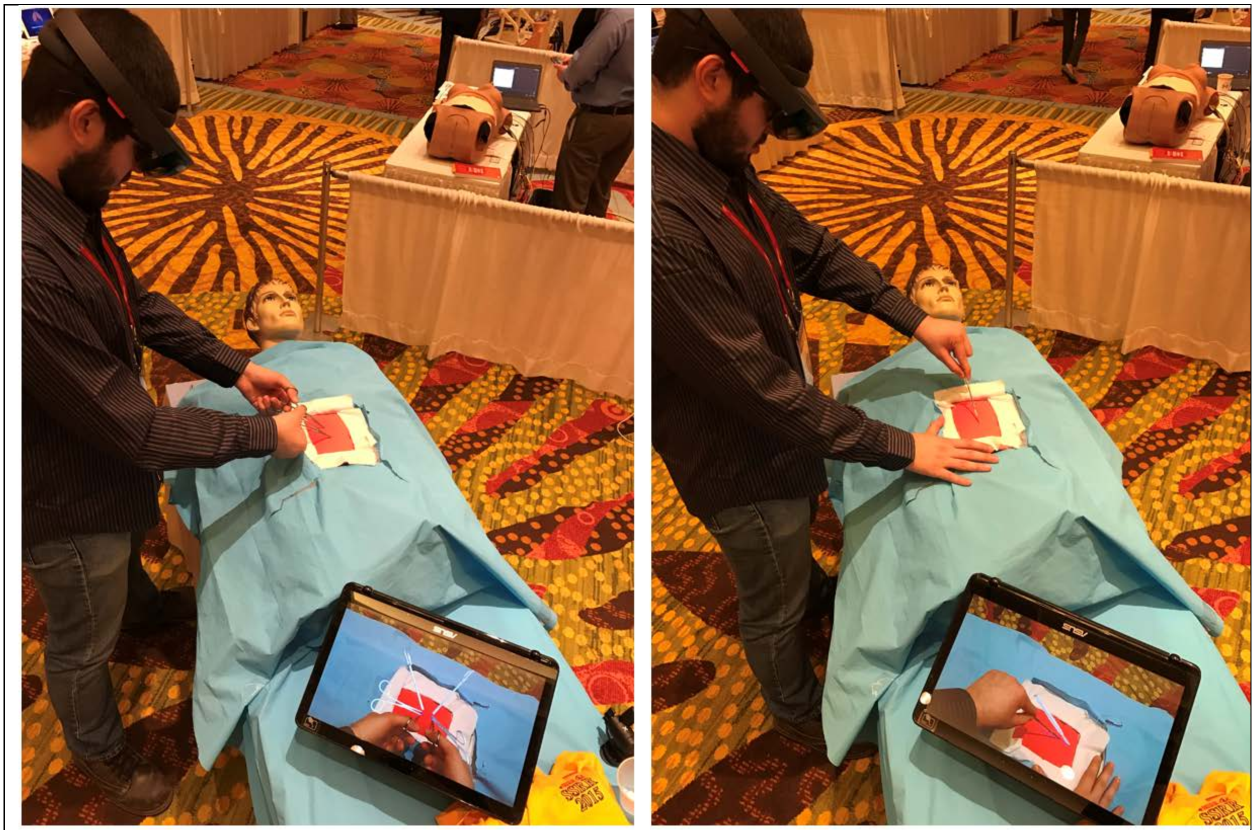

Figure 2. *Demonstration of the augmented reality HMD telementoring system.*

Task 1.2- Achieve visual overlay of information.

Subtask 1.2.2: Generate illustration of next steps of surgery through simulation.

<u>*Visualization of future steps*</u>

We developed a method of visualizing the future steps of a surgical procedure by using a tablet to display augmented reality imagery of an expert surgeon completing the procedure. We compiled our findings into a new journal that explores the potential of this augmented reality system in the context of self-guided medical training.

One solution to help bridge the gap between trainees in need of medical guidance and experts who can mentor them is to improve the quality of self-guided medical simulation training. Flexible access to simulator training provides trainees with more hands-on experience with simulators. For example, take-home simulator training is effective in the form of laparoscopic box trainers, which are used to help practice hand-eye coordination skills. In addition, simulator training with Deliberate Practice (DP), where a trainee completes focused and repetitive practice on a learning task, has been found to be more effective than traditional clinical education.

In order for simulator training to be effective, trainees must have the confidence that the actions they are performing are correct in the form of informative feedback from educational sources, and they must receive some feedback on how to correct or optimize their actions. Simulators are provided with textual and visual instruction in the form of training manuals, figures, and accompanying videos to teach the steps of the procedure. However, these represent a separate source of information that is not directly connected with the visual context that the trainee is interacting with while performing actions on the simulator. Such instructions must be interpreted and mentally mapped by the trainee onto the physical simulator. The accuracy with which trainees follow provided instructions is limited by the ability to translate them from the figure or video to the actual simulator.

Augmented reality has the potential to combine the haptic feedback of physical simulators with the improved visual accuracy. If a trainee using a simulator could perceive the virtual hands of a mentor being able to act out the correct surgical action, then the trainee could follow along without needing to mentally map the provided mentor instructions onto the simulator. Furthermore, if such instruction could be provided without a mentor having to be physically present -- or without a mentor having to be interacting in real time with the trainee -- then such benefits would be available to trainees without the limitations of time, schedule, travel, or expense described above.

We proposed a method of enhancing simulators by using a tablet-based augmented reality overlay through which the trainee views the simulator during practice. This augmented reality system shows pre-recorded imagery of an expert performing each future step of the procedure. The imagery is directly overlaid onto the trainee's view of the simulator, without the need for any mental remapping of instructional content. The trainee can follow along to precisely match the actions of the expert footage. We have implemented an initial prototype of this approach in the context of a cricothyroidotomy simulator (Figure 3).

Figure 3. *The display overlays a visualization of a future step of a cricothyroidotomy procedure onto the simulator.*

Such an approach provides several benefits. First, it provides a simple and accurate visualization of the future steps of an operation; the trainee simply follows what the expert's hands do. Second, the system does not interfere with the haptics provided by the simulator. Third, the system allows for easy content development without the complexity of animating 3D models of organs or gestures. Fourth, the system is low-cost and portable, which makes it an appealing solution for austere environments and developing countries.

In this section, we describe the components of the augmented reality training system, we illustrate a typical use case for a trainee using our system, and we describe the method by which we overlay augmented expert-sourced imagery onto the operating field of the simulator.

Our system is comprised of two main components: (1) a physical patient simulator that is specific to a particular operation (e.g. cricothyroidotomy, fasciotomy, etc.); and (2) a conventional tablet that is fixated above the simulator. The tablet is positioned such that the tablet screen is visible to the trainee user when looking down at the simulator, and such that the trainee user has room to move their hands freely between the tablet and the simulator. The tablet contains an onboard color video camera; during operation, the tablet displays the live video frames from the camera onto the tablet's screen. In this way, the trainee can view the surgical trainer and their own hands by looking "through" the tablet as if it were a window and perform each step of the simulated procedure.

During the trainee's process of completing the simulated procedure, our system provides contextual visual instruction in the form of augmented reality overlay videos, which offer a visualization of each step of the procedure. A set of videos are pre-recorded before use, in which an expert user performs the same procedure on an identical simulator. These videos are recorded from the same relative viewpoint as the trainee's tablet camera. The videos show each individual stage of the operation, and display the position of the expert's hands and any surgical instruments being used on the simulator during the operation. The videos are segmented into individual video clips representing each step of the procedure, and any background imagery is subtracted using green-screening methods.

When the trainee uses the augmented reality training system, each of the pre-generated video clips can be selected by the trainee and automatically overlaid onto the live video frames of the trainee's simulator. The video clips are displayed as semi-transparent overlays on the tablet screen, such that the trainee user can see their own hands and surgical instruments, and also those of the expert mentor as the expert carries out that step of the procedure. Because the pre-recorded expert video was captured from the same viewpoint as the trainee user's tablet camera, the imagery appears directly overlaid without visual artifacts, as if the virtual expert had actually interacted with the trainee's physical simulator. In this way, the trainee can view how an expert would perform each step of the procedure, and can follow along with their own hands and surgical instruments to mimic the procedure.

The augmented reality training system uses a touchscreen interface to allow the trainee to interact with the video instructions. The trainee can toggle the visibility of the visual instructions off (without virtual guidance) or on (to gain additional instruction). Onscreen buttons allow the trainee to quickly advance forward or backward between each stage of the procedure and visualize whichever stage the trainee requires guidance on. The trainee can also adjust the brightness and contrast of the overlaid videos to make the instructional videos more salient in different lighting conditions. In the case of slight misalignment of the overlaid video with respect to the physical simulator (which can result if the simulator is moved relative to the tablet or if the trainee slightly deviates from the expert's actions (e.g. in incision location), the trainee can use standard multi-touch controls to pan, rotate, and scale the overlaid video until it appears correctly aligned. Figure 4 shows our implemented system, which provides augmented reality annotations for a cricothyroidotomy simulator.

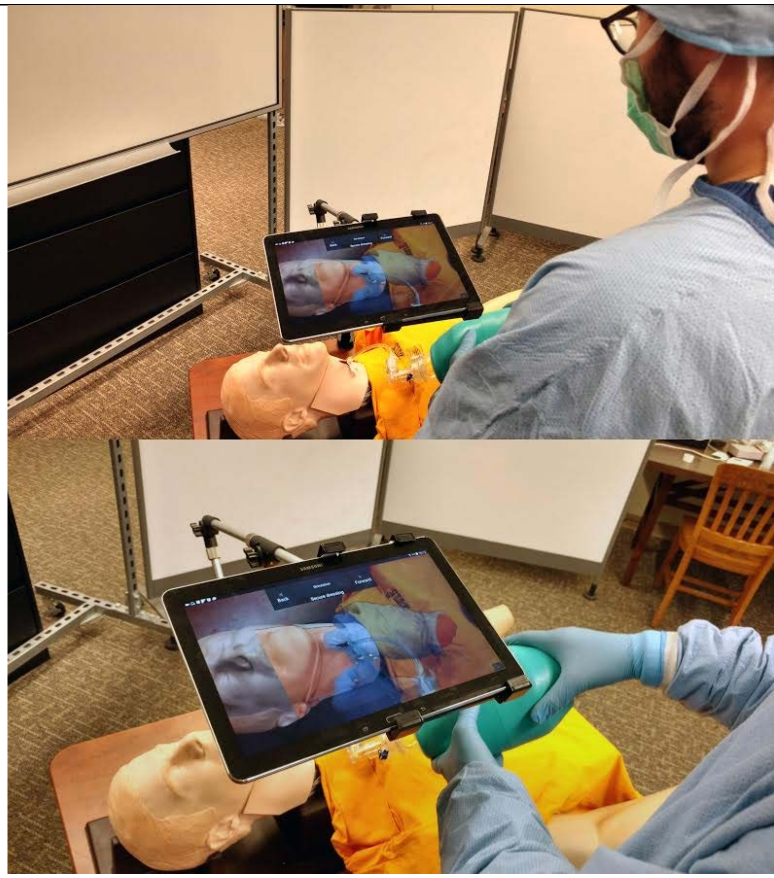

Figure 4. *Trainee surgeon using an augmented reality transparent display (top), and trainee's view (bottom). The display overlays a visualization of a future step of a cricothyroidotomy procedure onto the simulator.*

Our proposed system can provide expert mentor guidance to a trainee user directly in context on the operating field of the simulator. Furthermore, it does not require a mentor to be physically present or to be interacting in real time with a trainee, which allows training to proceed in a wider range of locations and a wider range of times. The trainee can view immediate feedback by seeing how their actions correspond to the expert's instructional gestures in the exact same frame of reference (Figure 5).

Figure 5. *Trainee surgeon using an augmented reality transparent display. The display overlays a visualization of a future step of a cricothyroidotomy procedure onto the simulator.*

Task 3.1- Specialize the system to practice cricothyroidotomies on patient simulator.

The Combat Trauma Simulator (CTS) system was purchased from Operative Experience and arrived on March 2017. This new patient simulator allows a comprehensive training preparation for treating Tactical Combat Casualty Care (TCCC) type wounds. These wounding patterns reflect injuries from an IED followed by an ambush. Figure 6 present a top view of the new patient simulator.

Figure 6. *Picture of new simulator*

This type of simulator fits into the scope of testing the STAR system in an austere environment; the CTS are designed for training in prehospital patient care in wound management and hemorrhage control.

Task 4.1- Specialize the system for fasciotomy on a cadaveric leg.

IU Visit for mentored lower limb fasciotomy training on cadaver model

On April 27 2017, the Purdue team traveled to IU's Eskenazi Health hospital to observe and record mentoring during fasciotomy training, in preparation of the project's future study aimed at detecting and quantifying any advantages of the STAR telementoring system in the context of fasciotomy training. Four medical students performed lower limb fasciotomies on a cadaver model, one on the calf and one on the thigh of each limb. PI Mullis mentored the students directly, in person, by standing next to them. The mentored fasciotomy training was recorded with multiple video cameras and real time depth cameras, i.e. Microsoft Kinects, which allow tracking gestures (Figure 7). Mentoring included drawing an overview of the procedure on the draping (Figure 8), drawing the incision line on the limb (Figure 9), demonstrating the use of hands during surgery (Figure 10), and demonstrating the use of surgical instruments (Figure 11). The information collected is currently being used to optimize the STAR platform for fasciotomy, and to design a fasciotomy user study that includes metrics for quantifying trainee performance.

Figure 7. *Surgical training lab where mentored fasciotomy was performed on cadaver model. The scene is recorded with multiple video and depth cameras.*

Figure 8. *Mentor sketching the limb anatomy with the various compartments that have to be released during the fasciotomy procedure.*

Figure 9. *Mentor drawing incision line on limb.*

Figure 10. *Mentor demonstrating the hand gesture to be used to release the fascia and verify that the fascia has been completely released.*

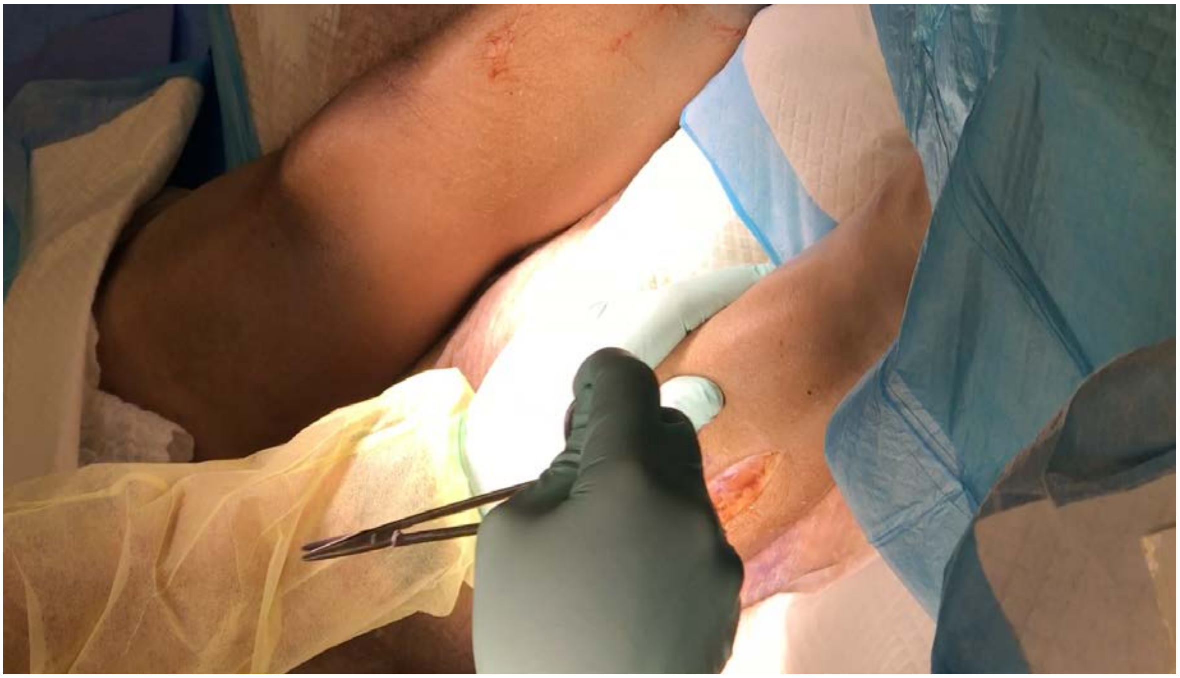

Figure 11. *Mentor demonstrating the proper use of scissors for cutting the fascia.*

Specific Objectives

Task 3.1- Specialize the system for a cric procedure on a patient simulator in an austere environment

<u>*Tracking of ultrasound device for mentee-to-mentor pose transmission*</u>

An approach to acquire the image from a portable ultrasound device was developed. Our approach streamed the image of the ultrasound device to the mentor site. The image from the device was displayed in the Mentor System's screen, updating in real-time.

As the final part of this module, an approach to update the position of the ultrasound image in the Mentor System based on the position of the ultrasound on the mentee's site was developed. The real-time pose of the ultrasound probe is acquired by the Mentee System using a 3D-printed structure with ArUco markers. The HoloLens' on-board camera captures the ultrasound probe, and these video frames are fed to a computer vision module that detects if the current video frame contains the pattern of markers that represents the ultrasound probe. The resulting detected markers in the frame can be unprojected into a 3D position and orientation relative to the camera. We combined this with the world-space pose of the camera itself to determine the world-space pose of the tracker.

This pose is streamed to the Mentor System through JSON messages, where it is unpacked and used to calculate the position of the probe in the image of the mentor site. The final position of the probe is calculated by combining the ultrasound probe position and rotation matrix with the image stabilization routines of the Mentor System. This last step is performed to account for the image distortion introduced in the Mentor System to make the image look as stable as possible with the respect to the mentee's point of view. Figure 12a showcases the mentee using the portable ultrasound device to scan the leg of a patient. The designed probe with the ArUco markers is presented in Figure 12b. Figure 12c showcases the view in the Mentor System of the current ultrasound slice being scanned. A close-up of the ultrasound image provided to the mentor is presented in Figure 12d.

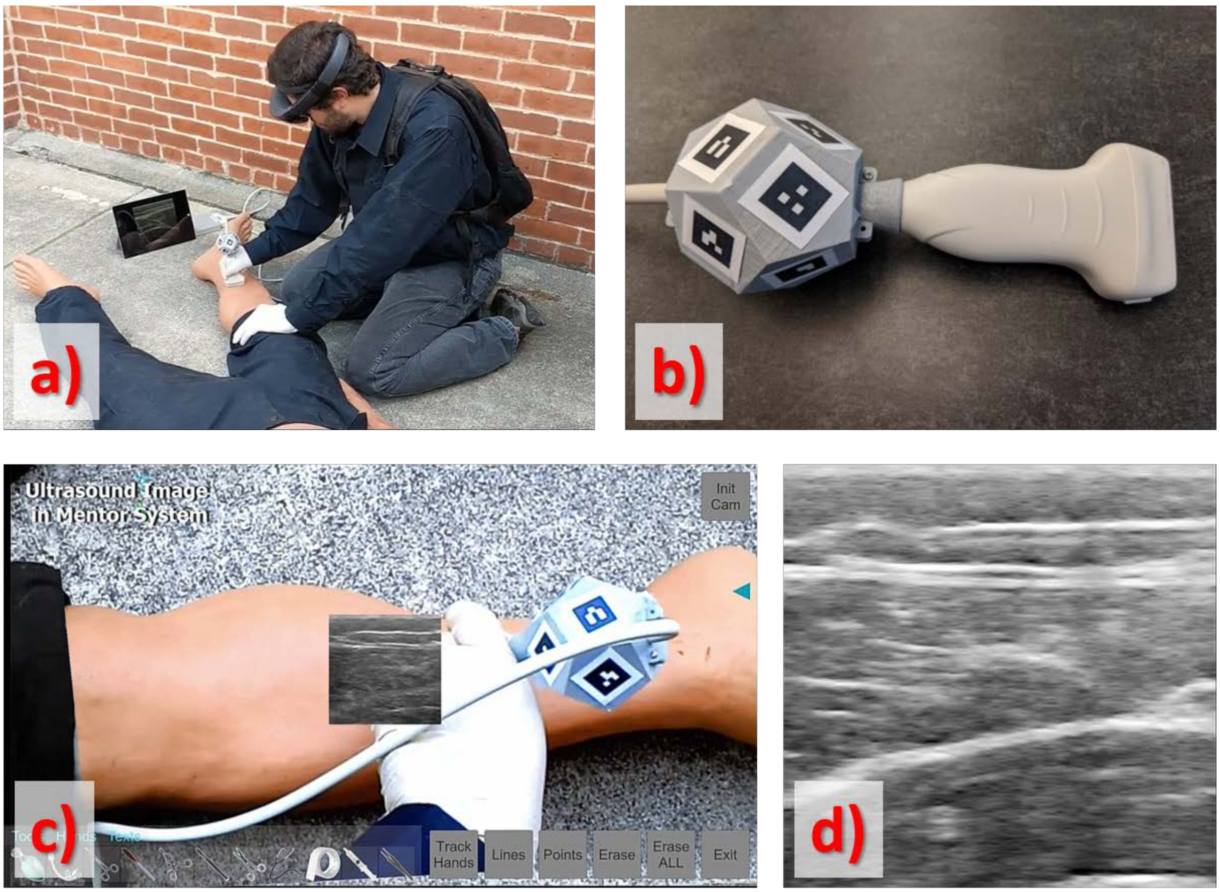

Figure 12. *Portable ultrasound visualization, streaming and tracking module.*

Figure 13 showcases an example of how the image of the ultrasound in the Mentor System changes with respect to the position of the ultrasound probe. The position of the tip of the probe is obtained from tracking the 3D-printed tracker and is then calculated in the image of the Mentor System for its correct visualization and placement.

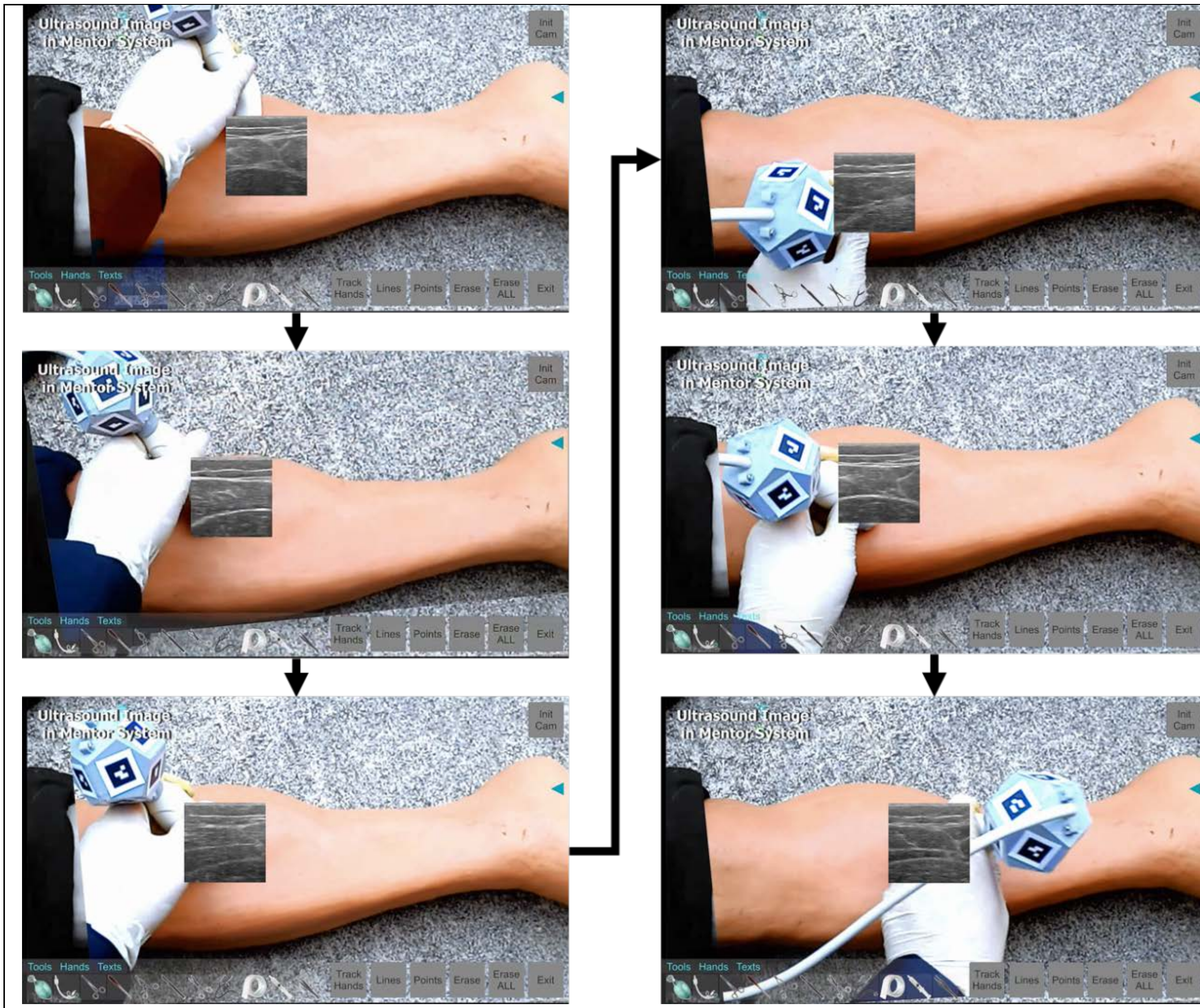

Figure 13. *Example of the real-time tracking of the ultrasound probe, visualized from the Mentor System's perspective.*

<u>*Transmission of patient vital signs data from mentee site to Mentor System*</u>

As a final step in this module, the values acquired from the vital signs are transmitted to the Mentor System to be visualized by the remote expert. The visualization of these signals is anchored to the Mentor System and presented in the same format in which it is presented to the mentee. Figure 14 presents an example of the vital signs of a patient being visualized in the Mentor System. Figure 15a showcases the vital signs values being obtain from the platform's oximeter sensor. The acquired values are transmitted through the internet and through Bluetooth, to be visualized in 2D the Mentor System (Figure 15b) and in 3D in the Mentee System (Figure 15c), respectively.

Figure 14. Example of the visualization of the vital signs in the Mentor System.

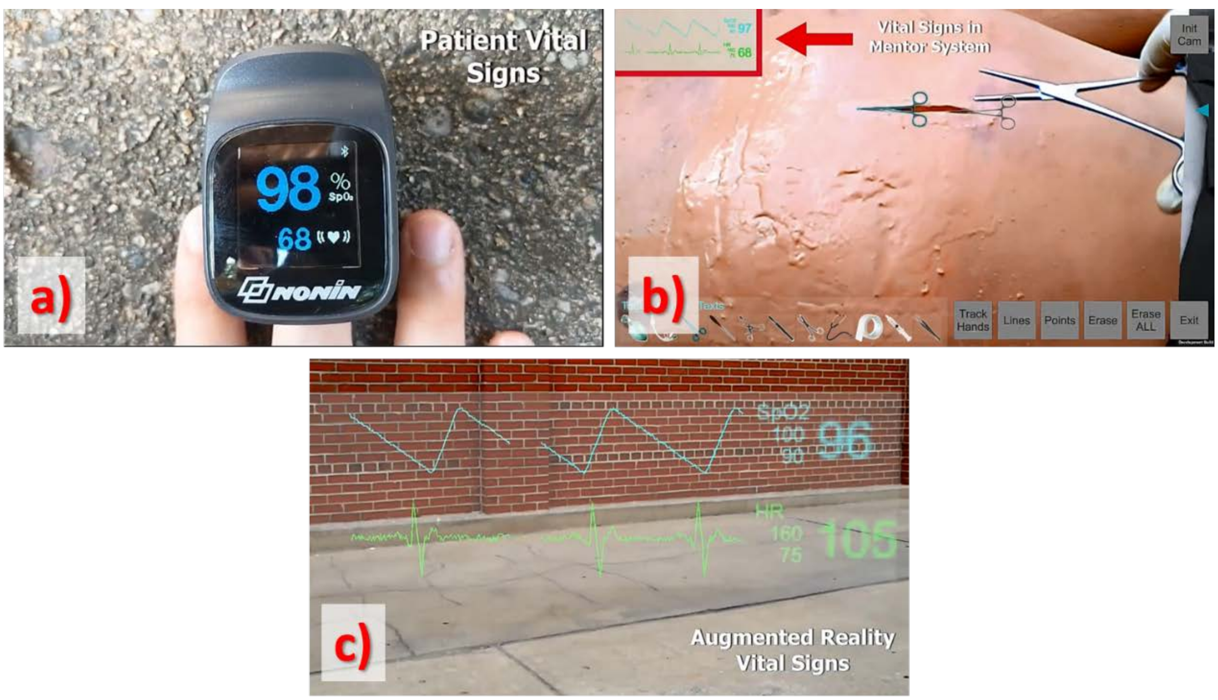

Figure 15. *Vital signs acquisition, transmission and visualization module.*

Development of a telementoring platform based on an Augmented Reality Head-Mounted Display

We performed additional analysis to analyze the existing methods with more rigorous statistical models and report the data in a more descriptive way. Our experiment tested the hypothesis of whether the STAR platform could help mentees perform an emergency cricothyroidotomy procedure with higher scores, as assessed by experienced surgeons, compared to audio-only telementoring. Participants were evaluated in terms of their performance, non-procedural skills and overall execution. The audio-only condition was selected as our control condition because it represents the bare minimum support a first responder can receive during a POI scenario.

We analyzed our data using an evaluation form is comprised of four main scores to evaluate the participants: Emergency Cricothyroidotomy Performance (ECP) scores, Global Rating Scale (GRS), Evaluator's Overall Rating (EOR) and Critical Criteria (CC). The ECP are 10 evaluation scores (ECP-1 to ECP-10) describing the performance of the cricothyroidotomies' substeps using a five-level Likert scale (from 1 = really bad to 5 = really good). Afterwards, each participant's ECP scores were summarized into an overall score (ECP-T), calculated as the average of all the other ECP scores. The Global Rating Scale (GRS) consisted of five-level Likert scale questions assessing non-procedural aspects such as knowledge of the procedure and instrument handling. The GRS included six criteria (GRS-1 to GRS-6), which were summarized into a comprehensive score (GRS-T) that assessed the non-procedural aspects of the procedure, and was calculated as the average of all the other GRS criteria. The Evaluator's Overall Rating (EOR) used a 0-100 score to evaluate the participants' overall performance. A score below 60 represents that the participant is not ready to perform the procedure. A score between 60 and 69 represents that the participant can perform the procedure guided by an expert, but not when left alone. A score between 70 and 79 represents that the participant could perform the procedure alone after quickly revisiting a text or guide. A score between 80 and 89 represents that the participant can perform the procedure alone with minimal difficulties. Lastly, a score above 90 represents that the participants is excellent at performing the procedure. Finally, the Tactical Combat Casualty Care Handbook's Critical Criteria (CC) are 0/1 scores evaluating the procedure in an overall manner: a score of zero in any of these represented an unsuccessful cricothyroidotomy. The three CC scores (CC-1 to CC-3) were summarized into a comprehensive score (CC-T) that represented whether the procedure was successfully performed. This CC-T score was calculated via the truth-functional operator of logical conjunction: the CC-T score took a value of 1 (true) if and only if all the other CC criteria were also 1, and a value of 0 (false) otherwise.

Based on these metrics, a within-subject statistical analysis was run to compare both conditions. The null hypothesis for all comparisons was that both conditions (Audio and STAR) will lead participants to comparable performance scores for all the comprehensive metrics (ECP-T, GRS-T, CC-T, EOR, Completion Time). The telementoring conditions were treated as independent variables, while the aforementioned metrics were treated as dependent variables. The data's normality assumption was checked with the Shapiro-Wilk test.39 In addition, the Levine's test was run to assess the data's equal variance assumption, revealing no need for a data transformation.40 Afterwards, two different analyses were run depending on the type of data. For continuous responses (ECP-T, GRS-T, EOR and Completion Time), a linear mixed model was run,41 as the variability introduced into the model by the different mentor-evaluator pairs needed to be considered. The introduced linear mixed regression model for the analysis is of the form:

$$Response = \beta_0 + \beta_1 I_{\{STAR\}} + \beta_2 I_{\{Pair\}} + \beta_3 I_{\{Order\}} + Participant\ ID + Error$$

where $I_{\{STAR\}}$ is an indicator variable for the condition level (for STAR and Audio), $I_{\{Pair\}}$ is an indicator variable for the Mentor-Evaluator pair, and $I_{\{Order\}}$ is an indicator variable for the order of the conditions (STAR-Audio and Audio-STAR). $Participant\ ID$ denotes the random effects for the different participants. $\beta_0, \beta_1, \beta_2,$ and β_3 are the regression coefficients of the model, and $Error$ represents the residuals containing variance not explained by the model. The same model was applied to the *Low First Responder Experience* and *Low Cric Experience* sub-groups. These separate analyses allowed to inspect the variance introduced by the participants' years of experience or training level in cricothyroidotomies without directly including them as effects in the regression model.

For binary responses (CC-T), a logistic regression for binary responses was run. Moreover, the proportional odds model was used to evaluate each of the sub scores (i.e. ECP-1, to ECP-10, GRS-1 to GRS-6) independently.43 The analysis of these binary and ordinal responses followed the same effects formulation as the previously described linear mixed regression model. Finally, the models' performance and validity were evaluated using regression diagnostics (QQ plots, residual plots, and histograms). The tests confirmed that there was no assumption violation in the models (e.g. normality and constant variance).

The linear mixed model revealed that both variables (Mentor-Evaluator pair and treatment order) had significant effects in the model. Specifically, both variables were significant ($p \leq 0.03$) for all metrics except Completion Time for the Overall Population and Low First Responder Experience groups. For the Low Cric Experience, however, the Mentor-Evaluator pair variable was significant ($p \leq 0.05$) only for the ECP-T, EOR and CC-T metrics, and the treatment order variable was not significant for any metric. These analyses indicated that participants' scores increased when using STAR after Audio. Contrarily, participants' scores decreased when using Audio after STAR.

All comparison groups obtained higher ECP scores when using STAR. The comprehensive ECP-T score was significantly higher when using STAR than when using Audio for the Overall Population, the Low First Responder Experience and the Low Cric Experience groups ($p = 0.01$, $p = 0.01$, $p = 0.03$; respectively). The summarized ECP sub scores are shown in Table 2. Finally, the procedure completion time did not reveal statistically significant differences between the conditions.

Table 1. Averaged results for the different comprehensive scores, for the Overall Population and both the experience-based subgroups. P-values with an asterisk (*) represent a significant difference between the telementoring conditions. [1] Mean (Standard Deviation); [2] 1-5 score; [3] 0-100 score; [4] 0/1 score; [5] time in seconds

Comprehensive Score	Overall Population (n = 19)		
	STAR [1]	**Audio [1]**	**p-values**
ECP-T [2]	3.38 (0.45)	2.99 (0.79)	0.01*
GRS-T [2]	3.82 (0.81)	3.37 (1.21)	0.05*

EOR [3]	80.84 (10.04)	73.94 (17.52)	0.02*
CC-T [4]	0.89 (0.32)	0.63 (0.50)	0.04*
Completion Time [5]	274.79 (91.86)	272.11 (108.67)	0.94
Comprehensive Score	**Low First Responder Experience (n = 16)**		
	STAR [1]	**Audio [1]**	**p-values**
ECP-T [2]	3.35 (0.46)	2.83 (0.75)	0.01*
GRS-T [2]	3.68 (0.79)	3.10 (1.13)	0.05*
EOR [3]	79.25 (10.18)	70.12 (16.35)	0.01*
CC-T [4]	0.88 (0.34)	0.56 (0.51)	0.04*
Completion Time [5]	287.19 (95.25)	285.00 (113.86)	0.95
Comprehensive Score	**Low Cricothyroidotomy Experience (n = 12)**		
	STAR [1]	**Audio [1]**	**p-values**
ECP-T [2]	3.20 (0.45)	2.73 (0.74)	0.03*
GRS-T [2]	3.54 (0.82)	2.95 (1.09)	0.10
EOR [3]	77.50 (9.88)	73.5 (12.12)	0.04*
CC-T [4]	0.83 (0.39)	0.58 (0.51)	0.16
Completion Time [5]	281.08 (105.87)	298.08 (117.55)	0.66

Table 2. Averaged results for the different criteria of the Emergency Cricothyroidotomy Performance scores, for the Overall Population and both the experience-based subgroups. P-values with an asterisk (*) represent a significant difference between the telementoring conditions ($p \leq 0.05$). [1] Mean (Standard Deviation); [2] 1-5 score

Emergency Cricothyroidotomy Procedure Evaluation Form Criteria	**Overall Population (n = 19)**		
	STAR [1, 2]	**Audio [1, 2]**	**p-values**
ECP-1	3.58 (0.61)	3.26 (0.87)	0.24
ECP-2	3.42 (0.77)	3.11 (1.10)	0.26
ECP-3	2.89 (0.94)	2.84 (1.01)	0.76
ECP-4	2.74 (1.28)	2.53 (1.58)	0.52
ECP-5	3.42 (0.61)	3.05 (0.91)	0.11
ECP-6	3.79 (0.92)	3.37 (1.50)	0.30
ECP-7	3.89 (0.46)	3.63 (1.01)	0.29
ECP-8	3.58 (0.61)	2.74 (1.48)	0.05*
ECP-9	3.53 (0.51)	2.68 (1.25)	0.02*
ECP-10	3.00 (0.82)	2.74 (1.05)	0.24
Emergency Cricothyroidotomy Procedure Evaluation Form Criteria	**Low First Responder Experience (n = 16)**		
	STAR [1, 2]	**Audio [1, 2]**	**p-values**
ECP-1	3.50 (0.63)	3.13 (0.89)	0.56
ECP-2	3.31 (0.79)	2.94 (1.12)	0.70
ECP-3	2.81 (0.91)	2.63 (0.96)	0.79
ECP-4	3.00 (0.89)	2.25 (1.57)	0.52

ECP-5	3.31 (0.60)	2.88 (0.89)	0.83
ECP-6	3.75 (1.00)	3.25 (1.61)	0.55
ECP-7	3.88 (0.50)	3.56 (1.09)	0.53
ECP-8	3.56 (0.63)	2.63 (1.54)	0.84
ECP-9	3.44 (0.51)	2.50 (1.26)	0.85
ECP-10	2.94 (0.85)	2.56 (1.03)	0.36
Emergency Cricothyroidotomy Procedure Evaluation Form Criteria	**Low Cricothyroidotomy Experience (n = 12)**		
	STAR [1, 2]	**Audio [1, 2]**	**p-values**
ECP-1	3.33 (0.65)	3.00 (0.95)	0.42
ECP-2	3.25 (0.87)	2.83 (1.27)	0.42
ECP-3	2.50 (0.90)	2.58 (1.00)	0.90
ECP-4	2.50 (1.17)	2.42 (1.44)	0.78
ECP-5	3.33 (0.65)	2.92 (0.79)	0.15
ECP-6	3.67 (1.15)	3.00 (1.81)	0.27
ECP-7	3.83 (0.58)	3.50 (1.24)	0.46
ECP-8	3.42 (0.67)	2.50 (1.45)	0.13
ECP-9	3.42 (0.51)	2.25 (1.29)	0.06
ECP-10	2.75 (0.75)	2.33 (0.98)	0.21

The linear mixed model analyses showed that using STAR was associated with higher procedural outcomes, as represented by the higher ECP-T scores. Specifically, ECP-8 and ECP-9 also reported a statistical significance, as assessed with the proportional odds model. A fine level of visual detail was required for both steps to be considered well executed: the amount of air inserted in the cuff needed to be carefully assessed; otherwise, the correct placement on the cannula through the cricothyroid membrane could be compromised. The remote mentors in the STAR condition were able to visualize the operating field as the mentees performed the procedure, which allowed them to assess whether the steps were being performed correctly.30 The visual feedback allowed the mentor to perform 4 corrections per participant on average (e.g. "You are not done yet; you need to check for bilateral breath sounds"). The visual feedback also allowed the participants to ask for instructions and confirmations an average of 5 times per procedure (e.g. "Should I make the incision longer?"). This type of feedback was not possible in the Audio condition, as mentors only relied on the mentees' verbal confirmation to provide their feedback. Additionally, participants in the STAR condition received guidance for 1 minute and 47 seconds on average, as opposed to only 57 seconds on average for participants in the Audio condition. These mentoring times represented 39% and 21% of the total task completion time, respectively. These values reveal that participants received remote guidance for almost double the time when they were in the STAR condition, which could have been one of the reasons of their higher ECP-T score.

Moreover, the mentors were able to guide the mentees better through the procedure using the AR annotations offered by the telementoring platform. The remote mentors created 9 annotations per participant on average. The use of the annotations can be divided into three situations: 1) demonstrating which surgical tools to use (e.g. placing the icon of a scalpel to represent "Incise here"); 2) locating anatomical structures (e.g. drawing circles to indicate the location of the cricothyroid membrane); and 3) showing the location and length of incisions (e.g. drawing a vertical line over a section of the cricothyroid membrane). By creating these annotations, the mentor was able to convey more guidance, a possible reason of the increased performance when participants used the STAR condition.

Moreover, the mentors were able to guide the mentees better through the procedure using the AR annotations offered by the telementoring platform. The remote mentors created 9 annotations per participant on average. The use of the annotations can be divided into three situations: 1) demonstrating which surgical tools to use (e.g. placing the icon of a scalpel to represent "Incise here"); 2) locating anatomical structures (e.g. drawing circles to indicate the location of the cricothyroid membrane); and 3) showing the location and length of incisions (e.g. drawing a vertical line over a section of the cricothyroid membrane). By creating these annotations, the mentor was able to convey more guidance, a possible reason of the increased performance when participants used the STAR condition.

On the other hand, the other ECP criteria did not show significant difference between the conditions. A possible reason for this finding is that the first responders, even those of low expertise, had the necessary knowledge to perform some steps of a cricothyroidotomy without requiring assistance. Examples of such steps include stabilizing the larynx and cutting through the cricothyroid membrane. Another possible reason is that the cricothyroidotomies were performed in a patient simulator, which could have reduced the participants' stress levels and mitigated the type of complications that could arise while performing the procedure. We hypothesize that the telementoring capabilities of our system will be particularly useful when complications arise.

Creation of a database of images and captions of surgical procedures

Telementoring surgeons as they perform surgery can be essential in the treatment of patients when in situ expertise is not available. Nonetheless, expert mentors are often unavailable to provide trainees with real-time medical guidance. When mentors are unavailable, a fallback autonomous mechanism should provide medical practitioners with the required guidance. However, AI/autonomous mentoring in medicine has been limited by the availability of generalizable prediction models, and surgical procedures datasets to train those models with. This subsection presents the initial steps towards the development of an intelligent artificial system for autonomous medical mentoring.

The methodology to create such an AI surrogate mentor includes: 1) the creation of a curated dataset of medical images and their respective step-by-step descriptions; and 2) the use of such a dataset by training a Deep Learning (DL) framework which generates medical instructions from images. This works presents a Database for AI Surgical Instruction (DAISI; https://engineering.purdue.edu/starproj/_daisi/). DAISI provides step-by-step demonstrations of how to perform medical procedures. This is done by including images and text descriptions of procedures from 20 medical disciplines. Each image-text pair describes how to complete a step in the procedure. The database was created via a mobile app containing input from 20 expert physicians from various medical centers, extracting data from academic medical textbooks related to the surgical technique, and acquiring imagery manually. Figure 16 showcases images from four procedures in DAISI.

We describe the process of obtaining medical images and caption from an existing mobile app created by expert physicians. The first step of the process involved searching for existing solutions that targeted part of the problem, such as online videos of medical courses. After exploring, our research team found a free app called Thumbroll. Thumbroll is an app created by the University of Washington School of Medicine, which allows medical students to learn critical techniques and procedures at their own pace through a scrolling functionality. Via simple touch interactions, the user can move between the different steps of a surgical procedure to receive a step-by-step demonstration of how to perform the procedure. Figure 17 showcases a screenshot of the app’s main screen.

As showcased in Figure 17, the app is organized in a hierarchical manner: the main screen groups procedures into different categories. For example, under “Training Level”, procedures are distributed into “Intern”, “Junior Resident”, “Clinical MD Trainee”, among others. Under “Medical Specialty”, procedures are distributed into “Internal Medicine”, “Anatomy”, “Radiology”, among others. Once one of these categories is selected, the app presents the user with all the procedures that fall into this category, as depicted in Figure 18.

Figure 16. *Example of four different images and their associated textual descriptions from four different procedures in the DAISI database. The database includes images from 20 disciplines such as emergency medicine, and ultrasound-guided diagnosis.*

Once a procedure is selected, the app shows a step-by-step explanation of how to perform the procedure. The procedure can be navigated using a scrolling touch interaction. Each step is explained with an image and a caption of the procedure, as depicted in Figure 19.

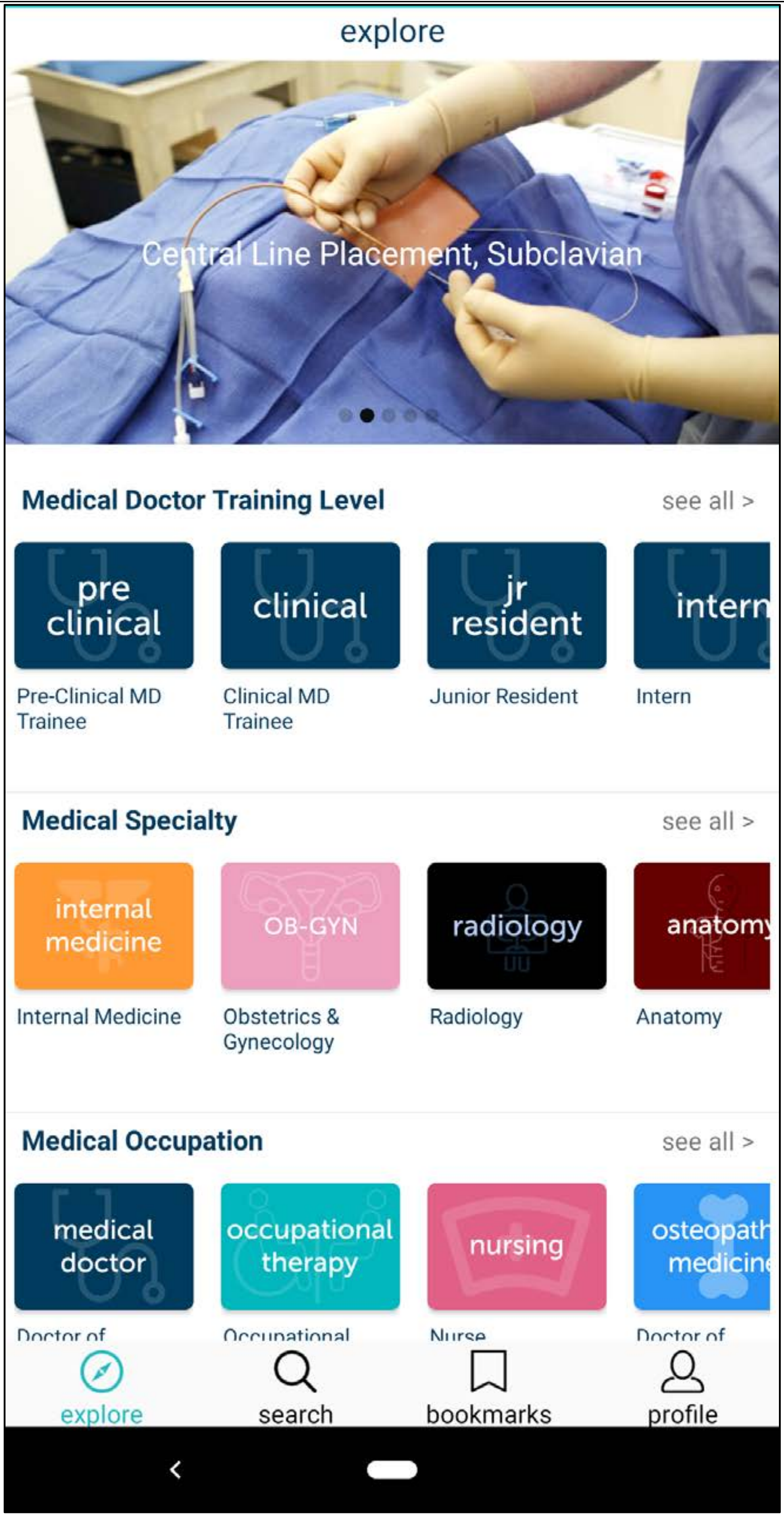

Figure 17. *Thumbroll's main screen. Surgical procedures are grouped into different categories to facilitate browsing through the app.*

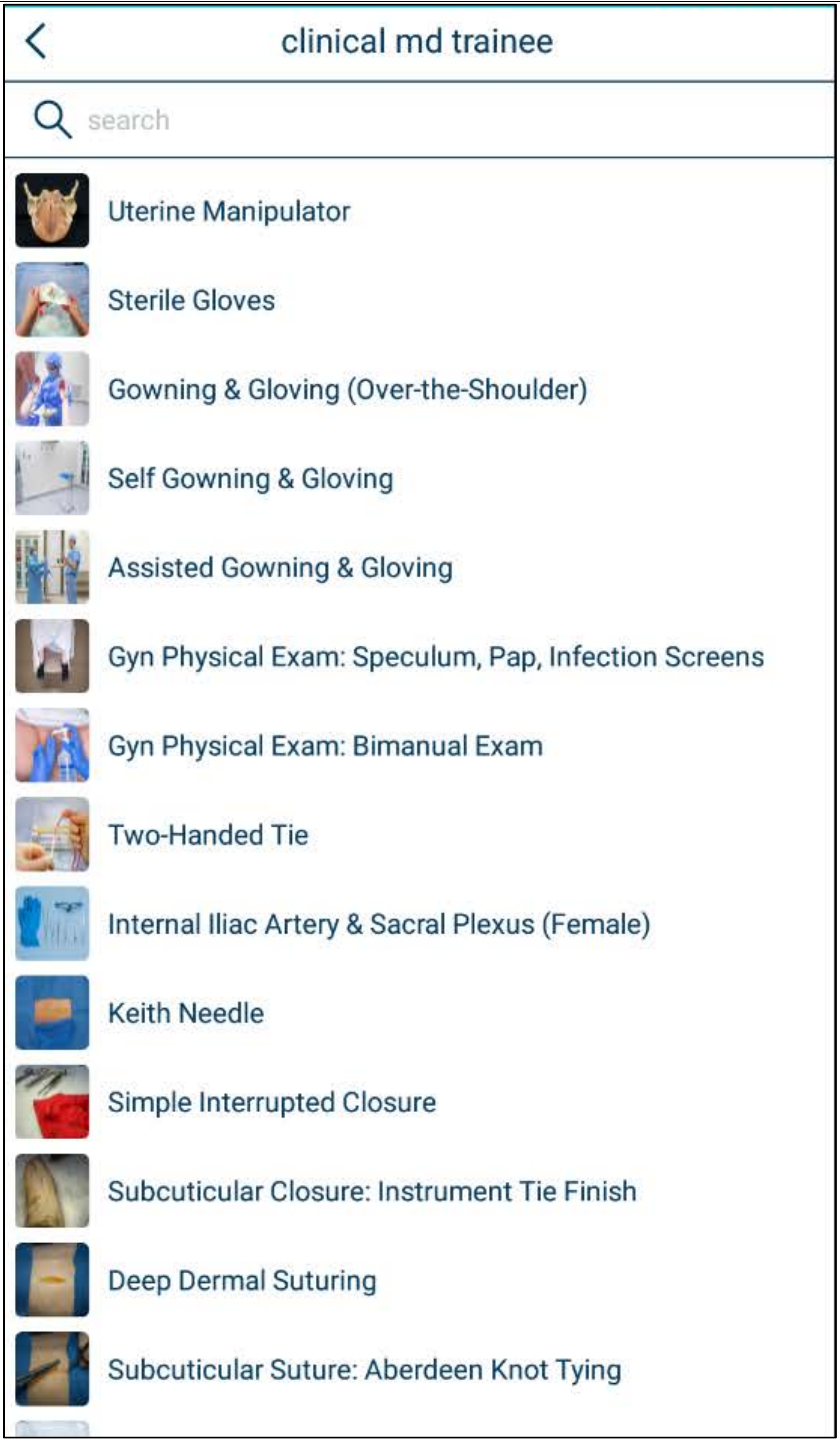

Figure 18. *Thumbroll's "Clinical MD Trainee" category. All surgical procedures in this category are related to the training that Clinical MD Trainees need to perform as part of their training.*

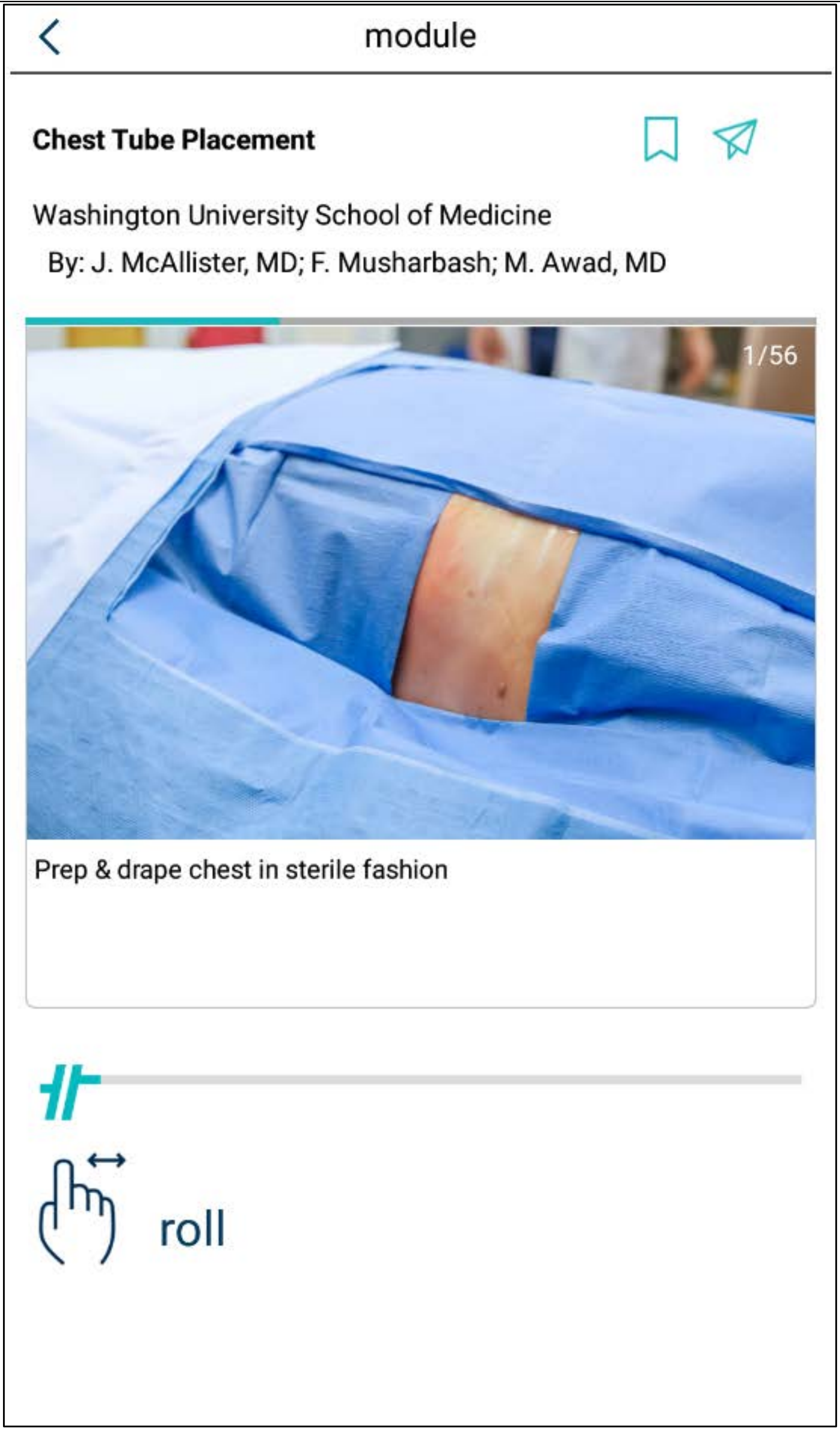

Figure 19. *First step of the "Chest Tube Placement" procedure. The user can scroll through the steps of the procedure using touch commands. Each step is depicted by an image and a caption.*

The improved DAISI dataset now contains 17,339 color images and text descriptions of instructions to perform surgical procedures. DAISI contains one example for each of the 290 medical procedures from 20 medical disciplines including ultrasound-guided diagnosis, trauma and gynecology. The image-text pairs from the dataset were compiled from: (a) medical images and instructions from the Thumbroll app, a medical training app designed by physicians from Washington University School of Medicine, Stanford Health Care; John Hopkins University, UCLA, and University of Southern California. Overall, we acquired 17,138 images with descriptions from various medical specialties (e.g. General Surgery, Internal Medicine), levels of medical training (e.g. clinical Medical Doctor trainee, senior Resident), and medical occupations (e.g. occupational therapy, osteopathic medicine). (b) Afterwards, we extracted 125 images and captions from anatomy textbooks using *PDFFigCapX*; (c) Lastly, we used a patient simulator (Tactical Casualty Care Simulator 1, Operative Experience) to acquire an additional set of 76 images from procedures as chest needle decompression and intraosseous needle placement. The dataset has 1086 duplicate instructions (i.e. the same instruction from more than one image), which represent approximately 6% of the instructions in the dataset. Additionally, no restriction was imposed regarding the length of the text descriptions.

We used a Deep learning (DL) based approach to develop an AI model using DAISI. The algorithm receives images from medical procedures as input, and predicts an instruction associated with it. To generate text information from images, an encoder-decoder DL approach using a ConvNet and a Recursive Neural Network (RNN) was adopted. The ConvNet extracts and encodes visual features from the input images, and the RNN decodes these visual features into text descriptions.

After training our DL model using DAISI, we evaluated it using a similar approach to the one described in previous reports. We validated our approach using four test folds. For each of these folds, we randomly divided the 290 procedures into training and testing sets based on their number of images: approximately 10% of the images of the entire dataset were separated to be used as test set. Additionally, we conducted *Inter-procedure* and *Intra-procedure* evaluations. For the *Inter-procedure* setting, the model had no prior information regarding the procedures in the test set. For the *Intra-procedure* setting, a fraction of the images P in the same procedure were assigned to the training set, while the rest remained in the test set. The test set consisted of every $\frac{1}{P}$ images from each procedure. In our case, P was set to 0.5. While the *Intra-procedure* setting reduced generalizability among procedures, it enhanced performance for procedures in the test set. Table 3 presents the distribution of image-text pairs into training and test sets, as well as the size of resulting vocabulary for each fold. Finally, we evaluated our AI mentor using three combinations of the *Word Count* parameter: 3, 5, and 7. Table 4 showcases the size of the vocabulary constructed for each fold, for the respective *Word Count* value.

Table 3. Distribution of image-text pairs into training and test sets per testing fold and testing approach (*Inter-procedure* and *Intra-procedure*).

Fold Number	**Number of Images**			
	Inter-Procedure		***Intra-Procedure***	
	Training	**Testing**	**Training**	**Testing**
F1	13232	1354	13909	677
F2	13302	1284	13944	642
F3	13256	1330	13921	665
F4	13284	1302	13935	651

Table 4. Vocabulary size for three different *Word Count* values.

Fold Number	***Word Count***		
	3	**5**	**7**
F1	2217	2214	2208
F2	2231	2226	2219
F3	2215	2213	2209
F4	219	2211	2207

Similarly, we evaluated our approach's performance by computing the BLEU score between the predicted and ground truth instructions. Figure 20 shows the resulting instructions predicted by our module. The predicted instruction is written inside the images, whereas the ground truth instruction is written below. The predicted instructions were semantically correct because of the relations between images and captions created in the network's embedding space.

Figure 21 reports the cumulative BLEU scores for *Inter-procedure* and *Intra-procedure* testing. The captions predicted by our model obtained up to 86±1% 1-gram and 36±1% 4-gram BLEU scores. Our results surpassed those reported in state-of-the-art approaches for medical instructions prediction. Overall, the BLEU scores were slightly lower for lower *Word Count* values. A potential reason is that an increased-size vocabulary reduced the chances of learning meaningful relations between the images and the text descriptions. Our algorithm tackles a challenging problem due to the interclass variance among different medical procedures, which in turns has an impact the prediction capability of the network. As a reference value, the BLEU 1-gram score when comparing the ground truth instructions with descriptions constructed using random words from the vocabulary is less than 0.1%. Therefore, our results show an improvement over random guess.

Figure 20. *Examples of instructions predicted by the AI-Medic. The predicted instruction is in white font, inside the images. The ground truth (GT) instruction is written below. The approach calculates the BLEU scores after removing special characters (e.g. punctuation marks). High and average scores are highlighted in green and yellow, respectively.*

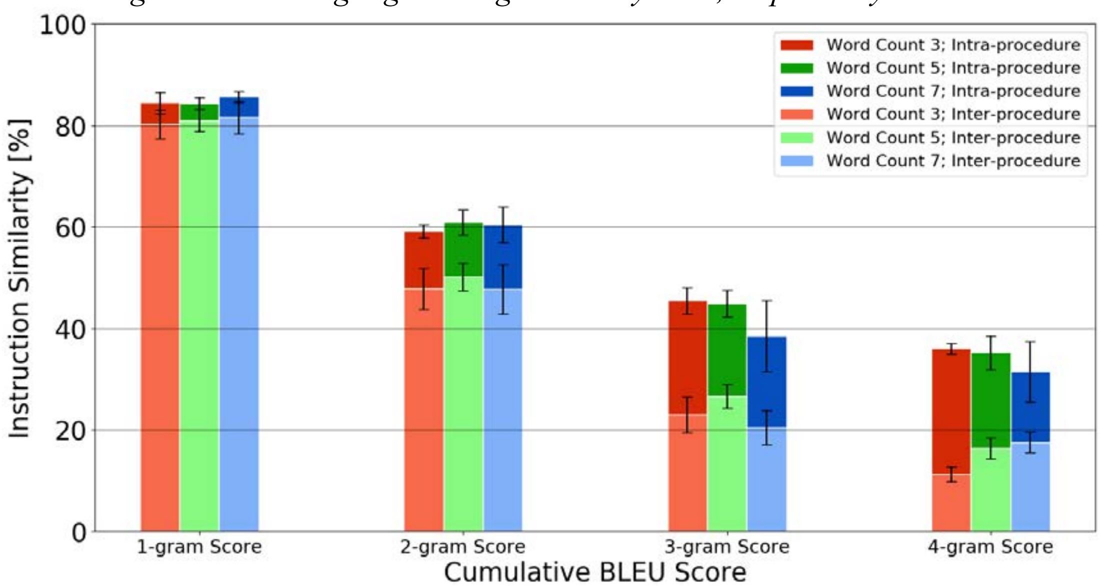

Figure 21. *Cumulative n-gram BLEU scores. Our model was evaluated using three {Word Count values (3, 5, 7) and two testing approaches (Inter-procedure, Intra-procedure). The model obtained up to 86±1% 1-gram, and up to 36±1% 4-gram BLEU scores*.

We created a prototype application of our platform. This prototype, called the AI-Medic, was built using a tablet (Galaxy Tab 3, Samsung). We used the camera of this tablet device to acquire and display the operating field to the user. In addition, every *n* seconds (as defined by the user), the system acquired a frame from the live video and analyze whether it presents undesired images artifacts (e.g. blurriness, out-of-focus). If the frame does not present any artifacts, it will be used as input to the DL model. The predicted instructions will be conveyed to the user via two modalities: showing it on the tablet's display, and via text-to-speech. For this prototype, we are using a socket connection to communicate the tablet device with the computer running the captioning model. The delay generated by this approach was less than one second.
In general, the AI-Medic provides guidance to a surgeon performing a medical procedure (a). The system captures the view of the operating field and predicts the instruction to perform (b). The instruction is conveyed to the surgeon using text-to-speech routines and by displaying it in the screen of a tablet device (c). Finally, a video illustrating a demo application of the AI-Medic was uploaded to YouTube, and can be accessed using the following link: https://www.youtube.com/watch?v=jYVt3sIGilg

Development of a commercialization plan for AI-Medic through the NSF I Corps program

Initial Business Thesis:
AI Medic is an artificial intelligence agent that mentors rural surgeons in performing surgeries, through augmented reality headset. The AI agent monitors the surgery scene and predicts the next step in the surgery
Overview:
Surgical expertise is scarce in rural areas. The reliance upon expert surgeons to mentor the generalists in rural areas has two fundamental problems – connectivity and availability. First, current telementoring methods rely on a stable and fast internet, which is often lacking in the rural and austere environments. Second, experts may not be available when needed due to scheduling problems. Through AI-Medic, we are developing an offline surgical telementoring platform powered by an Artificial Intelligence agent, which monitors the surgery scene and guides the surgeon in performing the surgical procedure, through natural language and an augmented reality headset.
Intellectual Merit:
We are developing an ecosystem of applications and hardware for telementoring with augmented reality and artificial intelligence (AI). Our infrastructure includes an innovative platform that relies on cameras, see-through displays and depth sensors to increase the quality of collaboration between mentor and trainee. Our platform enhances the mentor and trainee sense of co-presence through an augmented visual channel which leads to measurable improvements in the trainee's surgical performance. We are developing AI Medic to complement or substitute the expert mentors when needed.
AI Medic is a suite of applications and hardware that includes an AI module that allows telementoring of generalist surgeons to perform surgeries, through augmented reality headset. The AI agent monitors the surgery state and predicts the next instruction which is conveyed

verbally to the mentee. AI Medic is a portable standalone system that can be used in rural and austere environments, where there is no expert supervision and lack a stable internet connection.

Broader Impacts:

AI Medic aims to address the gap in lack of surgical care expertise in rural and austere environments. Usually most surgeries are delegated to large urban medical centers. When evacuation is not possible and immediate treatment is imperative, surgeons and medics rely on written guides, ZOOM calls, or video teleconferencing seeking for assistance. Lack of stable internet connection, and the unavailability of expert surgeons make the current mentoring practices ineffective. Given that AI Medic, is lightweight, portable, interactive, and standalone, we can address this challenge of lack of clinical expertise leading to more accessible healthcare in rural areas. AI Medic can also be helpful in training surgeons in using new tools, techniques, and surgical procedures without expensive and bulky simulators.

NSF I Corps Program

The goal of the I Corps program was to develop a commercialization plan for AI-Medic, with the inputs and feedback from customers, and the I Corps teaching staff. The entire program was designed around the business model canvas. We used many iterations of the business model canvas to reach the final commercialization plan.

Interviews

Customer Discovery Interviews are the backbone of the I-Corps program. We interviewed 100 people across the ecosystem to learn and validate our business model canvas. Interviews were conducted through phone or video conferencing. Learnings from every interview was documented in launchpad central (a web application for recording progress in the I-Corps program). Some of the documented interviews are shown below:

Dr. Jing Wang

Director of the Center for Smart and Connected Health, UT-Health San Antonio

Anirudh Tunga • Customer Interview • 11/11/2020 • Video Chat

KEY INSIGHTS

Rural medics cannot afford telementoring systems though they are useful to them.

INTERVIEW DETAILS

Dr. Jing Wang is the Director of the Center for Smart and Connected Health at UT-Health San Antonio.

She has a lot of experience in working in telemedicine and remote medicine programs.

She was part of the ECHO telementoring program.

Her group is using 5G technology to improve healthcare using connected devices.

She said that as part of the ECHO program she has experience in setting up a telementoring system. They only used video conferencing to conduct telementoring.

She said that though the telementoring system is actively used by the rural medics, they are not in a position to pay for it. Currently, the program is supported by research and infrastructure grants.

She believes that the rural healthcare system cannot afford a telementoring system by themselves, they'll need financial support from other institutions.

She also has the experience of reviewing SBIR grants.

Must Have | Nice to Have | Don't Care

CS | Surgeons (Directors)(DM)

Figure 22. *Interview with Dr. Jing Wang logged in Launchpad central*

Dr. Mark Ferguson

Professor of Surgery, University of Chicago

Anirudh Tunga • Customer Interview • 11/08/2020 • Phone

KEY INSIGHTS

Surgical performance is evaluated on a number of parameters, and detailed feedback is provided by the surgeons to the residents for improvement.

INTERVIEW DETAILS

Dr. Mark Ferguson is the professor of surgery at University of Chicago. He has years of experience in mentoring residents.

He said that the mentoring process is a graduated process, which starts of on simulators and progress to fairly complex procedures in live surgeries.

He said that simulator-based training is around 5-10% of resident's training program.

He also said that surgical performance feedback is given on a number of parameters, ex: the surgeons might suggest to practice more using the left hand, or improve tool placement techniques, or improve the accuracy of needle placement. He said that they don't measure the accuracy of such procedures based on numbers, but more on detailed feedback.

He also shared that they currently pay Intuitive robotics $2000 a month for the training platform.

Must Have | Nice to Have | Don't Care

CS | Surgeons (Directors)(DM)

Figure 23. *Interview with Dr. Mark Ferguson logged in Launchpad central*

The Potential of AI-Medic for Surgical Training

The interviews with surgeons helped us realize that our original idea for AI-Medic was not feasible in civilian medicine. However, we discovered another high potential use for AI-Medic – mentoring for surgical training. The surgeons mentioned that since the training is on cadavers or simulators, the elements of risk and accountability are eliminated. With the help of inputs from the NSF I Corps instructors, we pivoted to focus on an AI agent that mentors residents and surgeons to train for surgical procedures. We focused on discovering and learning different aspects of the business model canvas geared towards training for surgical procedures.

Through the interviews with residency directors, and surgeons who mentor residents, we learnt about the need for improvements in surgical training. Currently, most of the surgical training programs follow an apprenticeship model – where a resident learns by watching surgeons perform surgeries, and the resident is gradually allowed to perform minor parts of the surgery. Since the residents can witness surgeries only when a patient is undergoing a particular surgery, the residents are limited in number of cases they can practice on. Also, we learnt that the residents cannot effectively train on edge cases and on surgeries that are rare, as there are very few or no patients admitted with such conditions. Approximately, 30% of the residents are not confident of performing surgeries independently immediately after graduation.

Figure 24. *Surgeons and residents explaining the problems in current surgical training*

The surgeons mentioned that, these days the complexity of surgical procedures is increasing. Currently, the residents require 50-100 cases to acquire proficiency in a particular procedure, which is a drastic increase in what was required previously. One of the main reasons for this increase is increasing in complexity of surgical tools and the steep learning curve involved in learning to use them. The number of new procedures is also constantly increasing, whereas the methods of delivering surgical training remain the same. According to WHO, improper training and longer learning curves are the primary reasons for adverse events related to new technologies in surgeries.

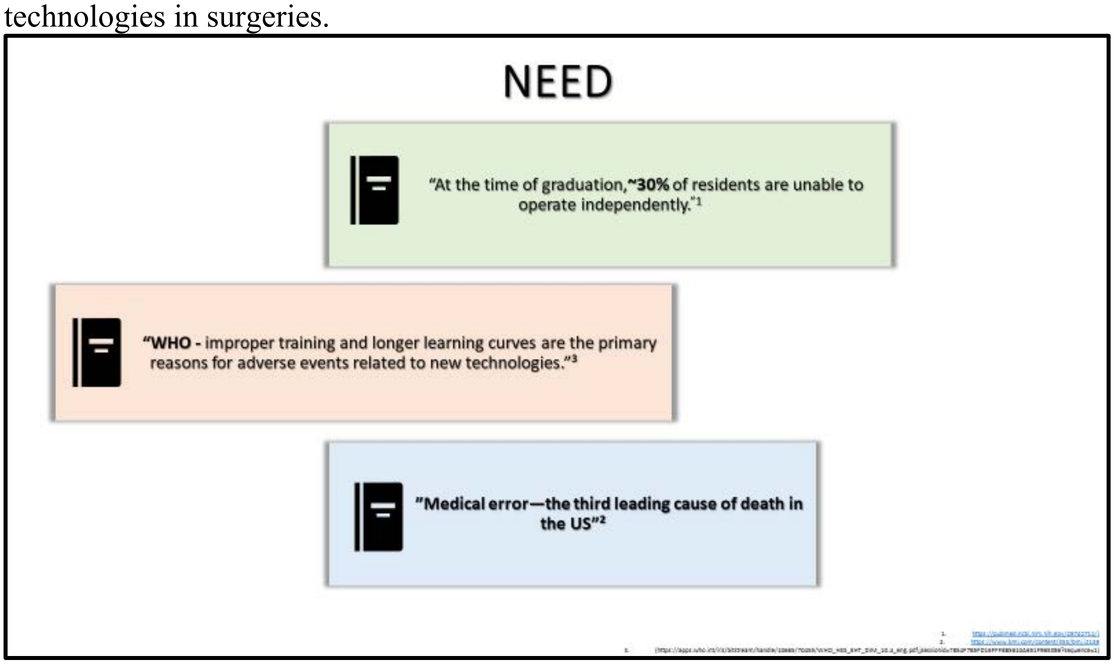

Figure 25. *The need for improving current surgical training*

Interviews with residents helped us realize the challenges they face in their training programs. The residents mentioned that in addition to not being able to practice on edge cases, they do not have the opportunity to practice on additional cases if they are not confident with a particular procedure. They mentioned that though they have simulators for training, they are rule-based and not interactive. Also, in most cases, the surgeons are not available for mentoring while practicing on simulators. The surgeons are busy performing surgeries on patients. The residents also mentioned that sometimes they record themselves performing procedures on simulators and cadavers, but they do not receive prompt feedback on the recorded videos owing to busy schedule of mentoring surgeons. They mentioned that having an automated way to review their videos and provide feedback will be very useful.
For the remainder of the program, we focused on discovering and learning different aspects of the business model canvas geared towards training for surgical procedures.

AI-Medic Final Business Model Canvas:
The final business model canvas was presented to successfully complete the I-Corps program and receive the grant of $50,000.

Business Thesis:
AI-Medic is a surgical telementoring platform powered by an AI agent that mentors residents and surgeons to train for surgical procedures, and reduce their revision rate.
It consists of a prediction module - to assist the residents while training, and an evaluation module – to analyze and provide feedback to the residents. The guidance is delivered using an augmented reality headset.
Final Canvas:

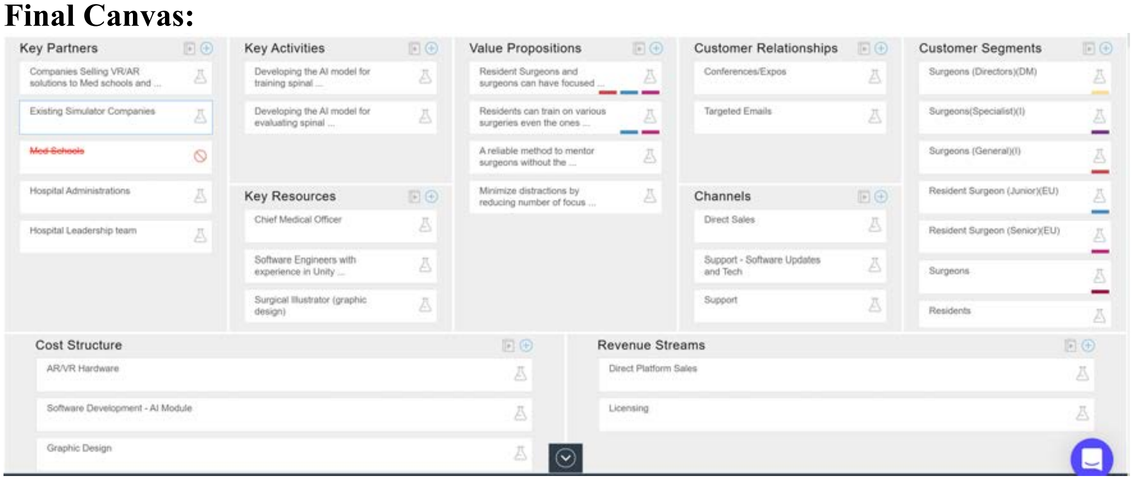

Figure 26. *Final business model canvas of AI-Medic*

Interview Statistics:
We conducted 100 interviews to validate and build our business model canvas. We interviewed a wide range of people in the ecosystem. Some people had multiple roles in the ecosystem, for example, the residency directors were both decision makers, and influencers. The figures below show the distribution of the interviews.

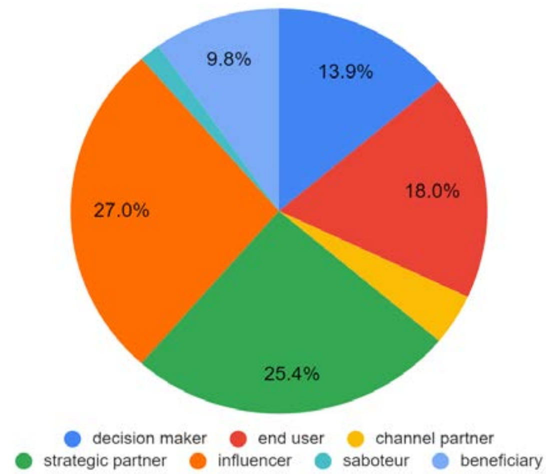

***Figure 27**. Distribution of interviews*

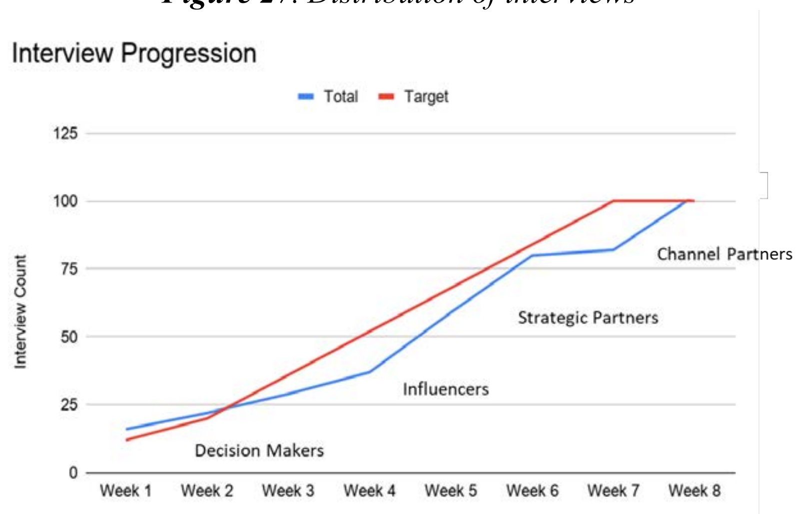

***Figure 28**. Interview progression over time*

Commercialization of AI-Medic

We applied to the NSF Partnerships for Innovation (PFI). The PFI program would have helped fund the development of a prototype for AI-Medic. The I-Corps program is a pre-requisite to apply for the PFI program.

Our PFI proposal got rejected with the following feedback from the committee:

Reviewer 1: Very Good
Reviewer 2: Fair
Reviewer 3: Good
Reviewer 4: Fair/Good

Intellectual Merit according to the Panel:
This PFI project focuses on developing an augmented reality system for the training of surgeons and surgical residents (AI-Medic). The product builds on the investigators previous work with a telementoring AR system. While their previous STAR system involved a live, but remote, mentor, the proposed system will use artificial intelligence to talk trainees through procedures. The educational plan is to have graduate students participate in a business model competition and other opportunities at Purdue management school. Overall, the committee found the concept interesting but there were concerns about the feasibility of the AI given the diversity of surgical procedures, possible errors, and conditions.

The broader/commercial impacts of this PFI project are in creating a training tool for surgeons that could be used to alleviate the demands for surgical trainers and could improve surgical skills, particularly in rural settings. The PI has included diverse undergraduates in his research. Overall, the committee found the commercial impacts may be limited by the market size and IP space.

According to the panel, the overall strengths are:

- The team has already developed a prototype system called STAR – a system for tele-mentored training using augmented reality.
- The team has successfully completed two rounds of I-Corps program. + The team has a well-developed commercialization plan.
- It would be an improvement of current VR training.

Overall Weaknesses: -

- The market does not appear large, and the system may be difficult sell.
- The commercialization plan should consider existing IP in the space.
- The proposed approach of using recurrent neural network (RNN) and long short-term memory (LSTM) to build a database for AI surgical instruction seems ambitious, there are questions about how successful it will be given the potential diversity of errors, procedures, and environmental (lighting) conditions.
- Team is missing strong medical advice on the surgical procedures.
- The broadening participation plan is inadequate.

Summary Statement:
This work proposed to develop an AI-assisted augmented reality surgical training tool that would allow residents and surgeons to train on techniques without the presence of the trainer. The committee found this to be an interesting proposal that might be most effective in military medicine settings. There were significant concerns about how well this AI system would work in complex surgical procedures and with unexpected errors by the trainees. There were also concerns about the potential market size for the product.

Development of Semantic Segmentation Module for Surgical Image Understanding

The anatomical landmarks and surgical instruments in the surgery scene need to be understood and identified to generate adequate guidance in context for specific medical procedures. For the development of the AI-Medic - an AI system for autonomous medical mentoring based on a comprehensive surgical dataset – we developed a semantic segmentation module for understanding surgery scenes, which can be later used to provide contextualized surgical instructions. Understanding what is happening in the current scene will help in providing accurate and relevant guidance.

category	#instances	category	#instances	category	#instances
background	6444	Abdominal W..	5810	Liver	6464
Gastrointes..	3618	Fat	5993	Grasper	4800
Connective ..	1295	Blood	563	Cystic Duct	197
L-hook Elec..	1818	Gallbladder	5490	Hepatic Vein	246
Liver Ligam..	192				
total	42930				

Figure 29. Statistics of the training data

To develop the semantic medical segmentation module of the AI-Medic, we trained a DL model based on the Mask RCNN architecture. Interest features were extracted from the input images using a convolutional backbone. These features were used to segment regions in the images such as anatomical landmarks and surgical instruments. The input image is passed through a backbone CNN – ResNet101 and Feature Pyramid Network (for extracting features at different scales), which acts a feature extractor. The features are extracted from different levels of the pyramid according to their scale, otherwise the architecture is similar to vanilla ResNet. A sliding window is used to classify if each precalculated anchor has an object or not, which is the first stage. In the second stage, the network predicts a binary mask per class based on the features in the first stage. The identified regions were afterwards superimposed over the original images using colored masks. The model was trained and evaluated on CholecSeg8k Dataset, which consists of 8080 frames of surgeons performing laparoscopic cholecystectomies. The predicted masks were classified into 13 landmarks commonly seen in cholecystectomy surgery, and the accuracy of the predictions was evaluated using mean Average Precision (mAP). The 13 landmarks were – Abdominal Wall, Liver, Grasper, Fat, Gallbladder, Gastrointestinal Tract, Connective Tissue, Blood, Cystic Duct, L-hook Electrocautery, Hepatic Vein, Liver Ligament, and Background. We used 80% of the frames (40k instances) for training the model and 20% for testing the model. The main idea behind developing the segmentation module is to extend it to other surgeries and improve the surgery scene understanding in general.

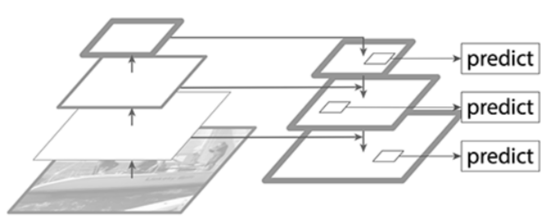

Figure 30. *Illustration of feature extraction at different scales*

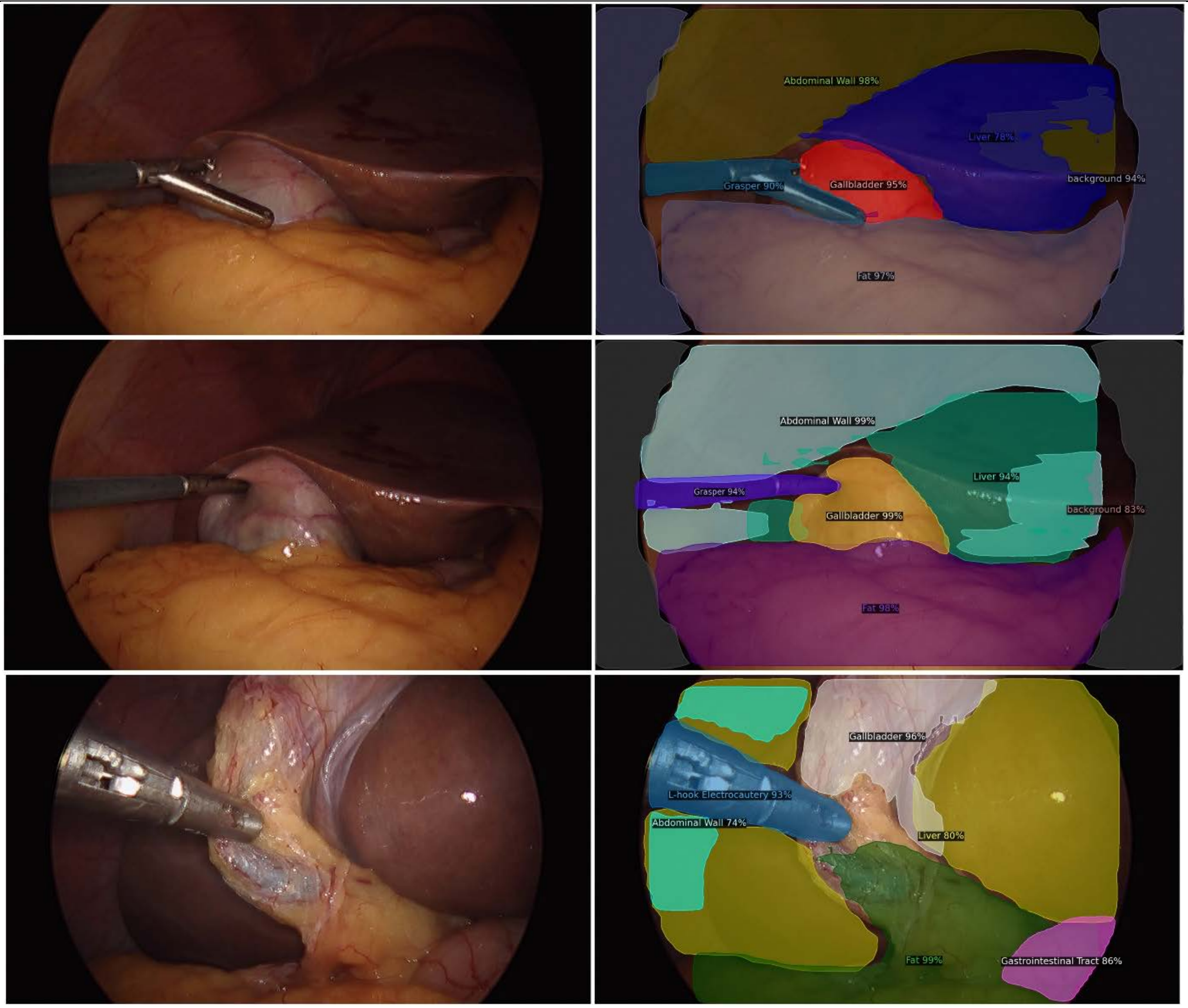

Figure 31. *Images from the laparoscopic surgery (left), semantic segmentation by the network.*

Our segmentation framework achieved a mAP of 83.7%. A prediction was considered positive only if the Intersection over Union (IoU) of the segmentation masks with the ground truth was more than 50%. The model was also evaluated qualitatively on videos from real-life cholecystectomy surgery videos provided by the Indiana University School of Medicine, and the segmentation maps were comparable to the segmentation maps on test images of the dataset.
The visualization of the video is presented here:
https://drive.google.com/file/d/1Q7973M7Kh0rgwIdtWSccp37WGvvOtk7B/view?usp=sharing

Task 4.1- Specialize the system for fasciotomy on a cadaveric leg
Evaluating STAR as means to provide coaching and confidence

We evaluated STAR as a platform that could provide surgery residents and medical students with coaching and confidence as they performed medical procedures. To do this, we leveraged our study in the context of fasciotomies. In this study, 20 participants were guided by remote expert surgeons to perform leg fasciotomies on cadavers under one of two conditions: telementoring (STAR), or independently reviewing the procedure beforehand. To investigate the effect of the mentoring conditions with respect to the participant's expertise, participants were recruited from three different strata to encompass various expertise levels: only medical students (n = 6; 3 per condition), only residents (n = 14; 7 per condition), and a combination of medical students and first-year residents (n = 10; 5 per condition). The latter was considered the sub-group who would benefit the most from the coaching experience due to their relatively lower expertise.

Based on the participants' video footage of the STAR participants, acquired as they performed the fasciotomies, six additional measurements were obtained to objectively describe the confidence scores and the overall coaching quality. These measurements were: 1) the number of surgical AR annotations created by the remote mentor; 2) the number of times the mentor asked the mentee for confirmation (e.g. "*That structure looks like the nerve to me, do you think the same?*"); 3) the number of times the mentee asked the mentor for instruction (e.g. "*There is muscle at the posterior border of the tibia, what would you like me to do?*"); 4) the number of times the mentee asked the mentor for confirmation (e.g. "*Are you sure I can cut this?*"); 5) the number of corrections given by the mentor (e.g. "*No, use your scissors for that, not the knife*"); and 6) the percentage of the total completion time during which the mentee received guidance from the remote mentor. These measurements were obtained only for participants in the STAR condition, as participants in the Control condition did not receive telementoring. Table 5 reports the measurements of confidence and coaching for participants in the STAR condition, divided by the three population sub-groups. Medical students received significantly more ($p = 0.04$) corrections when compared to residents.

Table 5. Quantifications of coaching and confidence for the different expertise-based sub-groups.

Measurements of Coaching and Confidence	**Med Students (*n* = 3)**	**Residents (*n* = 7)**	**Low-Expertise (*n* = 5)**
Number of AR annotations created, mean (95% CI), count	18.00 (13.52-23.49)	19.29 (16.17-22.83)	20.00 (16.27-24.33)
Number of times the mentor asked for confirmation, mean (95% CI), count	8.67 (5.66-12.70)	6.14 (4.45-8.27)	8.00 (5.72-10.89)
Number of times the mentee asked for instruction, mean (95% CI), count	5.67 (3.30-9.07)	4.29 (2.89-6.12)	5.20 (3.40-7.62)
Number of times the mentee asked for confirmation, mean (95% CI), count	3.00 (1.37-5.69)	5.29 (3.72-7.29)	4.20 (2.60-6.42)
Number of corrections given by the mentor, mean (95% CI), count	7.00 (4.33-10.70)	3.86 (2.54-5.61)	6.40 (4.38-9.03)
Time during which the mentee received guidance, mean (95% CI), percentage	44.2 (39.5-48.9)	49.15 (42.78-55.52)	44.51 (42.33-46.69)

STAR participants reported significant improvements in all evaluated aspects of their confidence scores. These results demonstrate that an interactive telementoring experience with STAR's ARHMD had a positive impact in participants' confidence. Although studies have shown that health practitioners' confidence in their surgical skills is correlated to competence and self-assessment of their skill, surveys report that the health practitioners' confidence in their skills is not particularly high. Extrapolating our results, integrating STAR to current coaching programs could help reinforcing surgical knowledge and enhancing the self-confidence of health practitioners.

The measurements of confidence and coaching elaborated on the self-reported confidence scores. The remote mentors created 19 annotations per participant on average. The use of the annotations can be divided into four situations: 1) exemplifying which instrument to use (e.g. placing the icon of a scalpel after saying "*Cut here*"); 2) showing the location of anatomical structures (e.g. drawing a circle around the peroneal nerve; 3) showing the length and location of incisions (e.g. drawing a line along the leg to depict where to cut); and 4) acquiring a better awareness of the operating field (e.g. drawing a circle around the toe to determine the orientation of the leg). By creating these annotations, the mentor was able to convey more guidance, a possible reason of the increased performance and confidence scores of STAR participants.

Moreover, transmitting the real-time visual feedback of the operating field allowed the remote mentor to provide better coaching. The visual feedback allowed the mentor to ask for confirmation 7 times per participant on average, and to perform 5 corrections per participants on average. The following transcription exemplifies one of these situations:

Mentor: "*That looks the saphenous vein*."

Mentee: "*What should I do with it?*"

Mentor: "*Continue with your incision, just make sure to stay away from the vein.*"

Mentee continues with the incision, and gets dangerously close to the vein.

Mentor: "*Wow! Be careful there, you almost got the vein in the last movement you did. Try not to get your knife too close to this area* (the mentor draws a circle in the screen)."

In this example, the mentor corrected the mentee and provided more details about which area to avoid thanks to the visual feedback and the AR annotations. The visual feedback also allowed the mentee to ask for instructions and confirmations an average of 5 times per procedure, as depicted in the following example:

Mentee: "*There is still some muscle here* (the mentee points at a specific point in the leg). *I think I should cut there more."*

Mentor: "*No, it is okay if there is still some muscle there."*

The percentage of time during which mentees received guidance from the remote mentor can be associated with the increased performance and confidence scores. On average, the mentees received guidance for 10 minutes and 48 seconds, which represented 47% of the total task completion time. These results represent that STAR participants received remote guidance for almost half of their task completion time without incurring into statistically significant completion time increases.

Finally, to analyze the usefulness of our platform even further, we inspected the errors performed the participants as they performed the fasciotomies. Our metric, the Individual Performance Score (IPS), included a description of 11 common errors incurred by surgeons as they perform fasciotomies (E1 to E11). Our expert evaluators annotated whenever the participants of our experiment incurred into these errors. Table 6 presents the distribution of the errors with respect to the mentoring condition for the different expertise-based sub-groups. The errors were divided into different levels of occurrence based on how many participants from each of the expertise-based sub-groups incurred in such error. The error was classified as low frequency if less than 20% of the participants in the sub-group incurred into the error. The error was classified as medium frequency if between 20% to 40% of the participants in the sub-group incurred into the error. Finally, the error was classified as high frequency if more than 40% of the participants in the sub-group incurred into the error. According to our low-medium-high frequency classification scheme, the sub-group with only medical students had 9 errors classified as low frequency, 1 classified as medium frequency, and 1 classified as high frequency; the sub-group with only resident had 8 errors classified as low frequency, 3 classified as medium frequency, and 0 classified as high frequency; and the sub-group with medical students and first-year residents combined had 6 errors classified as low frequency, 5 classified as medium frequency, and 0 classified as high frequency.

A 2-sample t-test was used to evaluate the hypothesis of whether receiving mentoring using STAR condition reduced the error occurrence was performed. The results revealed that participants in the STAR condition performed significantly less low frequency errors ($p = 0.05$), as well as significantly less medium frequency errors ($p < 0.001$). No statistical analyses were run for high frequency errors because not enough errors were classified into this category.

Breaking down the errors in this way allowed us to analyze which steps were more difficult, and whether receiving mentoring using STAR condition reduced the amount of times each specific error was performed. Based on our low-medium-high frequency classification scheme, errors E3, E5, E7, E9 and E11 were classified as low frequency for all the three expertise-based sub-groups. Most of these possible errors were related to incorrectly identifying and releasing the compartments (anterior, lateral and posterior). These results show that participants were able to release the outermost leg compartments without difficulties. Nonetheless, the process of releasing the deep posterior compartment (E10) was considered as medium frequency for both the only medical students and the medical students and first-year residents sub-groups. These results are not unexpected, as the process of releasing the deep posterior compartment can be more error prone. Therefore, considering this results, it is recommended paying extra attention to the instruction process of releasing this compartment while performing training for fasciotomies. Errors related to how participants used their tools (E1, E4, E6, and E7) were considered of medium frequency in most the cases (except E7). This reveals a deficiency in the way participants handled their surgical instruments. As a result, special emphasis should be placed in the correct use of surgical instruments during the residency years of future surgical personnel. Errors related to the identification and protection of anatomical landmarks (E2, E8, E7, and E11) were the most incurred during our experiment, to the point of being considered of high frequency for the only medical students sub-group. This reveal an aspect that should be reinforced in the current residency programs, as the ability of identifying and protecting internal anatomical structures is critical to proper surgical performance. These insights and the results from the statistical analyses reaffirm the validity of our platform as a novel method to increase medical confidence and provide accessible coaching.

Table 6. Distribution of the errors highlighted by IPS with respect to the mentoring condition for the different expertise-based sub-groups.

Error Code	Error Description	Med Students (*n* = 6)		Residents (*n* = 14)		Low-Expertise (*n* = 10)	
		STAR (*n* = 3)	CONTROL (*n* = 3)	STAR (*n* = 7)	CONTROL (*n* = 7)	STAR (*n* = 5)	CONTROL (*n* = 5)
E1	After initial anterolateral incision, uses scalpel or scissor instead of blunt instrument to avoid damaging the superficial peroneal nerve	0	0	1	2	0	1
		low frequency		medium frequency		low frequency	
E2	Does not protect superficial peroneal nerve while extending the intermuscular septum incision over the lateral and anterior compartments	0	1	1	3	0	2
		low frequency		medium frequency		medium frequency	
E3	Incorrectly identifies and releases the anterior compartment	0	0	0	0	0	0
		low frequency		low frequency		low frequency	
E4		0	1	0	1	0	2

	The tip of the scissors was not directed away from the intermuscular septum while releasing the anterior compartment	low frequency		low frequency		medium frequency	
E5	Incorrectly identifies and releases the lateral compartment	0	1	0	0	0	1
		low frequency		low frequency		low frequency	
E6	The tip of the scissors was not directed away from the intermuscular septum while releasing the lateral compartment	0	1	0	3	0	2
		low frequency		medium frequency		medium frequency	
E7	After initial posteromedial incision, uses scalpel or scissor instead of blunt instrument to avoid damaging the superficial peroneal nerve	0	0	0	0	0	0
		low frequency		low frequency		low frequency	
E8	Does not identify and retract the saphenous vein posteriorly	1	2	1	0	1	2
		high frequency		low frequency		medium frequency	
E9	Incorrectly identifies and releases the superficial posterior compartment	0	0	1	0	0	0
		low frequency		low frequency		low frequency	
E10	Incorrectly identifies and releases the deep posterior compartment	0	2	1	1	0	3
		medium frequency		low frequency		medium frequency	
E11	Fails to protect the neurovascular bundle while releasing the deep posterior compartment	0	0	0	0	0	0
		low frequency		low frequency		low frequency	

What opportunities for training and professional development has the project provided?

The team traveled to IMSH 2017 to present the developments done on the trainee HoloLens interface and the visualization of future steps application. Positive feedback was received and comments regarding system improvements are being incorporated to the final design of it. This conference presents topics regarding the state-of-the-art developments in medical simulation, which provided the team with a better understanding about where the community is moving.

To gain a broader understanding about how fasciotomies are performed, Co-PI Mullis gave the Purdue team a demonstration of the procedure on cadaveric legs. This provided the Purdue team with a better understanding on what are the necessary aspects that need to be incorporated to the system in order to provide surgeons with the enough mentoring capabilities to mentor this procedure.

One of the final extra technical modules added to the system was an AI agent capable of predicting surgical instructions from medical images and videos. PI Dr. Juan Wachs and Mr. Edgar Rojas-Muñoz explored the possibilities of commercialization of such a module by completing the National Science Foundation Midwest Node Introduction to Customer Discover program. Through this program, both team members were able to gain exposure some of the entrepreneurship processes required to formulate a business idea.

In addition to participating in the National Science Foundation Midwest Node Introduction to Customer Discovery program, PI Dr. Juan Wachs and Mr. Anirudh Tunga successfully participated in the National Science Foundation I-Corps program and were awarded $50,000 grant for customer discovery.

How were the results disseminated to communities of interest?

Purdue team traveled to IMSH 2017 (International Meeting on Simulation for Healthcare) to present the developments done on the trainee HoloLens interface and the visualization of future steps application. The medical simulation community received the system with a lot of positive feedback.

The HoloLens-based trainee system was demonstrated to Purdue University President Mitch Daniels during research showroom. The goal behind this activity was to communicate developments done by different Purdue University laboratories in augmented and virtual reality topics. Very positive feedback was received and our system was used first-hand by Pres. Mitch Daniels.

The work related to One-Shot Gesture Recognition was presented in the 12th IEEE International Conference on Automatic Face and Gesture Recognition, through oral presentations in the Doctoral Consortium and in the First International Workshop on Adaptive Shot Learning for Gesture Understanding and Production. Additionally, two posters were presented in two different sessions.

Several publications for academic journals and conferences have been submitted and accepted during this reporting period. In terms of journals, our submission to Nature Digital Medicine "Evaluation of an Augmented Reality Platform for Austere Surgical Telementoring: A Randomized Controlled Crossover Study in Cricothyroidotomies" was accepted for publication on April 2020. Moreover, our submission to Surgery "The System for Telementoring with Augmented Reality (STAR): A Head-Mounted Display to Improve Surgical Coaching and Confidence in Remote Areas" was accepted for publication on November 2019. Finally, our submission to Military Medicine "Telementoring in Leg Fasciotomies via Mixed-Reality: Clinical Evaluation of the STAR" was accepted for publication on July 2019. In terms of conferences publications, our submission "How About the Mentor? Effective Workspace Visualization in AR Telementoring" was accepted for publication in the IEEE Conference on Virtual Reality and 3D User Interfaces on March 2020; and our submission "The AI-Medic: an artificial intelligent mentor for trauma surgery" was accepted to the Journal of Computer Methods in Biomechanics and Biomedical Engineering.

We presented a poster at the 2019 Military Health System Research Symposium: "Training Effectiveness for Point of Injury Medical Care - A Portable and Self-contained Approach for Surgical Telementoring: Towards Remote, Point of Injury Care". Finally, a demo of our system was given at the Augmented & Virtual Reality in Medicine Workshop, in the 2019 Scientific Assembly of the American College of Emergency Physicians. We submitted an Abstract on

“The AI-Medic: an artificial intelligent mentor for trauma surgery” to the Military Health System Research Symposium 2021.

What do you plan to do during the next reporting period to accomplish the goals?

Nothing to Report.

4. IMPACT:

What was the impact on the development of the principal discipline(s) of the project?

This technology will increase the sense of co-presence in the operating room between mentor and trainee. This is a fundamental step towards telexistence. Telexistence is a concept used to describe the framework that allows humans to have a real-time sensation of being and interacting with objects in places somewhere different from their actual location. The fundamental premise is that a higher sense of co-presence has an impact on the quality of mentorship. For example, by allowing the mentors to physically interact with the patient’s anatomy though hand gestures (embodied interaction), the mentor’s level of immersion and engagement will be significantly increased.

What was the impact on technology transfer?

As part of the dissemination efforts and code handoff, an installation guide was created. The installation guide includes a detailed, step-by-step explanation of the steps to: 1) download the code from the GitHub repositories; 2) install the code and dependencies in a PC and Microsoft HoloLens device; 3) run each of the subsystems of our telementoring platform; and 4) connect the subsystems between them. The document can be downloaded using the following link: https://engineering.purdue.edu/starproj/wp-content/uploads/STAR_Installation_Guide.pdf.
Additionally, and with the help of Purdue University, PI Dr. Juan Wachs and Mr. Edgar Rojas-Muñoz have applied for patent protection for the AI surgical mentoring agent.

What was the impact on society beyond science and technology?

Currently the main instrument to improve surgical skills in trauma surgery requires animal models, one to one mentorship and lengthy and complex training sessions (e.g. the ATOM course attended by the PIs of this project). A more cost effective option that will make this training scalable consists of having the training surgeon teach the same ATOM class, remotely, through the STAR platform. This will allow tens residents (current there are only 10-15 per class) to participate concurrently with only one mentor.
Our augmented-reality approach to surgical telementoring is well suited to any field that requires mentor assistance, not just surgical applications. The main principles of encouraging co-presence between trainee and mentor, of visual annotation of an operating field, of two-way audio communication, and of video stabilization for a mentor view are all important factors in any remote guidance system. We anticipate that our advances hold potential for manufacturing and inspection and in training skills in rural or developing regions.

5. **CHANGES/PROBLEMS:**

Actual or anticipated problems or delays and actions or plans to resolve them

Changes that had a significant impact on expenditures

Significant changes in use or care of human subjects, vertebrate animals, biohazards, and/or select agents

Significant changes in use or care of human subjects

No changes

Significant changes in use or care of vertebrate animals.

No changes

Significant changes in use of biohazards and/or select agents

No changes

6. PRODUCTS:

- **Publications, conference papers, and presentations**

Journal publications.

1.
Title: Mixed Reality as a Medium for Improved Telementoring.
Journal: Military Health System Research Symposium (MHSRS).
Authors: Edgar Rojas-Muñoz, Daniel Andersen, Voicu Popescu, Maria Eugenia Cabrera, Glebys Gonzalez, Brian Mullis, Sherri Marley, Ben L. Zarzaur, Juan P. Wachs.
Status of Publication: Accepted for oral presentation.
Acknowledgment of federal support: yes.

2.
Title: Medical Telementoring Using an Augmented Reality Transparent Display.
Journal: Surgery (2016), 159(6), 1646-1653
Authors: Daniel Andersen, Voicu Popescu, Maria Eugenia Cabrera, Aditya Shanghavi, Gerardo Gomez, Sherri Marley, Brian Mullis, Juan P. Wachs.
Status of Publication: Published
Acknowledgment of federal support: yes.

3.
Title: An Augmented Reality Interface for Future Step Visualization in Simulator-Based Training.
Journal: Simulation in Healthcare.
Authors: Daniel Andersen, Glebys Gonzalez, Voicu Popescu, Edgar Rojas-Muñoz, Maria Eugenia Cabrera, Brian Mullis, Sherri Marley, Xin Zhong, Ben L. Zarzaur, Juan P. Wachs.
Status of Publication: Submitted.
Acknowledgment of federal support: yes.

4.
Title: Surgical Telementoring with Augmented Reality: A Randomized Control Crossover Experiment to Provide Remote Assistance at the Point of Injury
Journal: Nature Digital Medicine
Authors: Edgar Rojas-Muñoz, Chengyuan Lin, Natalia Sanchez-Tamayo, Maria Eugenia Cabrera, Daniel Andersen, Voicu Popescu, Juan Barragan Noguera, Ben Zarzaur, Patrick Murphy, Kathryn Anderson, Thomas Douglas, Clare Griffis, Andrew W. Kirkpatrick, Jessica McKee, Juan Wachs
Status of Publication: Published.
Acknowledgment of federal support: yes

5.
Title: The System for Telementoring with Augmented Reality (STAR): A Head-Mounted Display to Improve Surgical Coaching and Confidence in Remote Areas

Journal: Surgery
Authors: Edgar Rojas-Muñoz, Maria Eugenia Cabrera, Chengyuan Lin, Daniel Andersen, Voicu Popescu, Kathryn Anderson, Ben Zarzaur, Brian Mullis, Juan Wachs
Status of Publication: Published. E-pub ahead of print: https://doi.org/10.1016/j.surg.2019.11.008
Acknowledgment of federal support: yes.

6.
Title: Telementoring in Leg Fasciotomies via Mixed-Reality: Clinical Evaluation of the STAR Platform
Journal: Journal of Military Medicine
Authors: Edgar Rojas-Muñoz, Maria Eugenia Cabrera, Chengyuan Lin, Natalia Sánchez-Tamayo, Dan Andersen, Voicu Popescu, Kathryn Anderson, Ben Zarzaur, Brian Mullis, Juan Wachs
Status of Publication: Published. Volume 184, no. Supplement_1 (2019): 513-520.
Acknowledgment of federal support: yes.

7.
Title: The AI-Medic: an artificial intelligent mentor for trauma surgery
Journal: Computer Methods in Biomechanics and Biomedical Engineering
Authors: Rojas-Muñoz, Edgar, Kyle Couperus, and Juan Wachs.
Status of Publication: Published. Imaging & Visualization (2020): 1-9.

Books or other non-periodical, one-time publications.

Other publications, conference papers, and presentations.

1.
Title: A Hand-Held, Self-Contained Simulated Transparent Display.

Conference: International Symposium on Mixed and Augmented Reality (ISMAR), 2016.
Authors: Daniel Andersen, Voicu Popescu, Chengyuan Lin, Maria Eugenia Cabrera, Aditya Shanghavi, Juan P. Wachs.
Status of Publication: Published.
Acknowledgment of federal support: yes.

2.
Title: Qualitative Use Assessment of Non-Verbal Interaction Modalities during Telementoring.
Conference: International Meeting on Multimodal Interaction (ICMI), 2017.
Authors: Maria Eugenia Cabrera, Edgar Rojas-Muñoz, Daniel Andersen, Voicu Popescu, Gerardo Gomez, Sherri Marley, Brian Mullis, Juan P. Wachs.
Status of Publication: Submitted.
Acknowledgment of federal support: yes.

3.
Title: STAR – A System for Telementoring with Augmented Reality
Conference: International Meeting on Simulation in Healthcare (IMSH), 2016.
Authors: Dan Andersen, Voicu Popescu, Maria Eugenia Cabrera, Aditya Shanghavi, Edgar Rojas-Muñoz, Brian Mullis, Sherri Marley, Gerardo Gomez, Juan P. Wachs.
Status of Publication: Oral Presentation.
Acknowledgment of federal support: yes.

4.
Title: See-What-I-Do: Increasing Mentor and Trainee Sense of Co-Presence in Trauma Surgeries with the STAR Platform.
Conference: International Meeting on Simulation in Healthcare (IMSH), 2017.
Authors: Dan Andersen, Voicu Popescu, Edgar Rojas-Muñoz, Maria Eugenia Cabrera, Brian Mullis, Sherri Marley, Gerardo Gomez, Juan P. Wachs.
Status of Publication: Oral Presentation.
Acknowledgment of federal support: yes.

5.
Title: How About the Mentor? Effective Workspace Visualization in AR Telementoring
Conference: IEEE Conference on Virtual Reality and 3D User Interfaces (IEEE VR 2020)
Authors: Chengyuan Lin, Edgar Rojas-Muñoz, Maria Eugenia Cabrera, Natalia Sanchez-Tamayo, Daniel Andersen, Voicu Popescu, Juan Antonio Barragan Noguera, Ben Zarzaur, Pat Murphy, Kathryn Anderson, Thomas Douglas, Clare Griffis, and Juan Wachs
Status of Publication: Accepted and presented.
Acknowledgment of federal support: yes.

6.

Title: Training Effectiveness for Point of Injury Medical Care - A Portable and Self-contained Approach for Surgical Telementoring: Towards Remote, Point of Injury Care
Conference: Military Health System Research Symposium (MHSRS 2019)
Presenter: Juan Wachs; presented as poster.
Acknowledgment of federal support: yes.

7.
Demo: The System for Telementoring with Augmented Reality
Conference: Augmented & Virtual Reality in Medicine Workshop, in the 2019 Scientific Assembly of the American College of Emergency Physicians.
Presenter: Kyle Couperus
Acknowledgment of federal support: yes.

8.
Title: The AI Mentor: Towards Autonomous Surgical Telementoring
Conference: Military Health System Research Symposium (MHSRS 2021)
Authors: Anirudh Tunga, Edgar Rojas-Muñoz, and Juan Wachs
Status of Publication: Submitted
Acknowledgment of federal support: yes.

- **Website(s) or other Internet site(s)**

Official project website, with overview of research, links to publications, images, and videos.
https://engineering.purdue.edu/starproj

STAR Project Youtube page:
https://www.youtube.com/channel/UCSrh1dlsrvbGvE_hLenXwGQ

- **Technologies or techniques**

An approach to visualize future steps of a surgical procedure via a tablet application was developed. With this approach, pre-recorded videos of a specific surgical procedure are shown directly into the users' field of view. This was extended to more surgical procedures, especially a fasciotomy.
As part of the dissemination efforts and code handoff, an installation guide was created. The installation guide includes a detailed, step-by-step explanation of the steps to: 1)

Additionally, and with the help of Purdue University, PI Dr. Juan Wachs and Mr. Edgar Rojas-Muñoz have applied for patent protection for the AI surgical mentoring agent.

can be downloaded using the following link: https://engineering.purdue.edu/starproj/wp-content/uploads/STAR_Installation_Guide.pdf.

- **Inventions, patent applications, and/or licenses**

PI Dr. Juan Wachs and Mr. Edgar Rojas-Muñoz completed the National Science Foundation Midwest Node Introduction to Customer Discover program. Through this program, and with the help of Purdue University, PI Dr. Juan Wachs and Mr. Edgar Rojas-Muñoz are in the process of applying for patent protection for the AI surgical mentoring agent.

PI Dr. Juan Wachs and Mr. Anirudh Tunga completed the National Science Foundation I-Corps program, and were awarded a grant of $50,000 for customer discovery of AI-Medic.

Technology	Type of Patent	Country	Patent Application Number	Patent Application Date	Status
1- ARTIFICIALLY INTELLIGENT MEDICAL TELEMONITORING FAILOVER SYSTEM	Provisional	United States	63/046,298	30-Jun-20	Converted
PCT	WO	PCT/US21/38968	24-Jun-21	Nationalized	
NATL-Patent	United States	18/012,529	22-Dec-22	Filed	
2- ARTIFICIALLY INTELLIGENT MEDICAL PROCEDURE ASSESSMENT AND INTERVENTION SYSTEM	Combined with the above patent				
3- AUGMENTED REALITY TRANSPARENT DISPLAY FOR TELEMENTORING AND TELEPROCTORING	Provisional	United States	62/168,438	29-May-15	Converted
Utility	United States	15/167,011	27-May-16	Issued (9,503,681)	

- **Other Products**

The projects' installation guide can be downloaded using the following link: https://engineering.purdue.edu/starproj/wp-content/uploads/STAR_Installation_Guide.pdf

The following repositories can be used to acquire our platform's subsystems:

- Mentor System: https://github.com/edkazar/MentorSystemUWPWebRTC/
- Mentee System: https://github.com/practisebody/STAR/
- STAR Controller App:
  - PC Version: https://github.com/practisebody/STARController_UWP/
  - Phone Version: https://github.com/practisebody/STARController_Android/

7. PARTICIPANTS & OTHER COLLABORATING ORGANIZATIONS

What individuals have worked on the project?

Name:	*Juan P Wachs*
Project Role:	*Principal Investigator*
Researcher Identifier (e.g. ORCID ID):	*0000-0002-6425-5745*
Nearest person month worked:	*1.12 month*
Contribution to Project:	*Supervising the overall performance of the project. Coordinated visits to IUSM. Working with Maria Eugenia in all the aspects of gesture recognition and one shot learning. Working with Aditya Shanghavi for the design of the large interaction table. Helping with the journal publication.*
Name:	*Voicu Popescu*
Project Role:	*Co-Investigator*
Researcher Identifier (e.g. ORCID ID):	
Nearest person month worked:	*1.12 month*
Contribution to Project:	*Actively participated in and advised research assistant Daniel Andersen in the research and development of the first prototype of the augmented reality transparent display surgical telementoring system (i.e. the STAR platform); in designing, conducting, and analyzing the results of user studies aimed at assessing STAR; in disseminating the project results in a journal paper.*
Name:	*Brian Mullis*
Project Role:	*Co-Investigator*
Researcher Identifier (e.g. ORCID ID):	
Nearest person month worked:	
Contribution to Project:	*Provided formative feedback about the applicability of the prototype to austere environments, and specifically its benefits and drawbacks when used for orthopedic surgery. He also provide assistance regarding the fasciotomy procedure and the possibility to show case this procedure in Experiment 2, in a simulated environment.*
Name:	*Sherry Marley*
Project Role:	*Co-Investigator*
Researcher Identifier (e.g. ORCID ID):	

Nearest person month worked:	
Contribution to Project:	*Helped the Purdue team with the experimental design. Coordinated the attendance to the ATOM course three times. She provided consultancy regarding the surgical training process and actionable knowledge during the cric.*
Name: *Project Role:* *Researcher Identifier (e.g. ORCID ID):* *Nearest person month worked:*	*Dan Andersen* *Research Assistant* *5.25 months*
Contribution to Project:	*Responsible for architecting, programming and developing tablet system for mentor and trainee tablets. Researched and implemented feature detection / descriptor matching approach for current annotation anchoring algorithm. Was major contributor to journal paper demonstrating the STAR platfrom. Contributed to planning and conducting ongoing user studies to validate system.*
Name: *Project Role:* *Researcher Identifier (e.g. ORCID ID):* *Nearest person month worked:*	*Maria Eugenia Cabrera* *Research Assistant* *5.25 months*
Contribution to Project:	*Maria Eugenia worked together with Dan in the experimental design, recruitment of human subjects, development of the testing environment and mock surgical scenarios. She is now working on the one-shot learning concept for gesture recognition.*
Name: *Project Role:* *Researcher Identifier (e.g. ORCID ID):* *Nearest person month worked:*	*Edgar Rojas* *Research Assistant* *5.25 months*
Contribution to Project:	*Edgar developed the mentoring system architecture together with the software*

and libraries required to interact with the large display

Name: *Ben Zarzaur*
Project Role: *Co-Investigator*
Researcher Identifier (e.g. ORCID ID):
Nearest person month worked:

Contribution to Project: *Helped with the design of the multimodal mentoring assessment system at IUSM (Experiment 2) and provided formative feedback about the main features required for the cric procedure and assessment methods.*

Name: *Xin Zhong*
Project Role: *Supported collaborator*
Researcher Identifier (e.g. ORCID ID):
Nearest person month worked:

Contribution to Project: *She is helping with the recruitment of surgeons, residents and other participants to evaluate the system. Also Dr. Zhong is helping with the IRB documents and other paperwork related to human subject experiments.*

Name: *Maria Eugenia Cabrera*
Project Role: *Research Assistant*
Researcher Identifier (e.g. ORCID ID):

Nearest person month worked: *5.25 months*

Contribution to Project:
Maria Eugenia worked together with Dan in the experimental design, recruitment of human subjects, development of the testing environment and mock surgical scenarios. She is now working on the one-shot learning concept for gesture recognition.

Name: *Anirudh Tunga*
Project Role: *Research Assistant*
Researcher Identifier (e.g. ORCID ID):
Nearest person month worked: *5.25 months*

Contribution to Project:
Anirudh extended the AI platform and participated in the I-Corps program for possible commercialization of the technology

Has there been a change in the active other support of the PD/PI(s) or senior/key personnel since the last reporting period?
If there is nothing significant to report during this reporting period, state "Nothing to Report."

If the active support has changed for the PD/PI(s) or senior/key personnel, then describe what the change has been. Changes may occur, for example, if a previously active grant has closed and/or if a previously pending grant is now active. Annotate this information so it is clear what has changed from the previous submission. Submission of other support information is not necessary for pending changes or for changes in the level of effort for active support reported previously. The awarding agency may require prior written approval if a change in active other support significantly impacts the effort on the project that is the subject of the project report.

<u>Current</u>

Title: Collaborative Research: I/Ucrc For Robots And Sensors For The Human Well-Being

PI: Matson, Eric T
Time Commitments: Percentage Per Year: 2%
Agency: National Science Foundation
Agency Address: 4201 Wilson Boulevard,Arlington,VA 32230
Agency's Contact/Contracting/ Grants Officer: Shirley Byrd **Performance Period:** 09/15/2014 - 08/31/2021 **Funding:** $325,000

Objectives:

Overlap:
Enabling Research in Natural Communication with Virtual Tutors, Therapists, and Robotic Companions (NTP-14076 $57,015k, 2014-2017), Intellectual Merit: developed an instrument to accelerate research in optimized communicati between people and humanoid robotic with shared awareness. Broader Impact: Supports cross-discipline science t advance HRI. Publications: (A. Mollahosseini, G. Graitzer, E. Borts, S. Conyers, R. M. Voyles, R. Cole 2014). Evide Several institutions "purchased in" to the instrument and will have a copy(s).

No overlap

Title: Workshop Support To Encourage Student Investigation Of Gesture And Dialog

PI: Voyles, Richard M
Time Commitments: Percentage Per Year: 2%
Agency: National Science Foundation
Agency Address: 4201 Wilson Boulevard,Arlington,VA 32230
Agency's Contact/Contracting/ Grants Officer: Tatiana D. Korelsky I NSF
Performance Period: 06/01/2017 - 05/31/2021
Funding: $14,345
Objectives: Worshop to encourage the participation of students for the IEEE FG 2018 Conference
Overlap:

No overlap

Title: A Fundamental Theory For Dexterous Surgical Skills Transfer To Medical Robots

PI: Wachs, Juan P
Time Commitments: Percentage Per Year: 19.58%
Agency: Defense, U.S. Department Of
Agency Address: No Address in Rolodex **Agency's Contact/Contracting/ Grants Officer:** David P Ruane
Performance Period: 09/15/2018 - 09/14/2021
Funding: $1,285,500

We will develop a theoretical framework for supervised autonomy, capable to self-adjust autonomous behavior and perform procedures in never seen settings using a transfer

Objectives:

Overlap:
learning paradigm. Our working hypothesis is that an existing procedure can be adapted to a new domain using an encoding scheme to restore supervisory content combined with a zero shot learning framework. The architecture fo proposed investigation is shown at the right.

No overlap

Title: Multimodal Cognitive And Perception Sensing For Situational Awareness

PI: Yu, Denny
Time Commitments: Percentage Per Year: 1.17%
Agency: Ford Motor Company **Agency Address:** No Address in Rolodex
Agency's Contact/Contracting/

Grants Officer: Kwaku O. Prakah-Asante
Performance Period: 05/15/2019 - 08/31/2021
Funding: $200,000
Objectives: Develop algorithms to learn patterns associated with high and low cognitive load.
Overlap:

No overlap

Title: Real-Time Non-Intrusive Workload Monitoring-Integration Of Human Factors In Surgery Training And Assessment

PI: Yu, Denny
Time Commitments: Percentage Per Year: 6.25%
Agency: Phs-Biomedical Imaging & Bioengineering
Agency Address: 9000 Rockville Pike, Bldg 31, Room 1C14,Bethesda,MD 20892
Agency's Contact/Contracting/ Grants Officer: Turska, Florence (NIH/NIBIB) [E] [mailto:turskaf@mail.nih.gov]
Performance Period: 09/01/2019 - 06/30/2022
Funding: $395,296
The goal of this study is to develop and validate a non-intrusive tool for measuring
Objectives: Overlap:

intraoperative workload with analytics and user interfaces that can provide surgeons clinically relevant and actionab on task workload.
No overlap

Title: Fmitf: Collaborative Research: Track I: Embedding Constraint Reasoning In Machine Learning For Better Prediction And Decision-Making

PI: Xue, Yexiang
Time Commitments: Percentage Per Year: 3.83%
Agency: National Science Foundation
Agency Address: 4201 Wilson Boulevard,Arlington,VA 32230
Agency's Contact/Contracting/ Grants Officer: James Donlon **Performance Period:** 09/01/2019 - 08/31/2023 **Funding:** $406,814

Objectives: Overlap:

Our proposed approach provides a scalable method for machine learning over structured domains. The core idea is augment machine learning algorithms with a constraint reasoning module that represents physical or operational requirements
No overlap

Title: Pfi-Tt: A Portable And Real-Time System For Individuals With Visual Impairments To Explore Digital Images Using Alternate Feedback

PI: Wachs, Juan P
Time Commitments: Percentage Per Year: 1.5%
Agency: National Science Foundation
Agency Address: 4201 Wilson Boulevard,Arlington,VA 32230
Agency's Contact/Contracting/ Grants Officer: Jesus Soriano Molla
Performance Period: 06/01/2019 - 05/31/2022
Funding: $250,000
Firstly, the Tetratix system will use a unique portable haptic controller manufactured by H Robotics, a longterm collaborator of the team, and integrate it with an iPad.
Objectives:

Overlap:
Secondly, unlike the single modality used by competitor products, it incorporates a multisensory feedback interface comprising of modalities such as haptics, sound and vibration.

No overlap

Title: Nri: Int: Fingers See Things Differently (Fist-D): A Robotic Explosive Ordnance Disposal Based On Augmented Tactile Imaging

PI: Wachs, Juan P
Time Commitments: Percentage Per Year: 8.3%
Agency: National Science Foundation
Agency Address: 4201 Wilson Boulevard,Arlington,VA 32230
Agency's Contact/Contracting/ Grants Officer: Ralph Wachter **Performance Period:** 09/01/2019 - 08/31/2022 **Funding:**
$1,499,795
A novel solution to the problem of tactile exploration, target characterization and action is proposed through this proposal. The approach is integrative in the sense that
Objectives: Overlap:

manipulation, analysis and grasping strategies occur concurrently through human-robot co-learning.
No overlap

Title: I-Corps: An Offline Surgical Telementoring Platform That Guides The Surgeon Via An Augmented Reality Headset (Ai-Medic)

PI: Wachs, Juan P
Time Commitments: Percentage Per Year: 3.5%
Agency: National Science Foundation
Agency Address: 4201 Wilson Boulevard,Arlington,VA 32230

Agency's Contact/Contracting/ Grants Officer: Shuman, Ruth M. <rshuman@nsf.gov>
Performance Period: 01/01/2021 - 06/30/2021
Funding: $50,000

We are developing an ecosystem of applications and hardware for telementoring with au
reality and artificial intelligence (AI). Our infrastructure includes an innovative

Objectives:

Overlap:

platform that relies on cameras, see-through displays and depth sensors to increase the quality of collaboration bet
mentor and trainee. Our platform enhances the mentor and trainee sense of co-presence through an augmented vi
channel which leads to measurable improvements in the trainee's surgical performance

No overlap

Title: Connected And Autonomous Procedure Support Tools For Combat Trauma And Mass Casualty Management

PI: Wachs, Juan P
Time Commitments: Percentage Per Year: 8.33%
Agency: The Geneva Foundation
Agency Address: 917 Pacific Avenue Ste 600,Tacoma,WA 98402
Agency's Contact/Contracting/ Grants Officer: Kasey Zink <KZink@genevausa.org>
Performance Period: 10/01/2021 - 09/30/2023
Funding: $199,729
Objectives: Deliver surgical expertise using augmented reality and computer vision techniques
Overlap:

Some overlap in the area of computer vision.

<u>Pending</u>

Title: Beyond High Vs. Low Assessment Of Workload And Team Skills: Continuous Sensing Enables Prediction Of Incremental Changes In Cognitive And Team Skills

PI: Yu, Denny
Time Commitments: Percentage Per Year: 1%
Agency: Intuitive Foundation
Agency Address: 1020 Kifer Road,Sunnyvale,IN 94086-5304
Agency's Contact/Contracting/

Grants Officer: Behrouz Shabestari
Performance Period: 03/01/2021 - 02/28/2026
Funding: $300,000
Objectives: To assess cognitive load using machine learning and in a non-instrusive manner.
Overlap:

No overlap

Title: Automated Burn Diagnostic System For Healthcare (Ambush)

PI: Wachs, Juan P
Time Commitments: Percentage Per Year: 12.08%
Agency: Indiana University
Agency Address: 620 Union Drive,Indianapolis,IN 446202
Agency's Contact/Contracting/ Grants Officer: Dr. Mark Dertzbaugh
Performance Period: 09/01/2021 - 08/31/2023
Funding: $367,537
Objectives: The objective of this research is to develop a high accuracy and automated system that c assess burn injuries based on the measurement of the mechanical properties of the

Overlap:
subcutaneous tissue under the burned skin in absence of burn experts. Thus, it will predict the burn depth and burn conversion with high accuracy, improving the patient's prognosis and avoiding delays in the process

No overlap

Title: Ipa Assignment - Juan Wachs

PI: Wachs, Juan P
Time Commitments: Percentage Per Year: 100%
Agency: National Science Foundation
Agency Address: 4201 Wilson Boulevard,Arlington,VA 32230
Agency's Contact/Contracting/ Grants Officer: Wendy Nielsen
Performance Period: 06/21/2021 - 06/20/2022
Funding: $223,562
Objectives: Serve as a program manager at NSF at the Robust Inteligence Program
Overlap:

No overlap

Title:	Surrogate Agent Mentorship (SAM) Where the Generalist Meets the Specialist
PI:	Wachs, Juan P
Time Commitments:	Percentage Per Year: 2%
Agency:	Defense Advanced Res Projects Agency
Agency Address:	675 North Randolph Street Arlington, VA 22203-2114
Agency's Contact/Contracting/ Grants Officer:	Dr. Bruce Draper
Performance Period:	01/01/2022 - 12/31/2025
Funding:	$5,483,941
Objectives:	The objective of this proposal is develop aA Perceptually-enabled Task Guidance (PTG) assistant has the potential to "amplify" the capabilities of an individual performer to addre new tasks, never seen before, without the learning curve, costs, time and re- allocation associated with it. What is unique in SAM is that we bridge the perception, reasoning, an action gaps through aligning such capabilities around the user, thus
Overlap:	

taking an egocentric approach of sensemaking and instruction. That is, user models will be adopted to address eac the four challenges, perceptual grounding, perceptual attention, knowledge transfer, and user modeling (a meta-mo We propose several innovative methods and approaches in each one of these essential components of our SAM system.

This proposal

If there is nothing significant to report during this reporting period, state "Nothing to Report."

Describe partner organizations – academic institutions, other nonprofits, industrial or commercial firms, state or local governments, schools or school systems, or other organizations (foreign or domestic) – that were involved with the project. Partner organizations may have provided financial or in-kind support, supplied facilities or equipment, collaborated in the research, exchanged personnel, or otherwise contributed.
Provide the following information for each partnership:

Organization Name: Indiana University School of Medicine
Location of Organization: Indianapolis, USA
Partner's contribution to the project (identify one or more)

- *Experimental Design for experiment 2. The co-Investigators helped on the design of the fasciotomy experiment, provided the supplies and supported the completion of the experiment.*
- *In-kind support: they made available the surgical instruments and facilities to complete Experiment 2*
- *Collaboration: Dr. Gomez, Mrs. Marley and B. Mullis collaborated with the project staff on the project);*
- *Personnel exchanges: We visited IUSM for Experiment 2 and the graduate students participated in the discussions and experiments.*

8. SPECIAL REPORTING REQUIREMENTS

COLLABORATIVE AWARDS: For collaborative awards, independent reports are required from BOTH the Initiating PI and the Collaborating/Partnering PI. A duplicative report is acceptable; however, tasks shall be clearly marked with the responsible PI and research site. A report shall be submitted to **https://ers.amedd.army.mil** for each unique award.

QUAD CHARTS: If applicable, the Quad Chart (available on https://www.usamraa.army.mil) should be updated and submitted with attachments.

9. APPENDICES: Attach all appendices that contain information that supplements, clarifies or supports the text. Examples include original copies of journal articles, reprints of manuscripts and abstracts, a curriculum vitae, patent applications, study questionnaires, and surveys, etc.