Development and Demonstration of Augmented Reality Forward Surgical Care

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ABSTRACT

This project was a demonstration of an augmented reality (AR) forward surgical care system. A sample of six persons, two each of Military physicians (non-surgeons), physician assistants, and special operations medics used a lightweight, rugged, wearable AR display (ODG R-7) with telestration software, bi-directional voice and video, and voice-controlled on-board magnification to receive remote guidance from surgeons across cell networks, army radios, and simulated satcom. Two procedures (four-compartment fasciotomy; anterior exposure of femoral artery) were performed on synthetic-anatomy medical training manikins. The ODG R7's preserved user peripheral vision to enable tactical situational awareness while using the device. This technology integration project demonstrated that surgical specialty is plausible in far forward environments when timely access to in-person surgical care is impossible. The operational concept was to integrate commercial off-the-shelf (COTS) items into existing telecommunication systems within the U.S. Army to create a unique operative platform. A Mastery Learning Model was developed and employed to train and assess skill performance of both the mentees (non-surgeons) and a mentor (a surgeon) during the exercise. As an integration project, the effort was not designed to reach statistical significance. Even so, the six students opened 23 of 24 fascial compartments successfully and achieved control of the proximal femoral artery on all of the six test models. The fasciotomy completion rates exceed the success rate that has been reported for attending surgeons in some studies. This paper will discuss the development of the smart glasses system, the Army-approved training demonstration methodology and outcomes, lessons learned, and the roadmap for development of a fieldable system and best practices for future efforts based on our successful demonstration.

ABOUT THE AUTHORS

Jerry Heneghan is the Chief Design Officer for BioMojo, LLC, a woman-owned small business. BioMojo operates at the nexus of wearable platforms using AR/(mixed reality)MR, computational biology, biometric sensors, and advanced graphical user interfaces. Heneghan is a former U.S. Army Aviator (AH-64A) and holds an MBA from the Fuqua School of Business at Duke University and a BS in engineering from the United States Military Academy.

Tyler Harris, MD, COL has worked with medical simulation for over 27 years both in academic and hospital settings. As a former Advanced Trauma Life Support, Advanced Cardiac Life Support and Pediatric Advanced Life Support instructor, has led a variety of inter-professional in-situ simulation programs related to emergency response, process flow, and process modeling. He previously taught undergraduate and graduate students using traditional manikin-based scenarios and task training. He has four prior combat theater deployments and has contributed to the Joint Trauma Registry (JTR) on prior deployments.

Geoffrey Tobias Miller is an Assistant Professor, School of Health Sciences, at Eastern Virginia Medical School (EVMS) in Norfolk Virginia. Miller is also a Senior Research Scientist (2015) at the Medical Modeling, Simulation, Informatics and Visualization (MMSIV) Laboratory at the Telemedicine and Advanced Technology Research Center (TATRC), U.S. Army Medical Research and Materiel Command (USAMRMC). He oversees and conducts research and technology development into future generation medical modeling, simulation and visualization efforts focused on military health system needs. Miller focuses on simulation-based educational activities, curriculum development and educational outcomes and translational analysis, with an emphasis on the creation and improvement of operational and clinical competence assessment using advanced educational technology, modeling, simulation and visualization systems, specializing in immersive virtual environments, AR for remote medical care, serious gaming, and innovative educational technology development. Recently, Miller led the invention and development of an innovative, automated and immersive simulation technology, which was recognized by the National Academies of Sciences, Institute of Medicine as the Lead Innovation at the Global Forum on Innovation in Health Professional Education. Previously, he was an Associate Director at the Michael S. Gordon Center for Research in Medical Education (GCRME), University of Miami Miller School of Medicine.

Brandon Conover, PhD is the Chief Technology Officer at BioMojo, LLC, leveraging advanced-technology hardware and software solutions to produce training and job aids to meet evolving demands for combat casualty care and prolonged field care along with MR training and performance assistance to assure peak performance for the Warfighter. Dr. Conover is also developing multiple AR/MR solutions, wearable biometric sensors, computational biology applications and game-based modeling and simulation. Dr. Conover has served as PM/PI on more than 30 federal contracts, including SBIR/STTR, many of which depended upon human factors engineering. Examples include development of a VR training space for field medics, design of a see-through AR display suitable for next-generation fighter pilot helmets, and development of novel non-mechanical beam steering technology. Dr. Conover was also curriculum designer and lead instructor of science, technology, engineering and math (STEM) focused secondary and post-secondary enrichment programs aimed at attracting underrepresented students to STEM careers. Dr. Conover holds a PhD and MS in Electrical Engineering from North Carolina State University and a BSE in Computer Engineering from the University of Pittsburgh.

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METHODS

Background Information

Providing surgical care in remote environments presents a significant challenge. Dispersed medical operations and Anti-Access/Area Denial environments place casualties at risk of extended delays to forward surgical care sites. Postponed surgical care exposes casualties to avoidable suffering, loss of function or even loss of life (Pepe et al., 1987). Delayed emergency surgical care increases complications due to increased tissue damage and higher infection rates (Hull et al., 2014). Unnecessary complications increase the cost of providing care to wounded service members (Thakore et al., 2015). Far-forward telestrated surgery support promises to mitigate these risks by stabilizing combat trauma in situations where this care would otherwise not be available.

Military trauma treatment has shown remarkable improvement in survival rates from World War II through Operations Enduring and Iraqi Freedom, where “died of wounds” rates decreased from 19% to 9%. Much of the recent improvement in survival is attributable to the liberal use of tourniquets and to rapid evacuation from the point of injury to locations offering damage control surgery. Although tension pneumothorax and airway compromise are in the top three causes of preventable death on the battlefield, hemorrhage remains the top cause of preventable casualty death (Eastridge et al., 2012). Current and anticipated military operating environments threaten access to the forward surgical care necessary for damage control surgery that controls this hemorrhage. The lack of sufficient forward surgical resources has emerged as a critical capability gap.

The current U.S. military situation involves lower numbers of troops dispersed over a vast operating area. Additionally, near peer military rivals threaten U.S. air supremacy and military overmatch to the point that Area Denial and Anti- Access environments are expected in future conflicts (Gordon & Matusmura, 2013). Currently, Special Operation Forces (SOF) in Africa operate across such great distances that providing rapid access to a field surgical facility is difficult in many cases. These military factors lead to the anticipation that many future casualties will need aspects of their initial damage control interventions, including some surgical procedures and intensive resuscitation, performed in the field. Telemedicine and telepresence promise the ability to move subspecialty resuscitation far forward to field units that are too separated geographically or too dangerous due to enemy activity (DeSoucy et al., 2017).

Telepresence and telesurgery have the potential to bridge the gap between definitive care and non-surgical critical care for prolonged field care scenarios. AR telementoring for surgery has been demonstrated to be effective for craniotomy and for carotid endarterectomy on cadavers (Shenai et al., 2011). The first transatlantic telerobotic surgery was performed in 2002 by a surgeon in New York City who removed the gallbladder on a patient in France (Marescaux et al., 2001). Remote telerobotic proctoring was shown to be effective for life and limb saving procedures on cadavers between specialty surgeons and residents (Ereso et al., 2010). We anticipate that the life and limb saving capabilities augmented by these technologies will be necessary in the approaching Area Denial and Anti-Access environments. USSOF are already requesting these capabilities for their operational needs.

For the reasons and rationale stated previously, our research team reviewed potential candidate systems to begin to bridge this surgical capability gap. A concept of operations (see Fig. 1) was developed to provide a high-level view of the capability need and guide research and development of forward surgical support solutions. A demonstration study was conducted to evaluate candidate technologies, training requirements, and process model testing, leading to a focused research investigation into the effectiveness of AR and telestrated surgical support for point of injury combat casualty care. As part of this effort a communications feasibility assessment was conducted to determine minimum essential communications requirements to support the project.

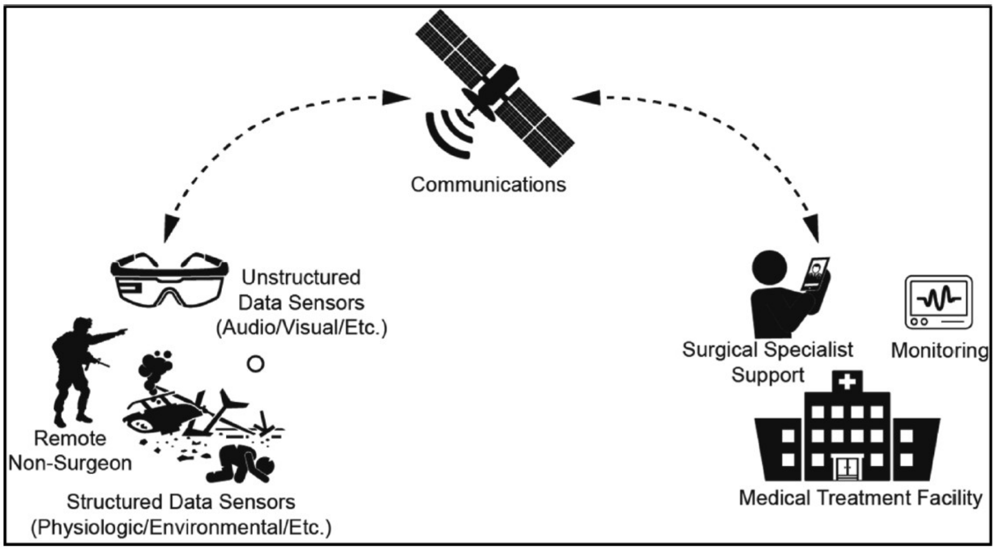

Figure 1. AR forward surgical support concept of operations.

Specific Aims of the Project

a) Integrate Osterhout Design Group (ODG) ODG-7HL glasses, Librestream telestration software with NuEyes® on-board magnification in order to telestrate over a satellite, wireless, and cell phone network.

b) Conduct a communications feasibility assessment at the United States Army Medical Research and Materiel Command (USAMRMC), Telemedicine and Advanced Technology Research Center (TATRC), Research, Development and Assessment Laboratory (RDAL).

c) Telestrate anterior exposure of the femoral artery between a surgeon and a non-surgeon.

d) Telestrate four compartment fasciotomy between a surgeon and a nonsurgeon.

Methods Employed

Osterhout Design Group (ODG) R-7 Smartglasses (San Francisco, CA), a lightweight wearable on-visual-axis display, were furnished by BioMojo, LLC (Cary, NC) with preloaded Librestream (Winnipeg, Manitoba, Canada) "Onsite Connect" telestration software and NuEyes® (Newport Beach, CA) magnification kits. The glasses were connected to a desktop workstation in a nearby building using an available wireless network.

The communications assessment investigated the ability to successfully telestrate between a remote consultant surgeon and a local provider non-surgeon using an AR head-mounted display (HMD) using a range of indigenous and secure military communications systems in a simulated environment. All telestration sessions were recorded and time synchronized for comparison, and transfer rates were controlled and limited through software control of the communications systems. The project investigated the ODG R-7 Smartglasses across the following communications systems during feasibility testing:

- Commercial Internet service
- Verizon® commercial wireless cellular service
- Persistent Systems® Wave Relay Radio Modules
- MANET system
- NOTE: BGAN satellite testing was attempted but was unsuccessful due to a technical failure.

For the purposes of the communications testing across the above systems a bandwidth protocol (see Table 1) was developed to determine feasibility of task completion (four compartment fasciotomy):

Table 1: Bandwidth Protocol for Communications Testing

	Resolution	Transfer rate	Frames/second
Extremely low	160 x 30	30 Kbps	5fps
Very low	320 x 240	120 Kbps	5fps
Low	320 x 240	250 Kbps	10fps
Medium	528 x 368	400 Kbps	10fps
High	720 x 480	1 Mbps	10fps
720p	1280 x 720	1 Mbps	10fps
1080p	1920 x 1080	1.5 Mbps	01fps

For purposes of this project, lower transfer rates were considered to be of high interest for operational environments. As such 720p and 1080p were not included in the initial feasibility assessment.

For the surgical components of the project, surgical kits used were typical of what is available in a field surgery setting. Forceps, Mayo scissors, Metzenbaum scissors, ring forceps, scalpels, Army-Navy retractors, and Weitlaner retractors were available for the physician's assistant (PA) to use during the procedure. An Operative Experience, Inc. (North East, Maryland) realistic anatomically correct manikin was used to simulate the anatomy of the femoral triangle where the common femoral artery and its branches are located. A training classroom from the Fort Bragg Medical Simulation Training Center was mocked-up to represent an austere medical care environment. The PA and an additional nonsurgical assistant wore surgical gloves only for simulation purposes, as no infection control issues were presented by the manikin.

Prior to performing the procedure, the PA underwent crawl-walk-run pre-training sessions. The surgeon and PA received training with the ODG-R7 glasses (see Fig. 2). The training also contained a review of the indications, anatomy and technique for the procedure (see Fig. 3). These training sessions were performed to simulate actual training that would be conducted for selected telestration procedures if this technology were applied in a real-world situation. Intensive, focused education and simulation-based training on anterior approach to the common femoral artery was provided. Verification of surgical skill competence was assessed on a newly developed surgical manikin. The PA and surgeon were trained to perform the procedure while wearing the HMD, to develop understanding and use of the AR and telestration technologies.

Figure 2. ODG R-7 Smartglasses

The team practiced the procedure, using the remote support technologies repetitively to assure mastery of both the technology and procedure. Feasibility was assessed by a final demonstration and assessment in a simulated environment representing a remote, improvised surgical environment with a non-surgeon operator and a surgical specialist at a separate location.

Technical and human factors assessments were conducted to evaluate the application, role and appropriateness of this surgical telestration and augmented reality capability. Assessments were conducted to evaluate the usability of the system, workload and the comfort/confidence of the telestrating surgeon and the operating non-surgeon. Areas of assessment included usability, ease of procedure, task load assessment, safety, efficiency, and operative time. Additional qualitative data was collected through participant interviews and free-response instruments.

Figure 3. Simulation-based procedural training between surgeon and non-surgeon. (Photo Credit: U.S. Army photo by Eve Meinhardt)

OUTCOMES

Communications Feasibility Assessment

It appears from this project that commercially available internet and cellular communications are able to provide the required data transfer rates for surgical telestration based on this candidate system for AR surgical telestration. Transfer rates below 250Kbps do not appear to be sufficient to support a fully robust telestration capability. Further analysis is indicated to more fully explore the minimum essential communication required to support AR surgical telestration in the operational environment. A full accounting of the results of this component are provided herein (see Table 2).

Table 2: Results of Communication Feasibility Assessment

	Resolution	Transfer rate	Frames/second	Results
Extremely low	160 x 30	30 Kbps	5fps	Unsuccessful real-time, audio/video telestration across communications systems. Static image transfer possible with significant delays and occasional communication failures requiring reconnection.
Very low	320 x 240	120 Kbps	5fps	Unsuccessful real-time, audio/video telestration across communications systems. Static image transfer possible with significant delays and occasional communication failures requiring reconnection.
Low	320 x 240	250 Kbps	10fps	Marginal real-time audio/video telestration was successful using commercial internet service and cellular service. Wave Relay Radio Modules and MANET systems were able to provide intermittent audio/video and static image transfer with occasional delays. No communication failures requiring reconnection were encountered.
Medium	528 x 368	400 Kbps	10fps	Reasonable real-time audio/video telestration was successful using commercial internet service and cellular service. Wave Relay Radio Modules and MANET systems were able to provide intermittent audio/video and static image transfer with occasional delays. No communication failures requiring reconnection were encountered.
High	720 x 480	1 Mbps	10fps	Successful real-time audio/video telestration using commercial internet service and cellular service. Wave Relay Radio Modules and

				MANET systems were unable to provide sufficient results.
720p	1280 x 720	1 Mbps	10fps	Not tested
1080p	1920 x 1080	1.5 Mbps	01fps	Not tested

Surgical Assessment

Using AR, the surgeon remotely guided (see Fig. 4) the PA via telestration through anterior exposure of the common femoral artery. An additional non-surgeon held retractors, functioning as a surgical assistant. The surgical assistant only took direction from the PA and did not offer any guidance. The PA performed exposure and clamping of the proximal common femoral artery, which represented success for this procedure.

Figure 4. Surgical specialist operating telestration console to guide anterior exposure of the femoral artery for bleeding control by a non-surgeon at a remote location. (Photo Credit: U.S. Army photo by Eve Meinhardt)

We successfully demonstrated a simulated, proof-of-concept use of lightweight wearable on-visual-axis display for surgical control. The PA/remote surgeon team, using augmented reality and telestration, were able to successfully perform junctional hemorrhage control, demonstrating the ability to project on-time, on-demand surgical expertise in a forward environment.

Six non-surgeon providers successfully released 23 of 24 fascial compartments, and all successfully obtained open proximal control of the common femoral artery in anatomically correct surgical models. These students did not require AR assistance to successfully perform these damage control skills in this model. We found that the visual field limitations of these glasses prompted the majority of students to look under the glasses during the critical phases of the procedures. Several of the students commented that the guidance offered by the AR glasses was reassuring, but that the current limitations in this wearable format outweighed the advantages of their use. Bandwidth and visual field limitations degraded the ability of the supervising surgeon to assess the completeness of the procedures. The observations of the co-located surgeon were relied on for scoring the procedure in several instances when the AR supervising surgeon was unable to score the release due to technical or subject specific (student looking under glasses) issues.

CONCLUSIONS AND NEXT STEPS

This project successfully demonstrated the ability to develop and integrate a commercial-off-the-shelf (COTS) hardware-software-communications solution using commercially available systems communicating across a wide range of open and secure communications systems, including simulated tactical radio networks. The study also demonstrated successful real-time, telestrated procedural guidance between a remote surgeon and point-of-care non-surgeons (18D medics, SOF Pas, and SOF assigned non-surgeon physicians) for two-incision, four-compartment fasciotomy and femoral vessel exposure and control on a realistic anatomical model. Finally, the study demonstrated a successful prototype training model for the use of AR and telestration to support procedural guidance.

Perhaps more importantly, the study also revealed several significant limitations in the current technologies. First, current telestration software systems do incorporate inertial movement units (IMUs), which allow for head-tracking however current software systems do not allow the users to “pin” (fix telestrated lines, guides, or other markers) to a specific reference point of the viewed image. The result of this is continuous movement of the telestrated guides with the wearers head movement, rather than the guides being fixed to the intended target object. As a result, the wearer of the AR HMD must maintain a fixed position or reorient to the exact same position during the procedure, a process which severely limits the users need to change viewing angles, retrieve equipment, or look off access for other reasons. The research team determined that development of image registration and stabilization and fixing of telestrated guidance to the target image is an essential feature and requirement to optimize the utility of AR telestration for future use in clinical procedural mentoring.

Second, continuous communications are required to provide real-time, two-way telestrated procedural support and guidance. This project conducted communications testing to telestrate four compartment fasciotomy between a remote consultant surgeon and a local provider non-surgeon using an AR HMD using a range of indigenous and secure military communications systems in a simulated environment at TATRC. Telestration sessions were recorded and time synchronized for comparison, and transfer rates were controlled and limited through software control of the communications systems. The following communications systems were analyzed; commercial internet service, Verizon® commercial wireless cellular service, Persistent Systems® Wave Relay Radio Modules, Mobile Ad Hoc Networking (MANET) tactical radio system, and BGAN satellite. From this testing, commercially available internet and cellular communications are able to provide the required data transfer rates for surgical telestration based on this candidate system for AR surgical telestration. Transfer rates below 250Kbps do not appear to be sufficient to support a fully robust telestration capability, however telestration was still possible using frame capture. The study team recommended further analysis to more fully explore the minimum essential communication required to support AR surgical telestration in the operational environment. Due to the concerns over communications bandwidth, quality of service and availability, the study team recommended exploration of methods to provide continuous decision support and procedural guidance in a no-or-degraded communications environment, as these are highly likely scenarios both today and in the future battlespace.

Third, current hardware and software operating systems and functionality was found to be complex, confusing and difficult to operate by both the supervising surgeons and remote care providers. Several aspects are identified related to hardware issues impacting user experience and user interface (UX/UI). First many of the input controls are difficult to use and may sometimes be inadvertently activated due to their location on the hardware. Second, the hardware is difficult to use when wearing medical/surgical or protective gloves and may not be possible to be worn when wearing a protective helmet (e.g., Army Advanced Combat Helmet and/or others). All of these identified challenges require further investigation to develop and pilot corrective strategies and recommendations for future hardware solutions. Software and operating systems are also identified as points of concern in that they are not well suited for the combat casualty care providers' needs. Menus are complicated and generally require too many selections to gain access to desired inputs, screens or information. Many if not all of these software applications require substantial revision and optimization to meet the identified end-user needs of the military medical provider community.

Telementoring and telestration using AR systems appears well suited to providing surgical support and training across dispersed groups of medical providers. Forward surgical support using augmented reality and telestration technologies are viable for point of injury surgical support and may be essential to filling this "missing middle" in the Combat Casualty Care continuum. We anticipate that the life and limb saving capabilities supported by this approach will be necessary in future Multi-Domain Battlefield Concept and in cases of remote and dispersed operations. Continued rigorous investigation is needed to ensure safe and appropriate medical care in this environment as well as to inform the development and improvement of new and future technologies to support this capability.

The next phases of our research and development of telestration for forward surgical support and telementoring will focus on improvement in the areas of deficiency identified in this project, to include the following:

1) Stabilization of telestrated annotations and lines within current, COTS AR solutions from head movement;

2) Improvement of the Graphical User Interface (GUI) of COTS AR solutions for telemedicine/telesurgical use cases to meet the needs of the dismounted Warfighter;

3) Integration of the improved AR solution interface with Artificial Intelligence (AI) clinical decision support resources; and

4) Systems usability and functionality testing to investigate the impact of candidate AR technology for point of need care, and enhanced casualty situational.

We also intend to focus on evaluating the clinical benefits of these technologies on surgical interventions (including accuracy of clinical procedural skill performance as compared to telestrated targets, task completion and duration, and levels of mentoring and telestration required for procedure completion), educational benefits of the training programs and processes, quality of telestration and telementoring, and user satisfaction with both the remote telementoring and telestration aspects, and human-computer aspects. A mixed methods study has thus been designed to accomplish this purpose. This protocol was developed to evaluate the following aspects of providing surgical support to remote environments:

1) Technology requirements and minimum specifications for telestration capabilities between a surgical specialist at a Medical Treatment Facility and a remote non-surgeon in a far-forward environment using existing telecommunication systems within the U.S. Army.

2) Training requirements to prepare surgeons and non-surgeons to control lower extremity junctional hemorrhage, and to use associated telestration hardware, software and communications systems.

3) Transferability of this training paradigm and technology suite to a wide range of medical care and clinical procedural skills to anticipated future military medical care needs and environments.

ACKNOWLEDGEMENTS

Major portions of this work were funded by the Telemedicine and Advanced Technology Research Center (TATRC) at the United States Army Medical Research and Materiel Command through the AMEDD Advanced Medical Technology Initiative (AAMTI). The authors wish to express appreciation for the significant efforts of the following individuals: Joe H. (Harvey) Magee (Uniformed Services Health Sciences University), Ollie B. Gray (TATRC), and Candice E. Middlebrook (Womack Army Medical Center).

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