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A First-Person Mentee Second-Person Mentor AR Interface for Surgical Telementoring

Chengyuan Lin*[1], Daniel Andersen[1], Voicu Popescu[1], Edgar Rojas-Muñoz[1], Maria Eugenia Cabrera[1],
Brian Mullis[2], Ben Zarzaur[2], Kathryn Anderson[2], Sherri Marley[2], and Juan Wachs[1]

[1]Purdue University
[2]Indiana University School of Medicine

ABSTRACT

This application paper presents the work of a multidisciplinary group of designing, implementing, and testing an Augmented Reality (AR) surgical telementoring system. The system acquires the surgical field with an overhead camera, the video feed is transmitted to the remote mentor, where it is displayed on a touch-based interaction table, the mentor annotates the video feed, the annotations are sent back to the mentee, where they are displayed into the mentee's field of view using an optical see-through AR head-mounted display (HMD). The annotations are reprojected from the mentor's second-person view of the surgical field to the mentee's first-person view. The mentee sees the annotations with depth perception, and the annotations remain anchored to the surgical field as the mentee moves their head. Average annotation display accuracy is 1.22cm. The system was tested in the context of a user study where surgery residents ($n = 20$) were asked to perform a lower-leg fasciotomy on cadaver models. Participants who benefited from telementoring using our system received a higher Individual Performance Score, and they reported higher usability and self confidence levels.

Index Terms: Human-centered computing—Human computer interaction—Interaction paradigms—Mixed / augmented reality;

1 INTRODUCTION

As surgery continues to specialize more narrowly and deeply, it becomes more and more challenging to provide all needed surgical expertise at all points of care. Surgical telementoring is a promising approach for transmitting surgical expertise over large distances promptly and efficiently. Consider a rural surgery center staffed with only a general surgeon. An expert surgeon from a major urban hospital could "virtually scrub in" to assist with a procedure that the general surgeon is not entirely comfortable performing alone. Consider the scenario of a critical patient who cannot be urgently transported to a facility where the required surgical expertise is available. This could be the case, for example, in a combat zone where a compartment syndrome relieving fasciotomy procedure has to be performed urgently at a forward operating base to save a patient's leg, and evacuating the patient is too slow or too dangerous. An orthopaedic trauma surgeon from a major military hospital could assist from thousands of miles away via telementoring. As a third example, a novel surgical procedure can be rapidly disseminated through surgical telementoring. Finally, telementoring could also benefit surgical training, with a single instructor working in parallel with multiple surgical residents, providing assistance on demand, to the trainees who need it.

The conventional approach for surgical telementoring is based on a telestrator that allows a remote mentor to annotate graphically a video feed of the surgery, which is then shown to the mentee on a nearby display. This requires the mentee to shift focus away from the surgery, and to map mentally the instructions from the nearby display to the surgical field, which can lead to surgery delays and even errors. Augmented Reality (AR) is a promising alternative for surgical telementoring because it allows to integrate the mentor-authored annotations directly into the field of view of the mentee. The mentee sees the annotations as if the mentor actually drew them onto the surgical field, which avoids focus shifts and the high cognitive load of having to map annotations to the surgical field.

One possible AR interface for surgical telementoring is a transparent display that is placed between the mentee and the patient and that shows the mentor annotations overlaid onto the surgical field. However, truly transparent displays are not yet available. Video see-through transparent displays simulate transparency by showing the real world scene with the help of a video camera. Such a display supports only monoscopic viewing of the surgical field, which reduces depth perception and can decrease surgical performance. Furthermore, the transparent display approach poses the challenge of work-space encumbrance, as the surgeon has to reach around the display. An alternative interface is an optical see-through AR head-mounted display (HMD). The AR HMD avoids work space encumbrance and it allows the mentee to see the surgical field directly, with natural depth perception.

We are a group of computer science and industrial engineering researchers, trauma and orthopaedic trauma surgeons, and surgery educators. In this application paper we describe a novel system for surgical telementoring based on an AR HMD, as well as an initial evaluation in a study where surgery residents performed lower-leg fasciotomies on cadaver patient models.

Fig. 1 gives an overview of our system. The surgical field is acquired with an overhead camera whose feed is sent to the remote mentor site where it is displayed on a custom full-size interaction table. The mentor annotates the surgical field using touch-based gestures. The annotations are sent to the mentee site where they are integrated into the mentee's view of the surgical field using an AR HMD. The annotations are converted from 2D to 3D by projection from the overhead camera view to the 3D geometry of the surgical field acquired by the AR HMD. In this way, the remote mentor can annotate the surgical field in real time, and the annotations are shown to the mentee anchored to the surgical field, with correct depth perception. Our AR interface provides a first-person view to the mentee, who sees the annotations from their own viewpoint, and a second-person view for the mentor, who sees the surgical field and authors annotations from the overhead camera viewpoint.

We have conducted a user study to test our system with fourteen surgery residents and six medical students, who were asked to perform a lower-leg fasciotomy on a cadaver patient model. The participants were assigned to two groups: a control group (*CG*), which

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*lin553@purdue.edu

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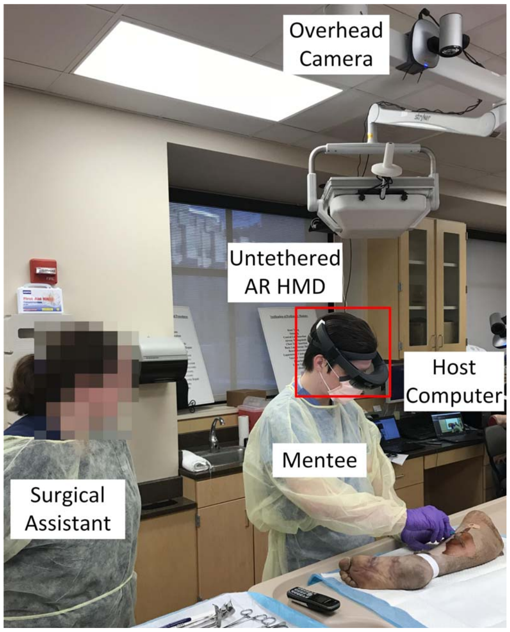
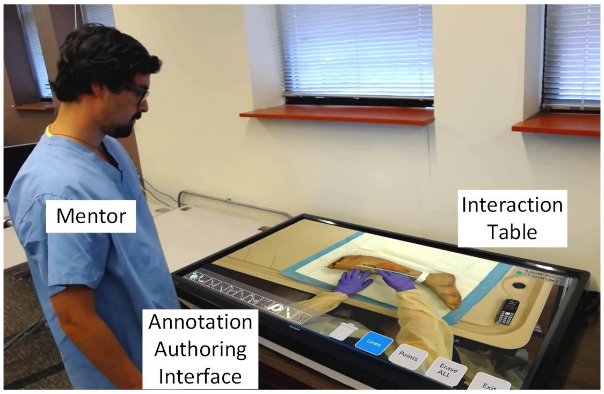


(a) Mentee subsystem



(b) Mentor subsystem

Figure 1: Our telementoring system based on an AR HMD at the mentee and on a full-size touch-based interaction table at the mentor.

performed the fasciotomy after studying the procedure from printed surgery course materials, and an experiment group (*EG*), which performed the fasciotomy under telementoring guidance using our system. Participant performance was rated by an expert surgeon who witnessed the procedure and quantified performance using an Individual Procedure Score (IPS) metric. The *EG* participants received an IPS score 16% higher than the *CG* participants. The two groups were also evaluated using a system usability questionnaire. The answers to all eight questions indicate a usability advantage for our system, and for four of the questions the advantage was statistically significant. Finally, the two groups were also evaluated based on self-reported confidence in the knowledge of the fasciotomy procedure, before and after the study. The *EG* group showed statistically significant growth for all four confidence metric questions, and they ended up with a higher confidence level than the *CG* group. We also refer the reader to the accompanying video that illustrates the operation of our system and the user study we have conducted.

2 PRIOR WORK

The conventional approach for surgical telementoring is based on a telestrator. The live video feed of the surgical field is transmitted to the remote mentor, who annotates it, the annotations are sent back to the mentee, and the annotated video is shown to the mentee on a nearby display [3]. Such annotations are not naturally seen by the mentee due to the lack of depth perception, due to the lack of parallax, and due to occasional occlusions. Another shortcoming is the need for the trainee to shift focus repeatedly from the surgical field to the nearby display. Each time, the mentee has to remember the position and type of individual annotations, and then to map them from memory onto the actual surgical field. These focus shifts increase the cognitive load of the mentee, which can translate to surgery delays or even surgical errors [3].

AR interfaces can provide a natural approach for overlaying annotations into mentee's field of view, as if the mentor actually drew them there, thus eliminating focus shifts. This potential of AR in surgery has been noted for a long time [13]. The recent leap forward of AR technology has intensified anew research efforts aimed at bringing AR into the operating room.

There are two major options for designing the AR interface: based on a transparent display interposed between the mentee and the patient, and based on an AR HMD [5]. In previous work we have explored the transparent display option [1]. A video-see through display, implemented by a computer tablet, was suspended above the surgical field. The camera built into the tablet acquires the surgical field, the video feed is sent to the mentor, and the mentor uses a touch-based interface to annotate the surgical field. The annotations are sent back to the trainee site, shown on the tablet, and superimposed onto the live view of the surgical field. The trainee can then follow the instructions from the mentor to complete the surgery, without having to switch focus away from the surgical field. Compared to a conventional telestrator system, a user study revealed that our system led to 57% smaller surgical port and instrument placement errors, and to 65% fewer focus shifts. One of the shortcomings of such a tablet-based AR interface is the lack of depth perception that ensues from the monoscopic visualization of the surgical field. A second important shortcoming is the workspace encumbrance brought by the tablet, which can require the mentee to deviate from their preferred arm and hand poses and motions during surgery.

In this paper we investigate the use of an optical see-through AR HMD interface, which has the potential to address these shortcomings. The mentee sees the surgical field directly, with natural depth perception. The annotations are drawn in 3D, with correct parallax between the left and right eyes, so the annotations are seen with depth perception as well. Furthermore, the HMD does not interfere with the mentee's arm motions. Prior work investigation of the use of AR HMD interfaces in the operating room have found benefits in the context of overlaying a static image or model onto the patient [2, 14], and of overlaying a visualization of patient specific data acquired with an imaging system [10].

3 SURGICAL TELEMENTORING THROUGH HEAD-MOUNTED DISPLAY AUGMENTED REALITY

The goal of surgical telementoring is to allow the mentee to see the mentor-authored annotations naturally, as if the mentor actually drew them on the patient. We have developed a system that allows the mentor to see and annotate the surgical field, and that integrates the annotations into the mentee's field of view of the surgical field. We first discuss the design of the AR interface at the mentor and mentee that enables telementoring (Sect. 3.1), and then we give an overview of the calibration (Sect. 3.2) and operation (Sect. 3.3) of our system that implements the AR interface.

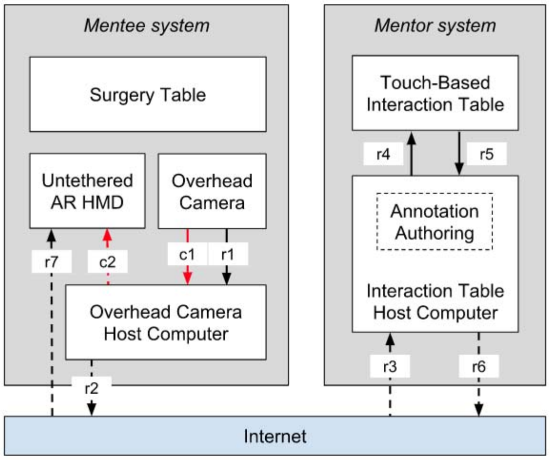


Figure 2: System diagram. Solid and dotted arrows correspond to wired and wireless communication, respectively. Red illustrates system calibration, and black illustrates system operation.

3.1 AR Interface Design

We developed the AR interface of our surgical telementoring system based on the following considerations. First, we wanted the mentee to see the annotations directly overlaid onto the surgical field. This was satisfied by using an AR interface. The second consideration was to provide the mentee with depth perception for the surgical field and the annotations. This was satisfied by resorting to an optical see-through AR HMD, through which the surgical field can be seen directly, and which visualizes the annotations stereoscopically. The third consideration was to avoid encumbering the mentee workspace, which reinforced our choice for an HMD AR interface, as opposed to interposing a display in between the mentee and the patient.

The fourth consideration was to provide the mentor with an appropriate visualization of the surgical field. Our first attempt was to use the on-board camera already built into the AR HMD. However, in our preliminary tests, such a visualization proved to be ineffective, as it changes frequently, abruptly, and substantially as the mentee moves their head. This unstable visualization of the surgical field is particularly disconcerting to the mentor when trying to draw an annotation. Furthermore, directly inheriting another user's first person view can be disorienting and it can even induce nausea [7]. To avoid these problems, we decided to deploy an external overhead camera that captures the surgical field from a stationary position above the surgical field. In conclusion, our interface uses a first person view for the mentee and a second person view for the mentor.

3.2 System Calibration

Fig. 2 gives an overview of our surgical telementoring system (Fig. 1). We describe our system using the $\xi_{A,B}$ notation for the $SE(3)$ transformation between coordinate systems A and B.

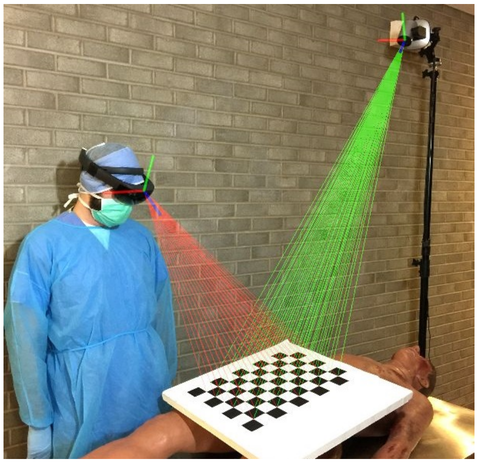


Figure 3: Calibration process. The overhead camera (green ray visualization) is registered with respect to the camera built into the AR HMD (red rays) using a calibration checkerboard.

Figure 4: Annotation projection. The incision line, the scalpel tip, and the textual label stem tip are projected from the overhead camera perspective onto the geometry of the surgical field. The incision line lies on the patient, whereas the scalpel and the label annotations float above the patient.

There is a one-time calibration process after which the system becomes operational. We use an untethered, self-tracking AR HMD, which, for every frame, provides the position and orientation of the HMD with respect to the world. The goal of the calibration stage is to determine the pose $\xi_{oc,w}$ of the overhead camera (OC) in the world coordinate system (W) of the AR HMD. Our AR HMD has a built-in video camera which we leverage for this calibration process. We use a standard calibration procedure [16] that first calibrates the intrinsics of the overhead and built-in cameras. Then the overhead and built-in camera extrinsics are found by showing a calibration checkerboard to both cameras simultaneously (Fig. 3). The overhead camera sends its image to the host computer (c1 in Fig. 2), where the checker corners are detected and the pose $\xi_{oc,cp}$ relative to the checkerboard pattern (CP) is computed by solving a perspective-n-point problem [6]. The pose of the AR HMD relative to the checkerboard pattern $\xi_{hmd,cp}$ is computed similarly. $\xi_{oc,cp}$ is sent to the AR HMD (c2), where the pose of the overhead camera $\xi_{oc,w}$ is finally computed with the following concatenation of transformations (Equation 1), where $\xi_{hmd,w}$ is the HMD pose tracked for the frame that captures the checkerboard pattern. $\xi_{oc,w}$ is stored on the AR HMD and used during operation to visualize the mentor annotations.

$$\xi_{oc,w} = \xi_{oc,cp} \cdot \xi_{hmd,cp}^{-1} \cdot \xi_{hmd,w} \tag{1}$$

3.3 System Operation

The overhead camera captures a live video feed of the surgical field (r1 in Fig. 2), which is sent to the remote mentor via the Internet (r2). The feed is received at the mentor subsystem (r3), where it is displayed on the touch-based interaction table (r4). The mentor examines the surgical field, zooms in and pans the view digitally, and authors annotations as needed using touch-based gestures. The annotation authoring commands are collected (r5) and sent to the mentee subsystem via the Internet (r6). The AR HMD is connected to the Internet and directly receives the annotation commands (r7), which it uses to draw the annotations for the mentee as follows.

Given a 2D annotation point p in the overhead camera image plane, its 3D position P is computed by unprojection to the overhead camera ray r_{oc}, by transforming the ray to world coordinates $r_W = \xi_{oc,w} r_{oc}$, and by intersecting the ray with the surgical field geometry G, i.e. $P = r_w \cap G$. We approximate G with the coarse geometric model of the scene acquired by our AR HMD. Fig. 4 illustrates the process of mapping 2D authored annotations to 3D by projection onto surgical field geometry along overhead camera rays.

4 RESULTS AND DISCUSSION

We implemented our system using a Microsoft HoloLens AR HMD which has the advantages of being untethered, allowing the mentee to move freely, of having a built-in video camera, allowing for overhead camera calibration, of self-tracking, allowing annotation anchoring as the mentee moves, and of acquiring a geometric proxy of the scene, allowing for annotation projection. The AR HoloLens display has a $1,280 \times 720$ resolution and a refresh rate of 60Hz. An important shortcoming of the HoloLens is the small field of view of the AR display (i.e. about 30 by 17.5 degrees), which restricts annotation display to the center of the field of view of the mentee. The overhead camera is a Logitech PTZ Pro 2, acquiring 1920×1080 pixel frames at 30fps. Audio communication between the mentor and the mentee was provided with a conventional phone in speaker mode. The interaction table at the mentor was built from a multi-touch interaction Sharp LCD (1920×1080 resolution, 60 fps, physical size of 52.3×29.4 inches), connected to a PC.

We first discuss system performance based on technical metrics (Sect. 4.1), then we describe a user study where we tested our system in the context of fasciotomy telementoring (Sect. 4.2), and we end the section with a discussion of the limitations of our system (Sect. 4.3). We also refer the reader to the accompanying video that illustrates the operation of our system and the user study.

4.1 System Performance

One important aspect of our real-time visual communication system is latency. One latency is the delay with which the overhead camera video feed is transmitted from the mentee site to the mentor site. We have measured ping times from 50ms within our Purdue servers, to over a second from Purdue to universities in South-East Asia and Australia. The encoding and decoding of the video stream are done with negligible delay. In our experiments network bandwidth was not a concern as it was sufficient to transmit the overhead camera feed at full resolution with levels of compression that did not affect video quality. Another latency is the delay between the mentee head movement and the required repositioning of annotations, which for our AR HMD is an almost unnoticeable 16ms. In other words, when the mentee moves their head, the annotations appear stationary in the 3D world, and do not ”follow” the mentee’s view direction.

The annotation display error is the cumulative effect of camera calibration, mentee head tracking, surgical field geometry, and HMD fitting errors. We have measured the annotation display error empirically, by placing a physical marker A in the surgical field, asking the mentor to annotate the position of the marker in the overhead camera feed, and then by asking the mentee to place a second physical marker B at the location where they see the annotation drawn. The annotation display error is the distance between markers A to B. By marking the entire surgical field, we measured a maximum and average annotation display error of 1.60cm and 1.22cm, respectively.

As the direction and length of the AB segment is consistent over the surgical field, we have devised an optional additional calibration procedure that improves annotation display accuracy under the assumption that most of the systematic error is due to an consistent overestimation of scene geometry by the HoloLens. Indeed, using the built-in Kinect-like depth camera, the HoloLens builds an approximate geometric model of the scene that consistently overestimates scene geometry, by wrapping a coarse geometric mesh over the actual detailed geometry. The additional calibration procedure is based on interaction between mentor and mentee. The mentor places an annotation and then asks the mentee to place and hold their index where they see the virtual annotation. The annotation display error is apparent to the mentor in their overhead camera view as a distance between the mentee’s finger tip and where the mentor drew the annotation. Using this visualization, the mentor shifts the approximate geometric model of the surgical field to reduce the annotation display error.

Figure 5: EG participant in the fasciotomy user study. The virtual incision line and instruments are only seen by the participant, and they were added here for illustration purposes.

4.2 User Study

We have conducted a user study at the Indiana University School of Medicine with $n = 20$ participants: 14 surgery residents and 6 medical students. The *task* was a four-compartment release by dissecting lower-leg fascia on cadaver models. Such a fasciotomy intervention is an emergency procedure for treating compartment syndrome, which is a lack of blood circulation to the limb due to excessive swelling as the result of blunt trauma. If left untreated, compartment syndrome leads to the loss of the affected limb. Fasciotomies remain challenging surgical procedures. In a recent systematic review on the surgical management of chronic exertional compartment syndrome, the overall success rate was reported at 66%, the satisfaction rate was 84%, and the rate of return to previous or full activity was 75% [4]. Furthermore, symptom recurrence was up to 44.7%, reoperation rate up to 19%, and overall complication rate was 13%.

Participants were randomly assigned to one of two groups: a control group (CG), which received instruction on how to perform the fasciotomy from an illustrated brochure, i.e. the Advanced Surgical Skills for Exposure in Trauma [11] course material on fasciotomies, and an experiment group (EG), which received real-time guidance with our telementoring system. The EG group did not receive any fasciotomy instruction prior to actually performing the procedure. Fig. 5 shows a participant in the experiment group. The additional interactive calibration procedure was performed by the mentor with each mentee, as the procedure depends on the actual surgical field geometry, and the cadaver lower leg models had great shape and size variability.

The two groups were compared based (1) on expert rating, (2) on self-reported usability, (3) on self-reported confidence in procedure knowledge, and (4) on procedure completion time. To analyze the data, we first check the data normality assumption using the Shapiro-Wilks test [12] and in our case no data was normal. For the unpaired (between subject) data (1, 2 and 4), we use the Mann-Whitney U test [9] to test for statistical significance. For the paired (i.e. within subject) data (3), statistical significance is tested with the Wilcoxon signed-rank test [15].

(1) An expert surgeon evaluated the performance of each participant during and after the experiment using the Individual Procedure Score metric [8], which we adapted to fasciotomy. IPS is a test that

Table 1: Self-reported support method usability. P-values with an asterisk (*) represent a statistically significant difference between the two groups. For questions 6 and 8, a lower score is indicates a higher preference.

Question	EG	CG	p-value
[1] Sufficient information provided	5.0 ±1.00	4.0 ± 0.50	0.024*
[2] Instructions easy to follow	5.0 ± 1.00	4.0 ± 1.25	0.018*
[3] Instructions conveyed effectively	4.0 ± 1.25	4.0 ± 1.00	0.415
[4] Cleared procedure doubts	4.0 ± 1.25	3.0 ± 1.50	0.063
[5] Expedited procedure completion	5.0 ± 2.25	3.5 ± 2.25	0.111
[6] Generated frustration	2.0 ± 1.25	3.0 ± 2.00	0.037*
[7] Better than side-by-side mentoring	2.0 ± 2.00	2.0 ± 1.00	0.139
[8] Worse than side-by-side mentoring	2.5 ± 2.25	4.0 ± 2.00	0.028*

Table 2: *EG* participant self-reported confidence scores. All p-values report a significant improvement.

Confidence Assessment Aspect	Self-Reported Confidence Difference	p-value
Identify anatomical landmarks	1.0 ± 1.25	0.014*
Knowledge of procedural steps	1.0 ± 1.00	0.006*
Instrument handling technique	1.0 ± 1.25	0.014*
Perform procedure alone	1.5 ± 1.00	0.006*

Table 3: *CG* participant self-reported confidence scores. p-values with an asterisk (*) represent a statistically significant improvement.

Confidence Assessment Aspect	Self-Reported Confidence Difference	p-value
Identify anatomical landmarks	1 ± 1.00	0.022*
Knowledge of procedural steps	1 ± 2.00	0.036*
Instrument handling technique	0 ± 1.00	0.225
Perform procedure alone	1 ± 0.25	0.11

assesses whether a training course is being effective on improving the overall surgical expertise of a participant. The test includes an objective analysis of the participants execution of the required procedural steps, as well as a subjective analysis to identify any errors that occur during procedure execution. *EG* participants received a median IPS of 81.15 with an interquartile range of ± 23.25, which was 16% higher than for *CG* participants (69.55 ± 33.40). The interquartile range is defined by the score received by the 25th percentile participant and the 75th percentile participant, and was used here as the data pointed to non-normality. However, the greater *EG* IPS scores were not statistically significant ($p = 0.26$).

(2) The two groups were compared based on self-reported usability through a five-level Likert scale questionnaire (Table 1). *EG* participants reported a higher preference for their condition than *CG* participants. For four out of the eight questions, the difference was statistically significant.

(3) The two groups were also compared in terms of self-reported confidence in performing a fasciotomy procedure. Table 2 and Table 3 report the increase in participant confidence level from before to after the experiment, for *EG* and *CG* participants, respectively. The confidence scores are assigned on a scale from 1 to 5. *EG* participants reported a statistically significant improvement in all four confidence categories, whereas *CG* participants reported statistically significant improvements in only half of the categories. Table 4 and Table 5 in Appendix A provide the initial and final confidence levels, for the two participant groups. The *CG* participants were more confident than the *EG* participants in their knowledge of the procedure before the task, but *EG* participants were more confident after the task.

(4) *EG* participants completed the procedure marginally faster (i.e. 4% faster, 1,379s median completion time with a ± 380s interquartile range) than *CG* participants (1,444s ± 685s).

This first study indicates that our AR surgical telementoring has the potential to provide surgical expertise remotely in an effective way. Not all advantages detected are statistically significant. One reason is the great variability and low number of participants. Another reason is that the remote mentor was a faculty member overseeing the surgery residency program, who was known to the participants, which added significant performance pressure on *EG* participants, whereas *CG* participants worked without the pressure of being evaluated by one of their professors. Furthermore, the telementoring sessions turned into practical lessons of surgery, which included revisiting of fundamental concepts in anatomy and in surgical procedures. This was of course not the case for *CG* participants. Not counting the tangential teaching mixed in with fasciotomy telementoring is difficult to do objectively, but it is likely to reduce the overall procedure completion times considerably for *EG* participants.

4.3 Limitations

Both the mentee and the mentor complained occasionally that the annotation showing the incision line would obstruct the view of the actual incision, as the incision progressed as it was executed. A possible solution for this problem that we will explore in a future study is to ask the mentee to transfer the annotation on the actual skin of the patient with a surgical marker before actually performing the incision.

Another limitation of our system is that the AR HMD is not very bright, and annotations appear faint when the background is brightly lit, as it is the case of surgical fields illuminated by surgical lights. A video see-through AR HMD is able to have opaque annotation pixels that completely erase the real world pixels, but an optical see-through AR HMDs can only draw semi-transparent annotations on top of the user's view of the real world.

Our system inherits additional limitations of the AR HMD, such as a small field of view of the active part of the display, which confines annotation display to the center of the mentee's field of view. Another limitation is the poor ergonomics of operating with a heavy and sometimes poorly fitting contraption attached to one's head. Several participants reported back and neck strain, especially the ones with little surgical experience who would tilt their head forward, moving the weight of their head and of the display away from their body.

5 CONCLUSIONS AND FUTURE WORK

In this application paper we have presented the design and implementation of a surgical telementoring AR interface, and we have validated our system in a user study where participants performed a cadaver-leg fasciotomy under telementoring. Our system promises surgical telementoring benefits, although not all benefits measured were statistically significant in this initial study.

Another direction of future work is to improve the mentor's sense of presence in the operating room. One option is to directly use the video feed acquired by the AR HMD from the mentee's viewpoint. As discussed in Sect. 3.1, the challenge is to stabilize this first-person view. This not only simplifies the system, but also potentially increases the accuracy of the annotations, by authoring annotations in a view similar to the one from where they will be seen. Another option is to not only provide a video feed of the surgery, but actually an RGBZ stream of frames with per pixel depth, which allows the mentor to choose his viewpoint interactively, to draw annotations more accurately in 3D (e.g. a non-planar incision curve), and even to visualize the surgical field immersively, e.g. with a Virtual Reality headset.

Telementoring could also benefit from extending the types of annotations supported with the ability to send a visual depiction of the mentor's hands, as surgical instruction includes mid-air gestures that sketch, for example, the use of an instrument. We foresee that the quickest path to achieving this is to capture the mentor hands with a video stream, to segment them, and to display them at the mentee.

Our current surgical telementoring system relies on a high-quality network, which is not always available in the case of austere environments. For this, the system should be enhanced with AI mentoring capabilities that can provide basic assistance to the mentee when the network connection is failing, or is not available at all. One of the major challenges is to recognize automatically the current state of the surgery, a difficult case for computer vision algorithms as surfaces are fragmented, with view-dependent reflective properties, with complex occlusions, and deforming rapidly.

Beyond system refinements, additional user studies are needed to specialize the interface and to optimize the surgical telementoring benefits of our system in the context of many other types of surgical procedures.

ACKNOWLEDGMENTS

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REFERENCES

[1] D. Andersen, V. Popescu, M. E. Cabrera, A. Shanghavi, G. Gomez, S. Marley, B. Mullis, and J. P. Wachs. Medical telementoring using an ar transparent display. *Surgery*, 159(6):1646–1653, 2016.

[2] E. Azimi, J. Doswell, and P. Kazanzides. Augmented reality goggles with an integrated tracking system for navigation in neurosurgery. In *Virtual Reality Short Papers and Posters (VRW), 2012 IEEE*, pp. 123–124. IEEE, 2012.

[3] E. M. Bogen, K. M. Augestad, H. R. Patel, and R.-O. Lindsetmo. Telementoring in education of laparoscopic surgeons: an emerging technology. *World j. of gastrointestinal endoscopy*, 6(5):148, 2014.

[4] D. Campano, J. A. Robaina, N. Kusnezov, J. C. Dunn, and B. R. Waterman. Surgical management for chronic exertional compartment syndrome of the leg: a systematic review of the literature. *Arthroscopy*, 32(7):1478–1486, 2016.

[5] L. Chen, T. Day, W. Tang, and N. W. John. Recent developments and future challenges in medical mixed reality. *arXiv preprint arXiv:1708.01225*, 2017.

[6] X.-S. Gao, X.-R. Hou, J. Tang, and H.-F. Cheng. Complete solution classification for the perspective-three-point problem. *IEEE trans. on pattern analysis and machine intelligence*, 25(8):930–943, 2003.

[7] J. J. LaViola Jr. A discussion of cybersickness in virtual environments. *ACM SIGCHI Bulletin*, 32(1):47–56, 2000.

[8] C. F. Mackenzie, E. Garofalo, S. Shackelford, V. Shalin, K. Pugh, H. Chen, A. Puche, J. Pasley, B. Sarani, S. Henry, et al. Using an individual procedure score before and after the advanced surgical skills exposure for trauma course training to benchmark a hemorrhage-control performance metric. *J. of surgical education*, 72(6):1278–1289, 2015.

[9] H. B. Mann and D. R. Whitney. On a test of whether one of two random variables is stochastically larger than the other. *The annals of mathematical statistics*, pp. 50–60, 1947.

[10] G. C. Meng, A. Shahzad, N. Saad, A. S. Malik, and F. Meriaudeau. Prototype design for wearable veins localization system using near infrared imaging technique. In *IEEE Colloquium on Signal Processing & Its Applications (CSPA)*, pp. 112–115. IEEE, 2015.

[11] A. C. of Surgeons Committee on Trauma, J. Fildes, J. Meredith, D. Hoyt, F. Luchette, M. Bowyer, P. Byers, E. Cornwell, J. Cuschieri, R. Gross, et al. *ASSET (Advanced Surgical Skills for Exposure in Trauma): Exposure Techniques When Time Matters*. American College of Surgeons, 2010.

[12] S. S. Shapiro and M. B. Wilk. An analysis of variance test for normality (complete samples). *Biometrika*, 52(3/4):591–611, 1965.

[13] J. H. Shuhaiber. Augmented reality in surgery. *Archives of surgery*, 139(2):170–174, 2004.

[14] H. Wang, F. Wang, A. P. Y. Leong, L. Xu, X. Chen, and Q. Wang. Precision insertion of percutaneous sacroiliac screws using a novel augmented reality-based navigation system: a pilot study. *International orthopaedics*, 40(9):1941–1947, 2016.

[15] F. Wilcoxon. Individual comparisons by ranking methods. *Biometrics bulletin*, 1(6):80–83, 1945.

[16] Z. Zhang. A flexible new technique for camera calibration. *IEEE Trans. on pattern analysis and machine intelligence*, 22(11):1330–1334, 2000.

APPENDIX A ADDITIONAL TABLES

Table 4: Participants self-reported confidence before the experiment.

Confidence Assessment Aspect	EG	CG
Identify anatomical landmarks	3.00 ± 1.25	3.50 ± 1.00
Knowledge of procedural steps	3.00 ± 0.50	2.50 ± 2.00
Instrument handling technique	3.00 ± 2.00	4.00 ± 1.50
Perform procedure alone	2.00 ± 1.25	3.00 ± 1.25

Table 5: Participants self-reported confidence after the experiment.

Confidence Assessment Aspect	EG	CG
Identify anatomical landmarks	4.00 ± 1.25	4.00 ± 1.00
Knowledge of procedural steps	4.00 ± 0.00	3.50 ± 1.25
Instrument handling technique	4.00 ± 2.00	4.00 ± 2.00
Perform procedure alone	3.50 ± 1.00	3.50 ± 1.50