The Effect of Augmented Reality Training on Percutaneous Needle Placement in Spinal Facet Joint Injections

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***Abstract*—The purpose of this study was to determine if augmented reality image overlay and laser guidance systems can assist medical trainees in learning the correct placement of a needle for percutaneous facet joint injection. The Perk Station training suite was used to conduct and record the needle insertion procedures. A total of 40 volunteers were randomized into two groups of 20. 1) The *Overlay* group received a training session that consisted of four insertions with image and laser guidance, followed by two insertions with laser overlay only. 2) The *Control* group received a training session of six classical freehand insertions. Both groups then conducted two freehand insertions. The movement of the needle was tracked during the series of insertions. The final insertion procedure was assessed to determine if there was a benefit to the overlay method compared to the freehand insertions. The Overlay group had a better success rate (83.3% versus 68.4%, $p = 0.002$), and potential for less tissue damage as measured by the amount of needle movement inside the phantom (3077.6 mm^2 versus 5607.9 mm^2, $p = 0.01$). These results suggest that an augmented reality overlay guidance system can assist medical trainees in acquiring technical competence in a percutaneous needle insertion procedure.**

***Index Terms*—Medical simulation, modeling, skill assessment, surgical training.**

I. Introduction

SURGICAL simulation can be defined as the imitation of a real surgical procedure in a controlled environment. It has the distinct advantage of allowing a trainee to practice a procedure as many times as necessary to achieve technical competence, prior to patient exposure [1]. This allows the trainee to learn how to perform the procedure without the risk of errors causing harm to the patient [2]. Additionally, simulation allows the trainee to self-study at his or her own pace, as much as it is necessary, at any time of the day [3].

Simulation-based educational programs are being widely implemented in medical training due to increased patient awareness regarding medical errors and patient safety, funding restrictions, and cuts in the maximum residency hours [4]. Further, technical competency improves precision and decreases operating time, reducing both costs and patient risks.

Augmented reality (AR) is the supplementation of the physical environment with computer-generated imagery. AR is most commonly used in the medical field for providing guidance to improve the precision of surgical techniques.

Proficiency in a procedural skill is achieved in a three-stage process: a cognitive stage, an associative stage, and an autonomous stage [4]. These stages refer to learning the steps of a procedure, learning to perform those steps, and automation of the procedure, respectively. This model combines the importance of both cognitive and technical skills. Previous studies have shown that training specifically with AR simulation makes residents learn faster, improves their operating room performance, and reduces the number of errors [5].

Our study focuses on a procedure used in the treatment of lumbar facet joint degeneration, which is a condition tied to the progressive degeneration of the intervertebral disks [6]. While MR imaging is widely employed in the evaluation of disk degeneration, currently there is no consensus on what methods are best to evaluate lumbar facet joint arthrosis radiographically. The difficulty in diagnosing facet-mediated pain leaves controlled, diagnostic nerve blocks as the only means of making a diagnosis [7]. One way these blocks can be accomplished is by intraarticular injection of an anesthetic agent. This percutaneous procedure requires precise placement of the injection needle into the facet joint, which can be difficult due to the relatively narrow target area and its distance from the skin. Radiographic skin markers can be used to identify the appropriate skin puncture site, but determining the entry angle of the needle and maintaining that angle during the insertion of the needle is a challenge for new learners.

The current clinical method of percutaneous needle insertion using computed tomography (CT) imaging requires the operator to look away from the patient to view the image on an external display. This can impair hand–eye coordination and as a result

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may require more vigorous training to master the procedure. Our hypothesis is that AR image guidance and laser overlay, which allows the operator to maintain eye contact with the insertion site throughout the procedure, may assist students in learning to maintain the correct needle trajectory to a point inside tissue, which is an essential skill in percutaneous procedures.

Researchers have been developing techniques to merge imaging with the patient or surgical field, which could lead to increased patient safety and increase the reliability and ease of the procedure [8]. Guidance with AR image overlay was introduced as a simple and effective method for needle insertions that allows the operator to visualize the scanned image slice in its real physical position and orientation, while also being able to see his or her hands and the tools being used, thus facilitating hand–eye coordination [9]. Laser assistance is another technique to guide the operator to achieve the correct position and orientation during needle insertions [10]. The Perk Station is a laboratory validation system for standardized training and performance measurement, with optional image and laser overlay guidance methods by simulated needle insertions into phantom targets [11].

The purpose of this study was to determine if AR image overlay and laser guidance systems can assist medical trainees in learning the correct placement of a needle for percutaneous facet joint injection.

II. MATERIALS AND METHODS

A. Spine Phantoms

A modification of the previously published Perk Station spine phantom was used [12]. Rapid prototyping was used to print plastic bone models, which are based on contours manually segmented from human spinal CT images. The bone models were placed in cast acrylic boxes of 238 mm width, 38 mm depth, and 200 mm height. Transparent polyvinyl chloride-based plastisol (M-F Manufacturing Company, Inc., Fort Worth TX) layers of different firmness were molded around the bone model to mimic the deformation and consistency of a 5-mm top layer of skin, 10-mm middle layer of subcutaneous fat, and a layer of muscle at the bottom. The plastisol layers are transparent, which allow visualization of the needle insertion procedure by the operator. The side of the phantom facing the trainee is covered to prevent visual access. The distance from the skin surface to the entrance of facet joint was 37 mm. The anatomical characteristic of the facet joint provided some realistic tactile feedback to the trainee once the needle entered the joint.

A reusable external housing is equipped with radiographic markers (stereotactic fiducials), and can be easily realigned under the Perk Station image overlay. Twenty-eight divot points were laser cut into the external housing to facilitate registration between the coordinate systems of the phantom and the electromagnetic tracker.

B. Hardware Setup

The design of our experiment setup was intended to create a simulator that mimicked clinical procedural conditions as closely as possible, and yet could be mounted using the existing Perk Station and tracked accurately at the same time. The main components of our simulator are shown in Fig. 1. The system consists of a laptop computer, the Perk Station, the phantom, an NDI Aurora electromagnetic tracker, a control box, and a sensor attached to a needle (Northern Digital, Inc., Waterloo, ON). An external monitor is also part of the setup, which visualizes the image slice and planned needle trajectory for the laser-only and freehand insertions. The Perk Station percutaneous surgery simulation system is designed with a semireflective glass that allows the trainee to view the CT slice as if it were floating in 3-D space inside the phantom. The laser guidance system that is mounted on the Perk Station indicates the trajectory of the needle using two perpendicular laser planes. For the freehand method, the location of the CT slice in 3-D space was indicated using a marked line on the skin surface.

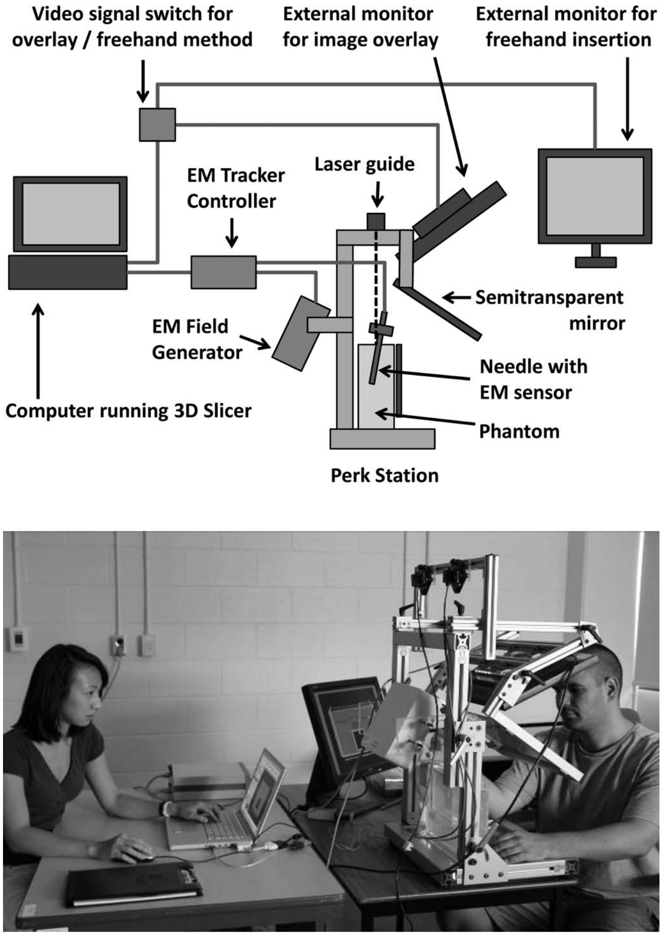


Fig. 1. Simulator setup. *Upper panel:* Conceptual design of the tool used in the experiment. *Lower panel:* Photo of the actual tools used in the experiment. The observer (left) sits opposite the trainee (right) and can monitor the insertion visually. The side of the phantom facing the trainee is covered to prevent the trainee from direct visual access to the target.

The electromagnetic tracker was positioned relative to the Perk Station to minimize the effect of metal parts on the tracking accuracy. Ferromagnetic materials were not built into the system mounting. An rms error of the electromagnetically tracked

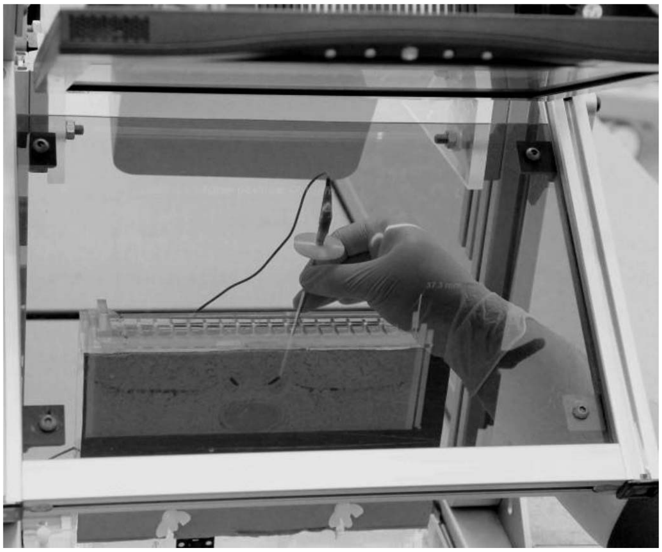


Fig. 2. Phantom and needle with image overlay and laser guidance as seen from the point of view of the trainee.

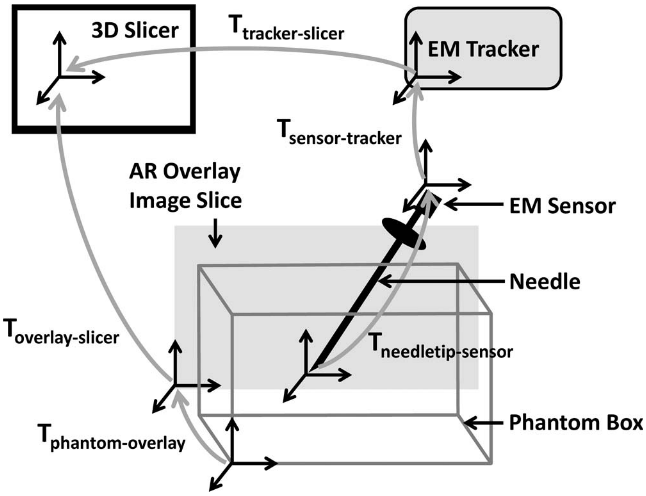
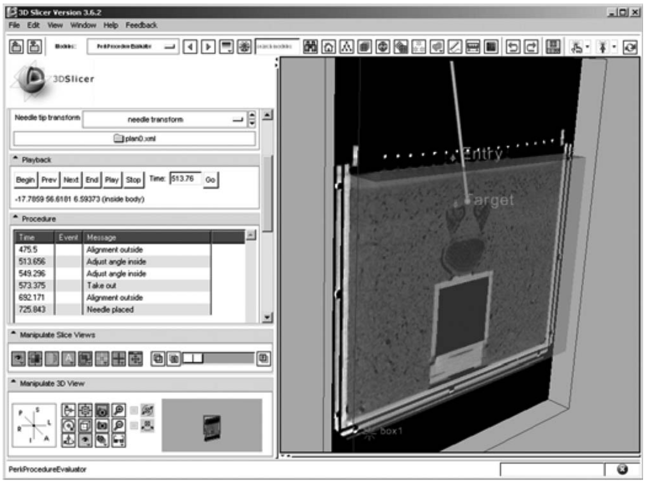


Fig. 3. Transforms (gray arrows) between coordinate systems used in the experiment setup. Both phantom box and needle tip positions are translated to the coordinate reference of 3D Slicer.



Needle tip transform: needle transform

plan0.xml

Time: 513.76

-17.7859 56.6181 6.59373 (inside body)

Time	Event	Message
475.5		Alignment outside
513.656		Adjust angle inside
549.296		Adjust angle inside
573.375		Take out
692.171		Alignment outside
725.843		Needle placed

PerkProcedureEvaluator

Fig. 4. Software module for the offline evaluation of recorded surgical gestures running in 3D Slicer. The right-side panel shows planned entry and target points, models of the phantom and the needle, image slice from the CT scan of the phantom, all in a 3D scene, according to the actual status of procedure playback.

needle tip position of 0.6 mm was measured within the operating range of the needle.

Adaptations were made to a surgical needle to allow tracking and enable use with the laser overlay system. An electromagnetic tracker sensor was attached to the hub of a 14-gauge needle, along with a white disk of 20-mm diameter to reflect the laser crosshair. The modified needle along with image overlay and laser guidance is shown in Fig. 2 from the trainee point of view.

To ensure accurate tracking of the needle tip relative to the CT image of the phantom, a series of coordinate reference calibrations were used to register the needle and the phantom with the 3D Slicer coordinate system (see Fig. 3). The phantom was registered to the virtual overlay image by manually adjusting the position and orientation of the overlaid CT slice so that the radiographic surface markers of the phantom were aligned with the image markers on the overlay $T_{\text{phantom-overlay}}$. The overlayed image to Slicer transformation $T_{\text{overlay-slicer}}$ was computed from the physical size of the display on the Perk Station and its pixel resolution. The translation between the needle tip and the electromagnetic sensor attached to the needle $T_{\text{needletip-sensor}}$ was determined by the pivot calibration procedure implemented in the IGSTK software toolkit.[1] The electromagnetic tracker provided position and orientation information of the electromagnetic sensor as sensor-to-tracker transforms $T_{\text{sensor-tracker}}$. The registration of the tracker in the Slicer reference frame $T_{\text{tracker-slicer}}$ is computed by the optimal alignment of the physical divot points of the phantom housing and their images in the CT volume, as described by Wood *et al.* [13].

C. Software

The Perk Station software has previously been implemented as an interactive module for the 3D Slicer program, and is used to calibrate and plan the needle insertion procedure [11]. The software is capable of calculating the laser angles according to the planned trajectory, as well as insertion depth for each plan. 3D Slicer is a free, open-source software package for visualization and image analysis.[2] Separate 3D Slicer modules have been developed for this study to record and evaluate the entire simulation process.

Signal from the electromagnetic sensor was tracked by the Aurora system. A new software module was created to record the position and orientation of the needle at a rate of 10 Hz and save the tracking information as XML files. To facilitate offline evaluation, the observer manually annotated the recordings for each key surgical gesture performed, by using buttons in the software interface.

A second module was developed to evaluate the recordings (see Fig. 4). The evaluator module is able to read the XML

[1] http://www.igstk.org

[2] http://www.slicer.org

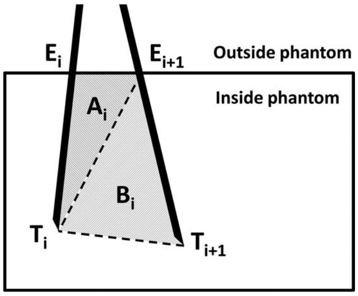


Fig. 5. Computation of potential tissue damage between two consecutively recorded positions, i and $i+1$, of the needle. The 3-D surface spanned by the two entry points (E) and the two tip points (T) is not necessarily in one plane. Approximate area is calculated as the sum of two triangles, $A_i + B_i$.

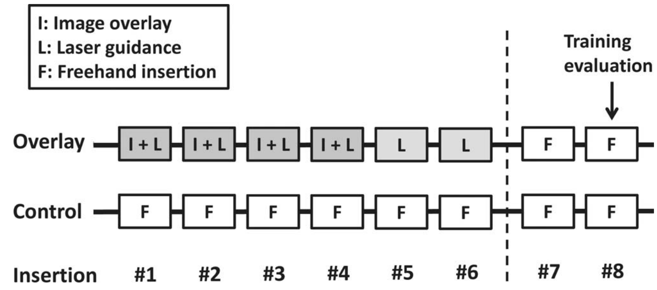


Fig. 6. Diagram shows sequence of needle insertions with different guidance methods in the Overlay group (upper row), and freehand method used in the Control group (lower row). Vertical dashed line indicates end of training phase. The final insertion (#8) was used to evaluate difference between the groups.

files and measure the following parameters of the recorded procedure.

1) *Total procedure time*: Time spent on each insertion from when the trainee looked at the insertion plan, until they signaled that the needle is in its final position.
2) *Time inside phantom*: Total time that the needle tip was inside the phantom.
3) *Path inside phantom:* Total distance covered within the phantom by the needle tip.
4) *Potential tissue damage:* Total surface covered by the needle, idealized as a 2-D object, inside the phantom. Computation of tissue damage between two consecutive recorded needle positions is illustrated in Fig. 5.
5) *Out-of-plane deviation*: Angle between the final placement of the needle and the planned axial plane.
6) *In-plane deviation*: Axial component of the final displacement angle.

The evaluator software module also displays a 3-D virtual model of the needle integrated with the CT scan of the phantom that can replay the entire needle insertion procedure. This ensures that the gestures are correctly annotated and can be used for analysis of trainee competence.

Eight needle insertions plans were predefined and saved with the Perk Station software module, and used consistently with all participants of our experiment.

D. *Participants*

A total of 40 volunteers were recruited from Queen's University to participate in this study. Participants included medical students (26), biomedical engineering students (9), and first year residents (5). Signed consent of voluntary enrolment was obtained from each participant, and the study protocol was approved by the Queen's University Health Sciences and Affiliated Teaching Hospitals Research Ethics Board. The students, with no prior experience in image-guided or intraarticular needle insertions, were trained during the study, and their performance was assessed posttraining. Residents who reported prior experience with intraarticular needle insertions were excluded from this study. Other residents were trained and assessed using the same method as was used with the medical students. Both medical students and residents reported no prior experience with facet joint injections.

E. *Experiment Protocol*

The experiment protocol is shown in Fig. 6. Participants were randomized by alternating time slots into two groups of 20. 1) The *Overlay* group received a training session that consisted of four insertions with image and laser overlay, followed by two insertions with laser overlay only. This gradual transition helps the trainee gain confidence in their ability to perform the procedure. 2) The *Control* group received a training session of six freehand insertions. Volunteers were not blinded with regard to which group they were in.

Each member of both groups then conducted two freehand insertions. The final insertion (#8) was used to evaluate the difference between the two training methods, and to assess the difference in benefit between training methods. All insertions were tracked and used for analysis to compare the use of overlay versus freehand training. The trainees were not informed of which needle insertions were training sessions and which were being assessed.

The trainees were allowed to brace their hands against the phantom box, just as a physician would stabilize his or her hands against the patient's body. Each needle insertion plan was initiated when the observer informed the trainee that they may look at the screen that contained the insertion plan. The trainee signaled the end of the needle insertion procedure by informing the operator that they felt that the needle tip was in place. The trainee was given feedback from the observer as to whether the needle was successfully inserted into the facet joint, or if they had failed the procedure. This verbal feedback was used in place of a confirmation image, which would be imaged in clinical circumstances after the needle insertion.

F. *Statistical Methods*

The success of needle placements into the facet joint was evaluated visually by the observer during the needle insertion procedures. It is expressed as a percentage of the total number of assessed trials, and statistically compared between the two groups by the chi-square test. Procedure time, time inside the phantom, distance covered inside the phantom, surface covered

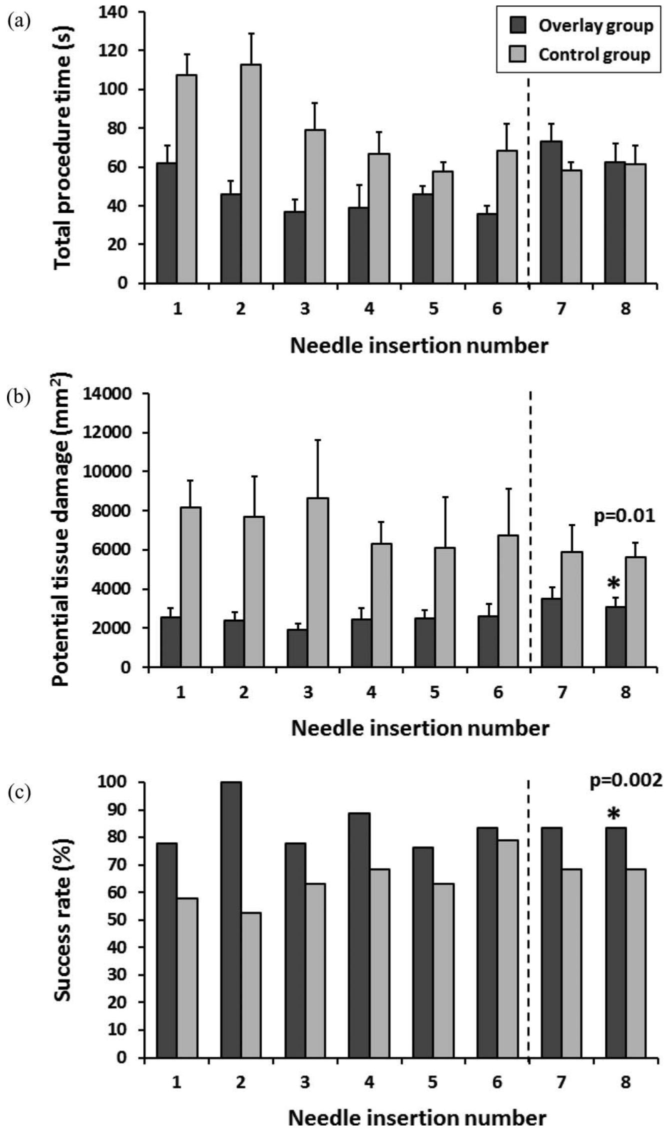


Fig. 7. Metrics of the needle insertion procedures in each step of the experiment. Data are shown as average ±SEM. Introduction of freehand method to the Overlay group is indicated by a vertical dashed line in the diagrams. $^*p < 0.05$ versus Control group in independent-samples T-test.

inside the phantom, and the amount of displacement were analyzed by independent-samples T-test, and are expressed as mean $\pm$ standard error of the mean (SEM).

III. RESULTS

All data collection experiments were carried out without technical difficulties; none of them had to be interrupted or discontinued for any reason.

The total procedure time [see Fig. 7(a)] seemed to converge to approximately 62 s in both groups. Control participants gradually decreased the time it took to find their target, whereas those with overlay training required maximum time at insertion #7, when they switched to freehand method, which was still less than the peak time required by the Control group.

TABLE I
METRICS OF LAST NEEDLE INSERTION (#8) IN BOTH GROUPS

Parameter	Overlay	Control
Sample size	20	20
Total procedure time (s)	62.3 ±9.7	61.3 ±9.8
Time inside phantom (s)	26.1 ±5.2	28.1 ±4.6
Path inside phantom (mm)	191.5 ±34	238.1 ±43.6
Potential tissue damage (mm^2)	*3077.6 ±417	5607.9 ±777
Out-of-plane deviation (deg)	3.6 ±0.5	5.1 ±0.9
In-plane deviation (deg)	4.1 ±0.4	4.0 ±0.6
Success rate (%)	*83.3	68.4

*p<0.05 vs. Control group.

Potential tissue damage caused by the needle [see Fig. 7(b)] was lower in the Overlay group for all insertions, and it remained significantly lower when the group performed the freehand insertion.

Success rate [see Fig. 7(c)] was higher in the Overlay group when receiving additional guidance for the first six insertions, and remained higher during the freehand insertions.

Of the parameters of needle insertions examined in this study, only two showed significant difference at the last insertion. Tissue surface covered was less, and success rate was higher in the Overlay group (see Table I). However, path inside phantom was also considerably higher in the Control group, indicating that withdrawal and reinsertion of the needle occurred more often in this group.

IV. DISCUSSION

This study compares the learning curve of facet joint needle insertions in students trained with AR, against a control group trained with the classical freehand method. The benefit of the Perk Station system in simulation training is presented. Literary searches revealed no other randomized control trials conducted on the possible benefits of AR-based percutaneous needle insertion simulation training.

The number of successful placements was higher in our Overlay group, compared to the Control group. Results show that the Overlay group performed the freehand insertions better, with the potential for less tissue trauma than the Control group after training with the Perk station. The Overlay system helped not only to avoid the initial period of high errors and lengthy procedures, but also improved overall accuracy and efficiency after the training session. Therefore, it is likely that this method would decrease the amount of practice required for medical students to become eligible for clinical procedures, or to master percutaneous needle insertion technique.

Insertion #7 demonstrates the adjustment from the overlay to the freehand system. Overall, this step has shown that becoming accustomed to the new conditions requires some time, however, the accuracy and efficiency of the insertion did not decrease with this transition. This suggests that surgical gestures involved in needle insertion might already be at a more advanced stage of the learning process by the end of insertion #6 for the Overlay group. We note here that initial experiments have been conducted to explore how many trials it takes for an average trainee to be ready for freehand insertions after training with overlay guidance. We experienced that after six insertions, new questions about the technique did not arise from trainees, and performance became steady.

The essential difference between the Overlay and Control groups was that the image guidance appeared at different positions in space. Although the AR overlay showed the same image as the external monitor used for the Control group, the alignment with the patient was different. It has been confirmed in other surgical cases that the alignment of the guidance image with physical reality has significant advantages [14]. For example, AR visualization in ultrasound-guided needle insertion resulted in higher accuracy and lower variability in setup and endpoint placements than conventional ultrasound [15].

Simulation laboratories are useful for procedural skill training, educational evaluation, and learning how to use technological innovations, such as AR systems. Studies done on simulation training have shown that training tools are improving and are recommended as part of medical training [16]. Simulation improves training efficiency by allowing the trainee to practice as much as necessary to achieve an acceptable level of performance [2]. However, one of the main challenges facing the implementation of simulation training is the lack of standardization. Current methods and equipment vary between training facilities. In order to fulfill educational objectives, deliberate and structured practice using performance-based endpoints is an ideal method for teaching with simulators. As opposed to most previous studies on the effect of surgical simulation training [17], we proposed only computerized performance metrics to minimize the need of expert surgeon presence at the training site. Standardization will allow the use of simulation laboratories to evaluate competency and can thus be employed for assessment purposes. By developing the Perk Station in public domain, we have attempted to contribute to this standardization process. Most of the work done in the area of simulated surgical training requires the development of new software; however software licensing often places a limitation on the ability of independent groups to reproduce these experiments. Therefore, all the software used in this experiment is open source, and the mechanical design has previously been published [11]. This allows the research community to freely reproduce or modify it, so that they may compare their methods with ours, or even to develop their own ideas using the current Perk Station as a base.

In order for the procedure to become automated, training requires scaffolding, repetition, and feedback to highlight errors and progress [1]. Scaffolding refers to the amount of assistance provided by a senior physician as the trainee becomes more independent. Slow reduction in the amount of supervision is shown to aid in skill retention [4]. This is reflected by gradually taking away the image overlay (insertion #5) and laser overlay (insertion #7) in the design of the presented training procedure.

It is known that feedback is one of the main motivators of performance improvement [18]. Reviews show that there is a higher level of mastery for computer-assisted learning when external feedback is used to teach technical surgical skills [19]. Therefore, it is important to develop metrics for surgical dexterity, and preferably use the same definitions across different simulators or institutions. We propose that the presented parameters be measured and given as feedback in needle-based percutaneous interventions. However, it is important to recognize that simulation-based learning should be considered an addition to traditional operating room learning, and not a replacement [20].

This study has some potential limitations, such as the low number of trainees involved and the narrow range of the participant recruitment pool. In addition, since needle insertion plans were always used in the same order, some patterns in Fig. 7 may reflect the different levels of difficulty of a particular insertion plan, on top of the effect of the learning curve. For example, the plan trajectories alternated between left- and right-side insertions. Although the trainees were instructed to use whichever hand they were comfortable with, since most of the population is right handed, this might explain the higher success rate at even insertion numbers. Also, the cases used in this study are limited to axial slices. More challenging oblique needle trajectories may be used in the future with little modification in the hardware and the calibration algorithm. Another limitation is that we chose not to perform a preprocedural measure of skill performance. We felt that a preprocedural skill assessment would prematurely expose the participants to the subject matter and thereby mitigate the full impact of simulation as a teaching tool. There was also a difference from real clinical circumstances, as trainees performed the insertions in a seated position, instead of setting up the Perk Station on a hospital bed. In the clinical setting, the procedure continues until successful completion is judged by the supervising physician, using CT imaging. In this simulation, trainees continued to the next needle insertion, even if the previous one was not successful. Finally, not specific to our study, but of concern for simulation in general is whether testing performance in a simulated setting, however life-like, reflects skills in an actual clinical environment.

To further this particular area of research, it would be beneficial to conduct this study with a larger number of participants and more training sessions. The data collected could also be used to grade the trainee's performance. Future software development could eventually lead to a simulation tool that is capable of providing constructive feedback to improve trainee technique, based not only on success but also on gestures. Other future areas of investigation include the following. What is the rate of retention of the knowledge and skills learnt in simulation training versus the traditional didactic teaching modalities [21]? What skills are best taught in a simulator? Is simulation of value only for the inexperienced provider or can experienced providers benefit? These are all questions that warrant further investigation in the area of AR simulation-based training.

V. CONCLUSION

In simulated facet joint injection experiments, AR image overlay and laser guidance improved the training process of needle placement. Participants trained with overlay guidance performed better even when required to do freehand insertions.

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Authors' photographs and biographies not available at the time of Publication.