Usability of a real-time tracked augmented reality display system in musculoskeletal injections

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ABSTRACT

PURPOSE: Image-guided needle interventions are seldom performed with augmented reality guidance in clinical practice due to many workspace and usability restrictions. We propose a real-time optically tracked image overlay system to make image-guided musculoskeletal injections more efficient and assess its usability in a bed-side clinical environment.

METHODS: An image overlay system consisting of an optically tracked viewbox, tablet computer, and semi-transparent mirror allows users to navigate scanned patient volumetric images in real-time using software built on the open-source 3D Slicer application platform. A series of experiments were conducted to evaluate the latency and screen refresh rate of the system using different image resolutions. To assess the usability of the system and software, five medical professionals were asked to navigate patient images while using the overlay and completed a questionnaire to assess the system.

RESULTS: In assessing the latency of the system with scanned images of varying size, screen refresh rates were approximately 5 FPS. The study showed that participants found using the image overlay system easy, and found the table-mounted system was significantly more usable and effective than the handheld system.

CONCLUSION: It was determined that the system performs comparably with scanned images of varying size when assessing the latency of the system. During our usability study, participants preferred the table-mounted system over the handheld. The participants also felt that the system itself was simple to use and understand. With these results, the image overlay system shows promise for use in a clinical environment.

KEYWORDS: Augmented Reality, Image-Guided Intervention, Image-Guided Therapy, Musculoskeletal Injections, Visualization, 3D Slicer, SlicerIGT, PLUS Toolkit.

1. PURPOSE

Computerized Tomography (CT) and Magnetic Resonance (MR) images are commonly used in practice for several musculoskeletal (MSK) medical interventions. These types of procedure are minimally invasive and can be performed under a variety of imaging modalities. With many procedures performed annually, clinicians must be able to perform these procedures quickly, and with minimal complications. With the current clinical practice for several image guided needle interventions, clinicians will often acquire several volumetric images throughout the insertion process to ensure a suitable trajectory and track the progression of the needle path. These methods of treatment may lead to patient discomfort due to long procedures, multiple needle insertions, higher cost, and, under CT guidance, an increased risk of ionizing radiation.

To limit the number of needle insertions and volumetric images acquired, augmented reality (AR) image overlay systems were proposed. AR systems take computer generated images and superimpose them into the user's field of view in the real world. This benefits the user by providing them with additional information that could only be provided by the computer itself. The first volumetric image overlay systems were static, and designed to place the image just above the patient (Figure 1A)[1, 2]. The mirror-monitor configuration was in such a way that produced a floating image on top the patient when observed through the mirror. MSK procedures have been trialed and

performed under image overlay guidance thoroughly in recent years[3 - 5]. It has been shown that using image overlay technology in practice is beneficial to patients and physicians compared to the conventional clinical methods used for MSK procedures[3 - 7]. Though, these static systems had several problems; they were fixed to the scanner's gantry, were prone to misalignment through unintentional contact, and required complex alignment and calibration processes[1, 2]. These systems also were restricted to use in the room where the scanner is present, which increase the cost per use of the system. Our goal is to create a system which is usable for overlay guidance at bed-side and away from the scanner's gantry.

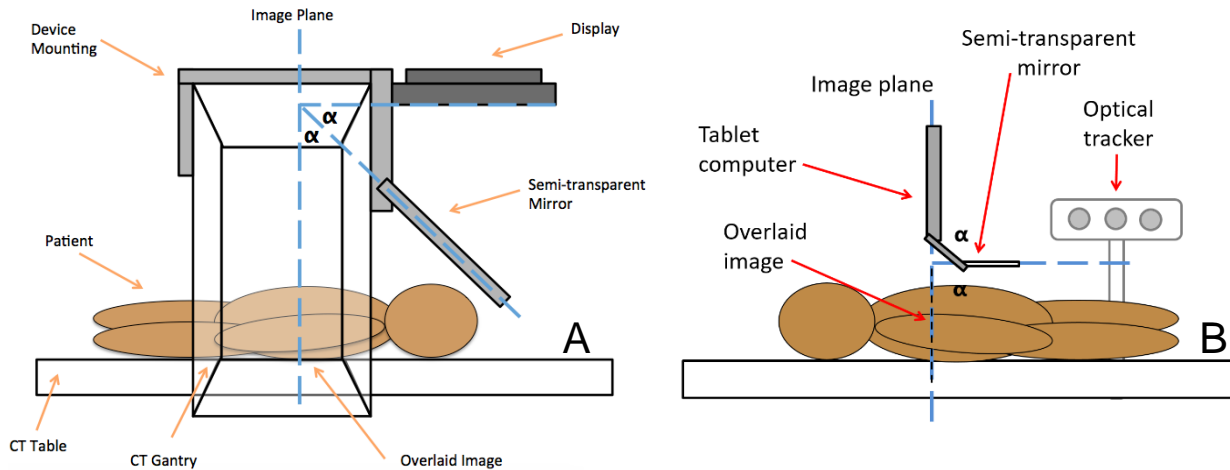Previously, we proposed an image overlay system (Figure 1B) with a modular viewbox design, self-contained

Figure 1: (A) Fichtinger *et al*'s static image overlay concept; (B) Baum *et al*'s image overlay concept.

system architecture and self-calibration process[8]. Although the system satisfied the accuracy requirements for a range of needle interventions, its use in clinical procedures was limited by the complexity and inconvenience of use, and lack of robustness in both hardware and software components. For acceptance in the clinical environment, the image overlay system requires calibration, patient registration, and navigation on a single user interface with minimal user interactions and short learning curve. We have developed a simplified viewbox and user-friendly image overlay software. Usability parameters in clinical settings, ergonomics, and performance of the system are presented.
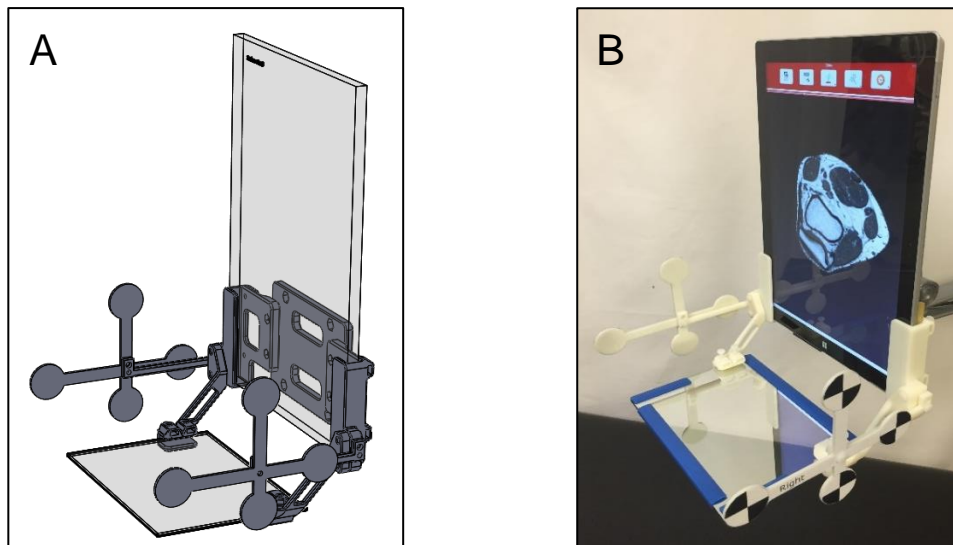

Figure 2: (A) Mechanical design of the viewbox and (B) the rapid prototyped viewbox with Surface Pro 3 tablet.

2. METHODS

2.1 System description

The image overlay system consists of an optically tracked frame, called a 'viewbox', which is designed to grip onto a semi-transparent mirror and a tablet computer (Figure 2). There are optical markers placed on both sides of the viewbox in order to determine the pose information of the plane of the overlaid image at all times during use of the system. A reference optical marker is attached to the patient for registration of scanned images, and to determine the location of the viewbox with respect to the patient's position. The tracking information from the optical tracker is streamed to the viewbox tablet computer via wireless network. With real-time tracking data available to the tablet computer, the image overlay system's IONav software can be put to use for navigation. The design of the image overlay system is such that the system can be handheld or mounted to a table at patient bed-side intraoperatively. The system can be setup by one user without any programming knowledge required before being used for image exploration and needle navigation.

2.2 IONav software

The IONav software was implemented in the Python programming language as a 3D Slicer module based on the Guidelet template[9]. IONav allows users to use the system to calibrate the viewbox to the virtual image plane, to calibrate any tracked tools, to register the viewbox to the patient and for navigation of scanned patient images. The MicronTracker H3-60 (Claron Technology Inc., Toronto, Ontario, Canada) passive optical tracking camera, connected to a computer that runs the PLUS Server Application[10], acquires the real-time tracking data and streams it through the OpenIGTLink protocol[11] to 3D Slicer to provide the tracking data necessary to re-slice the scanned patient images.
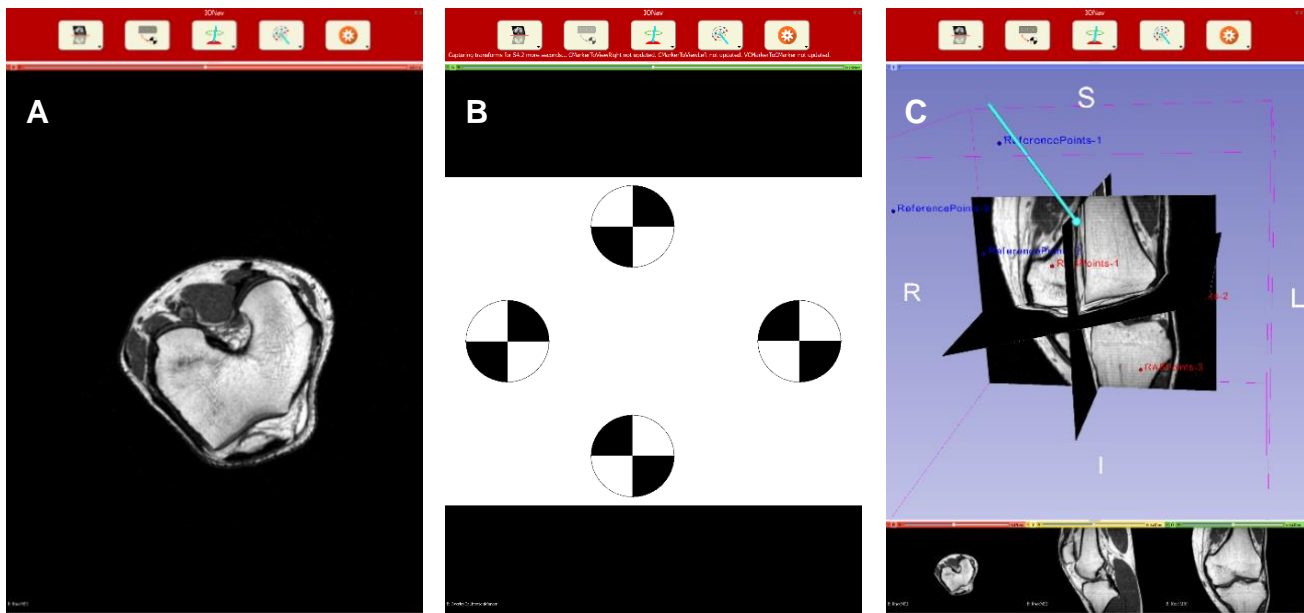

Figure 3: User interface in the IONav software showing (A) image re-slicing of an MR image of a knee, (B) MicronTracker marker rendering for the system calibration and (C) MR image of a knee in the 2D and 3D viewers for patient registration.

2.2.1 System calibration

To calibrate the viewbox, required only when the hardware configuration of the system is changed, the user can touch the System Calibration button in IONav's user interface on the tablet. Markers are then rendered on the screen of the tablet and are used to determine the transforms between the viewbox and the center of the virtual image using the MicronTracker (Figure 3B). The user can then move the viewbox and tablet through space to allow the

MicronTracker to view the required transforms and update the calibration accordingly. IONav will continuously look for any updated transforms which are required for calibration for a pre-set duration of time. When this time has passed IONav's user interface will display which transforms have been updated, and which have not. If the user captures all the required transforms before the pre-set time expires, IONav will automatically stop the calibration process.

2.2.2 Patient registration

To register the viewbox to the patient, the user can touch the Patient Registration button in IONav's user interface. The patient's scanned images are loaded to the screen and displayed in a 3D view, and in three anatomical 2D views. These images will have predefined registration points marked on them, selected beforehand, and the user can then use a pointer tool to mark those same anatomical points in the patient coordinate system to register the viewbox to the patient (Figure 3C). The user will place the pointer in the patient coordinate system in the correct location, and then touch the "Place Fiducial" button to place a new fiducial point for the registration. If the user makes an error in fiducial point placement, they may delete the previously placed point, or all placed points. If the registration created is not suitable for use, the user may also touch the "Clear Registration" button and reset the registration process and begin placing fiducial points again.

2.2.3 Patient volume navigation

Once the viewbox is calibrated and the patient is registered to the viewbox, the user may navigate and view oblique slices of the patient volumes by touching the Navigation button within IONav's user interface. The patient volumes will then be automatically re-sliced and overlaid onto the patient as the viewbox is moved through space (Figure 3A). As the viewbox has optically tracked markers on either side, the user is able to touch either the "Left" or "Right" button to change the configuration of the transform hierarchy to use the viewbox marker that is currently facing the MicronTracker.

2.3 System workflow

The proposed clinical workflow for the image overlay system aim to improve on current clinical practice for several image guided needle interventions, wherein clinicians will acquire several volumetric images throughout the insertion process. This allows them to continually ensure a suitable trajectory, and track the progression of their needle's path. With our proposed workflow, only two scans would be required and optimally, one needle insertion (Figure 4). Similar to the conventional clinical workflow described earlier, our proposed workflow begins with scanning the patient and acquiring their CT or MRI images on the tablet computer and loading them on the tablet computer. Once the patient images are loaded onto the tablet, the user can start IONav and then proceed to register the patient. Using the registration method outlined in *2.2.2 Patient registration*, users can prepare the system for
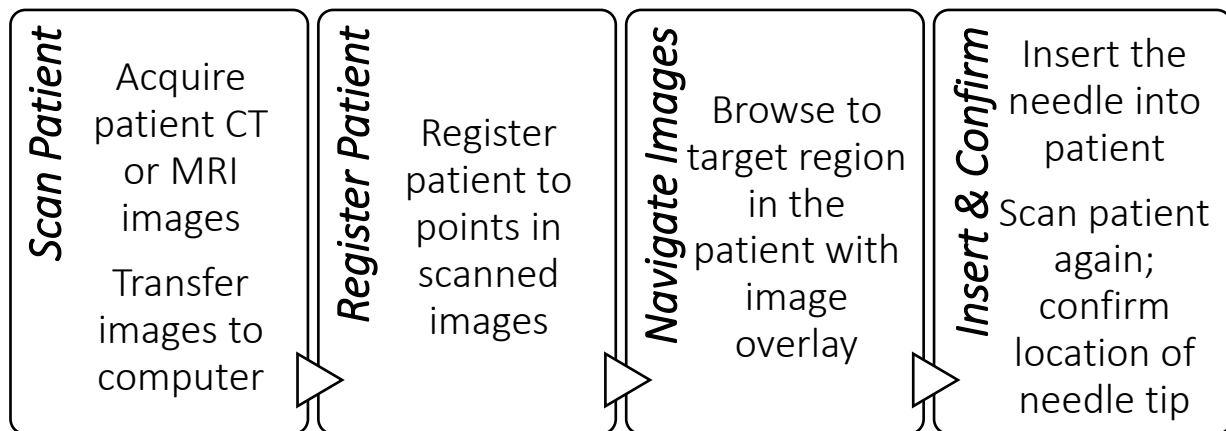

Figure 4: Flowchart illustrating the image overlay system's proposed clinical workflow.

patient image navigation for needle guidance or image exploration. Once the system and the loaded medical images are registered to the patient, the user can setup IONav to navigate patient image volumes as outline in *2.2.3 Patient volume navigation*, then navigate the patient images and find their target region using the system. Once the user has located their target, they can insert the needle under AR image overlay guidance using the system and IONav software. After inserting the needle, the patient would be scanned again to confirm the location of the needle tip from the insertion.

2.3 System latency evaluation

A series of experiments were conducted to evaluate the latency of the image overlay system with image volumes of different sizes. Three different latencies were measured. The first measured the latency when moving the image overlay system from rest. This latency was defined as the time between when the image overlay system had begun moving through space and when the image on the screen of the tablet first updated. The second measured the latency when stopping the image overlay system's movement. This latency was defined as the time between when the image overlay system had stopped moving through space and when the image on the screen stopped updating. The third measured the performance of the image overlay system while in motion. This latency was defined as the average time between displayed images changing while the system was in motion.

2.4 Usability study

In addition to our latency evaluation, we assessed the usability of the image overlay system and the IONav software, by having five physicians navigate a patient MR image using the image overlay system. The system was registered to the patient to provide the participants with a realistic usage experience of the image overlay. Each participant was asked to use the overlay while (i) it was table-mounted to an adjustable arm and (ii) it was a handheld device. Each participant was asked to browse the patient images with the image overlay system and plan needle insertions (Figure 5). Participants then completed a questionnaire, rating on a Likert scale, as to the performance, usability and effectiveness of the image overlay system and the IONav software. Participants were also asked to compare the table-mounted and handheld variants of the system.
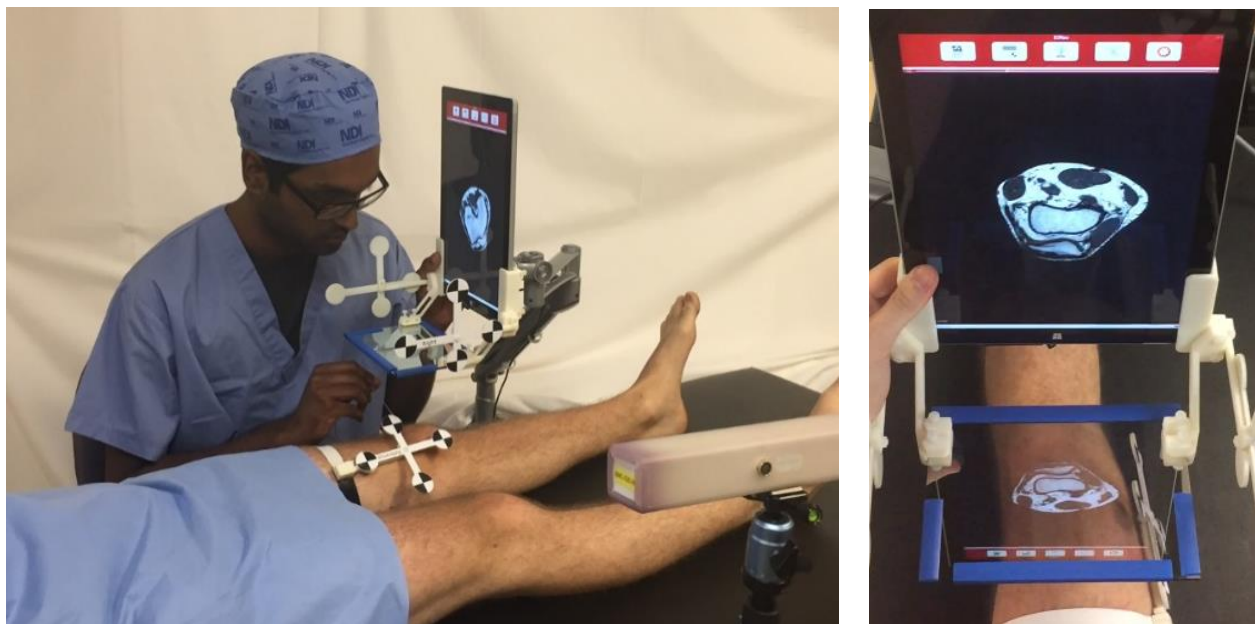

Figure 5: *Left:* Usability study participant using the image overlay system and IONav software to plan a needle insertion path with the adjustable table-mounted arm, *Right:* participants view of the overlaid image on patient's leg while using the image overlay system

3. RESULTS

3.1 System latency evaluation

Given the image overlay system's architecture, there are several steps in the system architecture between viewbox movement and image re-slicing which may bottleneck the performance. In our experimental setup, the MicronTracker's measurement rate, the wireless network's bandwidth, and the image re-slicing time could not be altered. Therefore, to assess the re-slicing capabilities of the image overlay for potential bottlenecks, we observed the effect of different scanned patient image resolutions. The first experimental latencies were obtained with a volume measuring 512 x 512 x 120 pixels. The average of the first defined latency was found to be 418.0 ± 78.1 ms (n = 7). The average of the second defined latency was found to be 465.6 ± 107.5 ms (n = 7). The average of the third defined latency was found to be 193.8 ± 18.0 ms (n = 87). The second experimental latencies were obtained with an image volume measuring 226 x 226 x 364 pixels. The average of the first defined latency was found to be 415.6 ± 134.7 ms (n = 7). The average of the second defined latency was found to be 503.7 ± 121.6 ms (n = 7). The average of the third defined latency was found to be 195.5 ± 30.5 ms (n = 75).

The MicronTracker has a manufacturer-stated lag of approximately 60 ms, and a processing time per frame with four markers tracked of approximately 15 ms[12]. Additionally, the MicronTracker has a manufacturer-stated measurement rate of 16 Hz[12]. With measured in-motion refresh rates of approximately 5 FPS, and the MicronTracker providing tracking data at 8 FPS, it can be seen that the measurement rate of the tracking device, transmitting tracking data over a wireless network, and re-slicing the image may limiting factors to the system refresh rate.

3.2 Usability study

In our usability assessment, once participants had used the image overlay system, they were asked to respond to a series of questions and asked to answer using a Likert scale, with 1 being strongly disagree and 5 being strongly agree (Table 1). In the questionnaire, all participants responded to questions about the image overly system in general, and concerning the use of the image overlay system while it was table-mounted device on an adjustable arm, and as a handheld device. The responses from the handheld and table-mounted comparisons were analyzed with a one-tailed Student's T test (Figure 6).

Number	Description
1	It was easy to learn how to use the image overlay system
2	It was easy to understand where the plane of the image overlay was located on the patient
3	I could recognize when my needle was in the plane of the image overlay
4	I could bring the image overlay to the knee joint cavity
5	I could easily adjust the location and position of the image overlay
6	Navigating through the MRI using the image overlay was not mentally demanding
7	Navigating through the MRI using the image overlay was not physically demanding
8	I could place myself in a position where I would be comfortable performing needle insertions
9	I was able to see the overlaid image from wherever I was standing
10	The image shown on the patient was optically stable

Table 1: Image overlay and IONav usability questionnaire questions.

The responses showed that all participants strongly agreed it was easy to learn how to use the image overlay system, and to understand where the projected image was located on the patient. Furthermore, when comparing the use of the image overlay system as a handheld device versus the use of the image overlay system as a table-mounted device, there was a statistically significant increase in how mentally (p = 0.049) and physically (p = 0.002)

demanding the system was to use when using the handheld variant. Additionally, participants felt they were significantly more able to position themselves comfortably (p = 0.005), adjust the system itself more easily (p = 0.026), and navigate the system to a desired anatomical landmark (p = 0.026) when using the table-mounted system. All participants seemed to favour the table-mounted device when they were asked if they could always see the overlaid image from their standing position, and if the displayed image was optically stable.
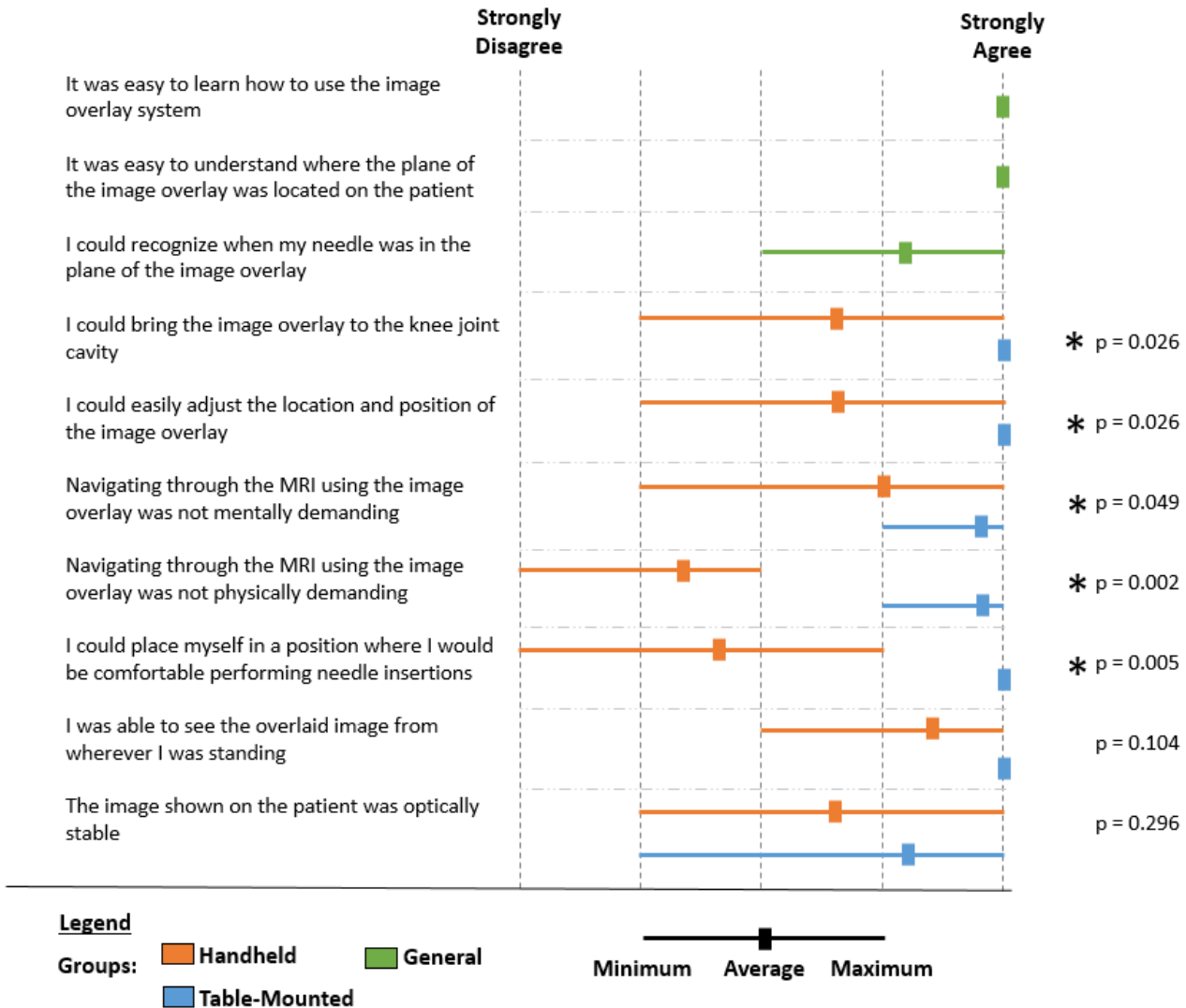
Figure 6: Max-Min-Average chart assessment of questionnaire responses.

4. CONCLUSION

The image overlay system was designed and developed with the goal of bringing usable AR guidance with MR and CT images to the patient's bed-side. In assessing the latency of the system, it was determined that the system performs comparably with scanned images of varying size. In validating the usability of the image overlay system and IONav software, the study participants preferred the table-mounted variant of the system for bed-side use. The study participants also felt that the system itself was simple to use and understand. Our image overlay system offers real-time browsing of patient images for needle interventions through a robust, open-source platform without the need for pre-planning or image review before the intervention. In combination with these results, the small footprint

of the system, and the simple setup process show promise for the system to be used in clinical practice for image exploration and needle navigation.

5. ACKNOWLEDGEMENTS

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