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Trust, Safety and Efficacy of Autonomous Robotic Ultrasound Vascular Imaging Collection on Human Subjects

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***Abstract*— This paper describes the safety and efficacy of an autonomous robotic system to collect ultrasound (US) images of the peripheral vasculature of 31 human participants, while also assessing their trust and comfort with the procedure. The procedure used a custom restraint mechanism and robotic arm guided by RGB-D imaging to collect clinically meaningful US images of human vasculature in the peripheral forearm safely and autonomously. All initial presses and scanned trajectories were executed under a safety force threshold (13N), included vasculature in imaging (from trajectory selected by non-clinician), and had a full scan completion success rate of greater than 80%. Participants indicated increased trust and perception of safety in the robotic system after the procedure. The positive findings suggest that careful attention to patient safety and well-designed patient/robot interactions can positively affect human-robot interaction and change the perception of robotic systems in medical contexts.**

Keywords: medical robotics, trust, HRI, safety

I. Introduction

There is an increasing pervasiveness of robotics in medicine, but still very limited systems that actuate on the patient that can, or are trusted to, act autonomously without a clinician. In procedures where the patient is not under anesthesia, like in diagnostic ultrasound(US) procedures, there is a unique opportunity and challenge to interact with the patient. These autonomous procedures require trust from users, which also allow users to perform simple actions instead of requiring a separate clinician. For these autonomous robotic medical procedures to proliferate, medical robotic systems would need to ensure safety, efficacy, comfort, and trust for users with diverse backgrounds and body types.

There is a research gap in defining what safety parameters are needed in a safety-critical medical system, when the operator of the robot is also the subject of the robot's task. Further, there is even less known about what safety and confidence requirements are when the operator is a layperson who does not have any pre-trained knowledge regarding the task the robot is designed to accomplish. Safety requirements would include measuring and limiting applied force on the patient, common limits described in Courreges et al to be 5-20N,[1] and ensuring appropriate steps are followed throughout the procedure. No studies, to the researchers knowledge, have explored the trust and comfort of US-guided procedures on multiple participants, where the user is also controlling the system. This study explores the safety, efficacy, and user trust of performing an autonomous robotic US scan on the arm, with considerations for safe control and human-robot interaction throughout the procedure. Specifically, this paper explores the development, safety assessment, and user interface/experience of a platform device for US navigation by a robotic arm on a clinically untrained user which trusts and engages in the clinical procedure.

A. Prior work in Vascular Localization

Currently, autonomous peripheral vascular localization systems use infrared (IR) imaging to target near-surface veins. This works for most patients, but people who are frail, obese, or undergoing cancer treatment, require deeper vein targets, demanding US to identify key targets. Prior autonomous US imaging systems can identify and differentiate larger diameter vasculature, such as the jugular vein and carotid artery.[2], [3] These vasculatures are larger than peripheral vasculature in the arms, with 4mm target veins the procedure of intra-venous (IV) insertion.[4] Peripheral vasculature also has a more variable pattern compared to larger vasculature in the body, making it critical to segment and track for IV placement.

When identifying deeper vasculature with US, one needs to differentiate veins from arteries. Clinically, this is done either with venous doppler or by pressing down on the vasculature with the probe. With venous doppler, multiple, sequential, low-resolution images are used to deferentially color veins and arteries based on flow rates. However, the low resolution hinders accurate position measurements, especially with small vascular targets. Applying pressure can distinguish veins and arteries because veins collapse under low pressure, while characteristically thicker-walled arteries stay open.[5]

B. Ensuring Safety in Human Application

Safety in robotics is a developing field. Historically in industrial applications, safety in HRI was ensured simply by avoiding it, mostly by putting robots in cages.

Medical robots, must by definition interface with humans, demanding a new safety paradigm. Towards this, safe force thresholds have been established for human contact,[1] and successfully maintained using a UR5e on a tissue phantom.[6] Force sensing, such as that from Robotiq force sensor attachment, can enhance speed and accuracy of force measurements, eliminating drift and heating effects that bias internal joint torque sensors.[7]

Many autonomous robotic US systems generate initial arm trajectories from a 3D image of the scanning surface.[8]–[10]

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The phantom or participant must remain still after the image has been taken, which can be ensured by additional sensing and/or restraints. Further, when performing the scan, it is better that the system does not assume the trajectory from the initial imaging is perfect. Depending on the sensing modality, lighting, noise, and small motion artifact can affect the accuracy and efficacy of the trajectory.[11], [12] These artifacts can be corrected with proper filtering and using an appropriate controller. Some systems use force or imaging as inputs for the controller,[10] enhancing safety and/or quality of data collected. While inconvenient for human medical procedures, some US scanning systems avoid these issues by performing experiments in a water tub, which can replace US gel as an acoustic couple.[13], [14]

C. Developing and Assessing Trust

Although trust can be difficult to measure, it is critical to the adoption of safety-critical systems in medical robotics. Human robot interaction trust surveys have been developed[15] and further guiding principles detailing appropriate steps to take have shown experimentally to enhance trust.[16] Surveys have been developed for use in many different types of robotics HRI applications from animatronics to collaborative experiments. Most prominently,[17] is well-sourced and has been translated over 10 times for various experiments on perceived safety. Intuitively, repeated positive or negative reactions with a robotic system will influence user trust, so the number and kind of interactions must be consistent across all experimental participants. Perceived reliability is another form of trust that can be measured in surveys to determine confidence in the system before and after the interaction.[18] Finally, assurances have been shown to affect and enhance trust in a robotic procedure by clarifying how and what decisions the robotic system makes.[16]

D. Problem Statement

To the best of the researchers knowledge, there is no medical robotic system testing where the clinically untrained user is also the controller of the system for a full medical US procedure. This work addresses the novel development and assessment of safety force thresholds/controller design (translated from research on phantoms) for human arm scanning, safe operation procedures in a procedure autonomous of clinical intervention on an awake user, and a trust assessment to better understand current and future adoption of this specific and similar autonomous robotic US procedures.

II. Methods

A. System Hardware

This system includes five main components: a UR5e robotic arm (Universal Robots, Denmark), Interson US probe (Interson Corporation, CA), a Realsense SR305 RGB-D camera (Intel Corporation, CA), Robotiq FTS 300 end effector (EE) force sensor and a custom arm securement mechanism containing non-contact US sensors (Adafruit Industries LLC, NY). The Robotiq FTS 300 end effector force sensor is secured to the EE and used to measure the robot force contacts at 100Hz streaming with a signal-to-noise ratio of 0.1 N. The US probe and RGB-D camera are attached to the robotic arm's EE with a 3D-printed stage. The surface image is retrieved by the Intel Realsense SR305. With a range of 0.2-1.5 m and up to 640 × 480 resolution at 60 frames per second (fps), it depicts the stationary surface of the participant's arm.

TABLE I: Anthropometric Arm Restraint Considerations

Area Measured	Percentile Range	Anthropometric measurement range (in)	Relevant components with measurements
Relaxed Bicep	1-99	10.1-14.5 in circumference	Pressure cuff housing 6in inner diameter
Shoulder Elbow Length	1-99	12.8-15.9	Strap and cuff housing width
Radiale-Stylion Length	5-95	9.3-11.9	Tables 5.4in each
Finger Crotch Length	1-99	4.3-5.7	Hand-stop length 6in
Hand Breadth Across Thumb	1-99	3.6-4.5	Gap between pin holders 6in

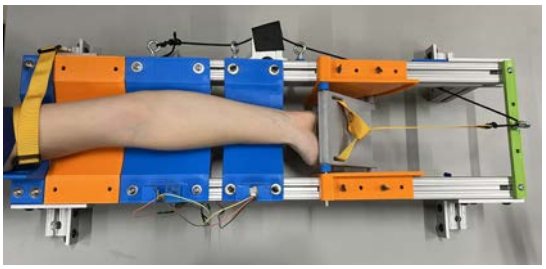

Fig. 1: View from above of full arm securement mechanism with adjustable aspects to fit 90%+ of individuals[19]

The participant's arm was secured using a custom system developed to fit 90%+ of arms as described in Table I.[19] The arm restraint was designed to secure participants of various shapes and sizes and minimize potential movement in 6 degrees of freedom. The wrist was secured with a hand restraint, as shown in Fig. 1, which kept the wrist facing upwards and limited twisting in the forearm below the elbow. Additionally, we hypothesized that keeping the elbow straight and a wrap securement with blood pressure cuff and strap would make twisting only possible if one was able to rotate their entire shoulder, nearly impossible while sitting. The participant's arm was not able to move along its length due to the hand restraint and friction along the arm the strap at the elbow. These constraints also limited movement side to side and up and down relative to the arm restrained, with full system shown in Fig. 1.

The surface of the restrained arm determined the US probe orientation for smooth and safe movement across the arm for each trajectory. An initial RGB-D image captured the full surface, assuming no movement of the tissue throughout the procedure. This was necessary as the camera, connected to the robot arm EE, must be 0.2m from the tissue surface for effective RGB-D data collection, but the EE is much closer

Fig. 2: Check-in step for User Interface for Participant to approve approximate motion plan

to the surface during US collection. The US image data was collected with Interson's (SP-101) USB US Imaging Probe, with 7.5 MHz and 5 cm depth range. The low frequency (7.5 MHz) enabled penetration to deeper tissue and is widely used for vessel detection in human arms. Low frequency (LF), 754×494 pixel, B-scan US images were collected at 30 fps. The resolution and speed of the US probe allowed fast image analysis.

B. Participant Procedure

Participants were led through the steps with a user interface, with an example step shown in Fig. 2. Through videos, pictures and descriptions, the user interface, with researcher oversight, explained to the user how to secure themselves to the arm restraint mechanism. The arm mechanism has restraints in the hand and upper bicep, along with the wrist fixed by open hand and straight elbow, as shown in Fig. 1. Then, the user interface gave timers for the initial RGB-D image to be acquired to generate a trajectory and initialization of the sensors. The participant then approved a similar trajectory to their individualized trajectory used in the procedure using the user interface, as shown in Fig. 2. The user interface then guided the user through US gel application, as prior application could corrupt RGB-D imaging. Finally, a timer communicated remaining procedure time to the user. Note: This study was completed in accordance with the IRB approved protocol 2022-0163 at Duke University.

C. Calibration

As in previous work,[20] iterative RGB-D camera calibration was used to solve the HandEye calibration problem.[21], [22] US EE transformation was determined using CAD files paralleling the calibration procedure defined in.[20] Force calibration was performed with 100 readings while robot EE was pointing down with US probe, as during the procedure, but not in contact with the surface.

D. Trajectory Generation and Tracking

Autonomous US movement requires a robust robot control strategy to traverse the deformable surface of the arm. The robot must minimize jolting movement, avoid excessive forces, and maintain contact with the arm for usable images and a safe procedure. As described in,[20] physical robot movement follows a surface trajectory, with proposed positions and normals generated from the a priori point cloud data. Additionally, PID force control along the normal responds to the surface-based forces in the EE force torque sensor. This force feedback is critical for safe scanning.

E. Press and Scanning Procedure

During the procedure, half of the participants were randomly selected to have a blood pressure cuff at 60mmHg applied, like a tourniquet.

Once the trajectory is developed and confirmed by the participant, the robot slowly arrives at 1mm above and normal to the surface at the trajectory start and then slowly calibrates with the surface of the skin with a target force of 3N. Second, the robot slowly moves into the arm to press 10N maximum, to collect data for visualizing veins versus arteries. Third, the robot slowly rises back up to the surface to the same target 3N force and completes the linear trajectory chosen by the researcher and approved by the participant. Finally, the arm EE returns to a home position well above the participant's arm. The total autonomous robotic procedure takes approximately 3 minutes.

If at any point during the procedure the force sensor detected a force above 13N, the procedure was ended and the arm rose to above the participant, as if it had completed the entire trajectory.

F. Data Collection

After participants had filled out an eligibility survey screening for injury, age (18-65 years), and eye sight (20/20 corrected), 31 participants were scheduled for a 20 minute appointment to complete the procedure. After reviewing and completing their consent forms, which included a thorough description of the procedure and risks involved, participants then completed a demographic and pre-survey. These surveys collected information on age, gender, education level, experience with robotic arms, feelings of safety and comfort with the procedure, and questions about trust in the system. After the procedure, participants completed an identical post-survey with the questions about comfort, safety, and trust in the system. The pre- and post-survey separated the effects of the arm securement mechanism and the arm procedure. All questions were scaled on a 5 value Likert scale.

Throughout the procedure, several modalities of data was collected to better inform the quality of procedure. First, RGB-D data was collected above the arm and used in trajectory generation, including positions and normals along the arm. Second, US image, force, and offset (distance from initial trajectory as set by PID controller) were collected throughout the press and full trajectory and indexed together for post hoc processing.

G. Data Processing

For the RGB-D image, data preprocessing was used to delete outliers below the surface of the table or over a meter

above the table. Additionally, the researcher further ensured the images were smooth before generating a trajectory by visualizing the data with Klampt.[23]

A 5th order low-pass Butterworth filter was applied to the force data to continuously use the past 50 measurements for force control. Additionally, each raw force reading was used to make sure the 13N threshold was respected during the procedure. For each control loop, an index was saved with the force, offset, and US image. Force and offset data for each participant were analyzed for total offset, maximum and variance of force readings, to describe the efficacy and safety of the procedure. To find variance of force during the initial press, all participant data-sets were individually fitted with a line of linear fit and residuals were used as a variance measurement.

US images were analyzed post-hoc for vascular localization and tracking for the press and scanning procedure by US-trained, board-certified emergency medicine physicians.

Descriptive statistics were calculated for the demographic, pre-survey, and post-survey data and Likert scale data were numerically analyzed using the Wilcoxon signed rank test as the data were not normally distributed and change in participant perception of the procedure was the desired outcome.[24]

III. Results

A. Initial Stationary Press

The initial press was completed for all participants (100%) recording forces between 3-10N, normal to the surface defined by initial imaging. a representative resulting force data is shown in Fig. 3. All participant data were individually fitted with a line of linear fit and variance from that line was an average of 0.18N during the press procedure, or less than 1oz of water in weight variance.

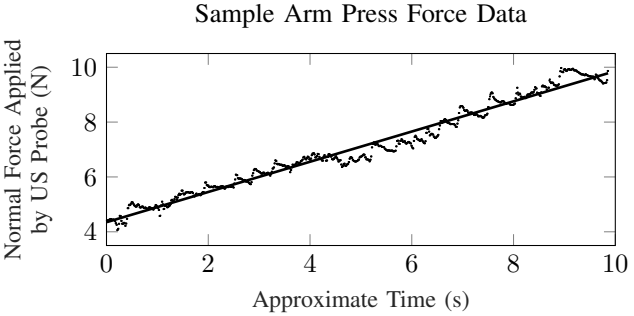

Fig. 3: Initial press force data and line of best fit for one participant.

B. Effect of Press on Vasculature

Vasculature in US images was analyzed with US-trained emergency medicine physicians. Vasculatures were tracked to monitor if they collapsed as pressure was applied by the probe up to approximately 10N. Of the 66 vessels found in all sets of images for the participants, with at least one per participant, 21 collapsed.

Half of the participants were randomly selected to have a blood pressure cuff at 60mmHg applied, like a tourniquet. Approximately the same number of vasculature were identified for both those with and without the tourniquet, but there was large variation in the number of vasculature identified per participant (1 to 6 total). Double the number of vasculature collapsed for participants with the tourniquet than without tourniquet, but the force at which vessels collapsed ranged from 5N and 10N with and without the tourniquet. The force of collapse had a mean and variance of 7.8 +/- 3.3N.

C. Ultrasound Scanning Along Trajectory

The scanning trajectory defined by initial imaging was completed for most participants ($\tilde{8}1\%$, 25/31). Example force and offset are shown for one successful scan in Fig. 4. All participants that did not complete the full scanning procedure were adjusting towards an offset higher above the surface, even though they hit the maximum force for the system (a single measurement above 13N would trigger the system to stop). All participant data that completed the trajectory were analyzed individually and then collectively for the applied force average and variance, with target force for the system of 3N during scanning. The average mean and variance for all completed participants was 3.09+/-0.26N, with a minimum range of 0.84N and a maximum range of 7.00N.

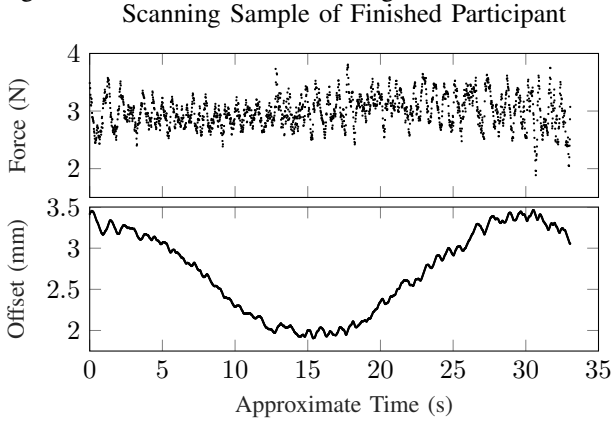

Fig. 4: Example of Successful Scanned Trajectory with applied Force and Offset from initial imaging

D. Participant Population

Gender was evenly distributed with 15 female and 16 male participants. Occupation was split between students (undergraduate (6), masters (4), and PhD (7)) and industry positions (14). The age of the participants ranged from 20 to 60 years old, with two-thirds of participants between 20 and 33 years old. Only two participants had controlled a robotic arm before.

E. Safety

Participants were separately asked for their perceived safety due to the arm securement mechanism and the robot procedure. The vast majority were neutral or increased their perceived safety, with post-procedure average of 4.8/5

(most "Very Safe") for both the robot procedure and arm securement, as shown in Fig. 5. Changes in perception of safety were significant for both questions using the Wilcoxon signed rank test. No demographic statistically different differences were found.

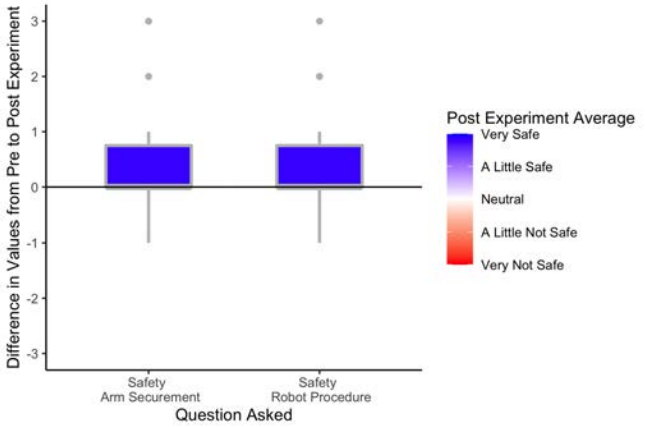

Fig. 5: Change in perception of safety for arm securement mechanism and robotic procedure before and after procedure as measured in survey data

F. Comfort

Participants were asked for their perceived comfort due to the arm securement mechanism and the robot procedure. The comfort due to arm securement had a final mean of 3.4 or closest to "Neutral", as shown in Fig. 6. Significant difference was found for change due to the arm securement for the entire set of participants in the negative direction, towards less comfort. Additionally, there was significant difference between males and females in the change in perceived comfort of the arm mechanism, where males changed to be much less comfortable, post-procedure average of 2.8 closest to "Neutral", while females stayed mostly the same, pre and post average 4.1 closest to "A Little Comfortable," as shown in Fig. 7. There was no significant difference in comfort found due to the robotic procedure in pre/post testing, with a final mean of 4.3 or closest to "A Little Comfortable" for all participants.

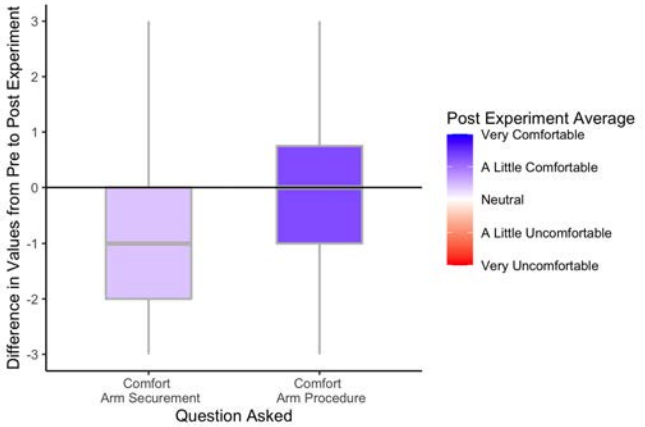

Fig. 6: Change in perception of comfort for arm securement mechanism and robotic procedure before and after procedure as measured in survey data

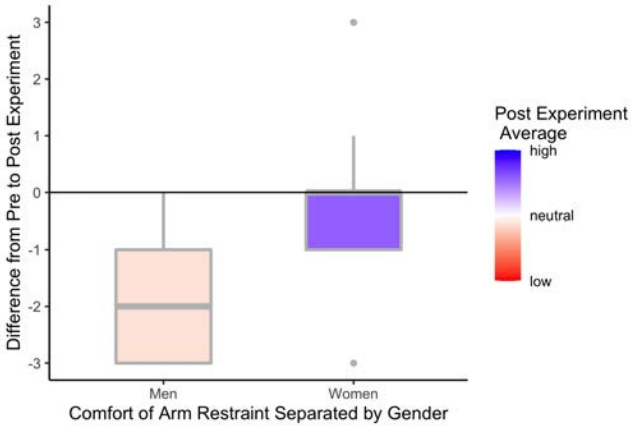

Fig. 7: Change in perception of comfort for arm securement mechanism before and after procedure as measured in survey data separated by gender

G. Trust

Participants were asked if they trusted the robotic system is capable and, separately, reliable at collecting vein US images. Participants mean changed from 3.8 to 5 (or mostly "Most of the time" to "All of the time") for a significant difference concerning if the system was capable of collecting US images, as shown in Fig. 8. Participants mean changed from 3.8 to 5 (or mostly "Most of the time" to "All of the time") for a significant difference regarding if the system was reliable for collecting US images.

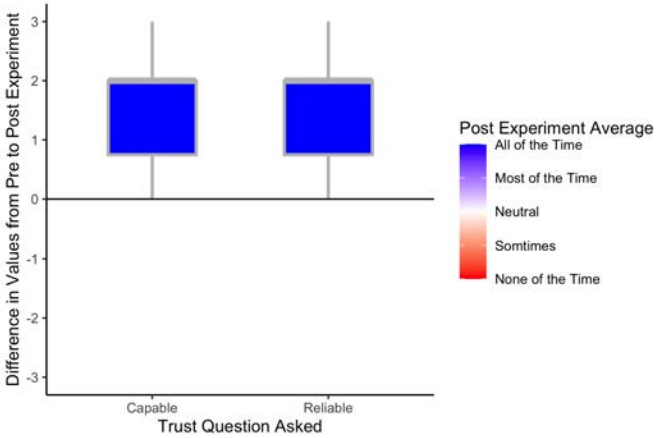

Fig. 8: Change in perception of trust values before and after procedure as measured in survey data

IV. Discussion

This research explored full human robot interaction for autonomous US procedure on multiple participants. For this work there was IRB approved collection of force data and testing of the efficacy of PID controller on multiple participants, where application of most previous autonomous US scanning research has been limited to one or two example demonstrations. The results demonstrate the potential need for controller tunability to individual subjects for increase efficacy of the system.

Additionally, there was collection of comfort and trust in the securement procedure and, separately, autonomous scan. There was significant positive change in trust with only one interaction with the autonomous procedure. Still, comfort data showed different genders, possibly affected by different body types, had significantly varied comfort in using the securement device, despite its theoretical adaptability to 95% of the population. Future work could include understanding if there is a gendered or body dependent effect of the physical setup and expectations on these autonomous medical procedures.

From these pre/post surveys of the autonomous robotic US procedure, we can see how this procedure, which emphasizes agency of the user in go/no go decision making and self securement, increased the comfort and trust in the procedure.

Based on prior work,[20] the system was shown to be effective at following multiple straight line and zigzag trajectories and precisely identifying and tracking phantom vasculature. Our contribution of moving from phantom to human vasculature is significant, as phantoms consist of a homogeneous substance, versus the heterogeneous nature of human tissue. The 31 experiments with volunteers were collected over 2 weeks and showed the efficacy of the system to safely perform this procedure on human subjects, who ranged greatly in size and shape. Force on participants was never more than 13N, a safety threshold enforced with measurements by the Robotiq force sensor, less than recommend by previous work.[1]

A. Initial Stationary Press

Trajectories were chosen by the researcher without clinical knowledge and the low cost US probe was set to maximal depth (making vasculature less clear). Still, vasculature was observed in all participants in the initial position for the stationary press. This suggests minimal clinical knowledge is needed to determine trajectories that a robot could scan autonomously in the forearm. Additionally, all trajectories were near the inside of the elbow (cubital fossa). This required a restraint mechanism, like the one used, which had the elbow pronated and large forearm surface area exposed.

All participants' US probe press procedures were completed with a maximum of target 10N (max less than 11N) applied before coming back to calibrate at 3N, with small residuals of average 0.18N, indicating a safe and effective procedure. Data collected will be used to train models for identifying vasculature automatically in the future. Initial clinician-led data processing identified over 60 vasculature, of which 21 collapsed. This indicates that the applied pressure could distinguish between veins and arteries, as arteries. Clinicians reading the US vasculature images were blinded as to whether the participants had the tourniquet used (50% of participants had the blood pressure cuff inflated to 60mmHg). Use of the tourniquet did not increase the number of vessels identified nor did it change the force at which the vasculature collapsed. Anecdotally, the use of the tourniquet did affect the comfort of the procedure for participants, as any 3-4 min blood pressure cuff procedure would.

B. Scanning Along Trajectory

The system performed a preselected trajectory on the participant's arm, a straight-line movement from approximately 2cm from the opposite of the elbow to midway on the forearm, about 6cm trajectory. In most participants (81%), the system completed the full trajectory, while in (19%), the system stopped midway and the experiment prematurely ended. For those that completed the trajectory, the PID controller tracked the 3N target well, with a mean force and variance force applied of 3.09+/-0.26N. For those that did not complete the trajectory, the PID controller regulating towards the target force, as shown in the offset of the EE relative to the initial imaging increasing, or rising above the surface. For some participants, the PID controller could not respond fast enough and the procedure was ended. Anecdotally, this seemed to be with more muscular participants, where the measured force quickly increased as the edge of the US probe hit a more muscular region, which is firmer compared to a softer tissue it was exiting. There was not a noticeable difference with perception of trust, comfort, or safety of the experiment for those that did not complete the full scan. This could have been in part because participants who did not complete were not informed of this. Additionally, the robot arm came back up like other participants' procedure and the force applied of less than 11N was reasonably comfortable.

C. Arm Restraint System

When developing an arm restraint for human experiment for an autonomous robotic system to collect US images of vasculature, the two main goals were safety and efficacy, with a tertiary goal of comfort. Safety in this procedure required the arm to be still after initial RGB-D images were taken, as the trajectory used in the experiment was predeveloped based on this imaging to generate a spline of target positions and angle of the probe normal to the surface. The controller changed the trajectory based on the force along the normal direction from the target position from this initial imaging.

As the system was able to fully complete the procedure on 25/31 participants, with all participants staying within safe force threshold of 13N, including for the vein press with a target 10N, the arm mechanism was effective in restraining participants for collecting US imaging data. The success of the second goal of efficacy was made possible by the restraints, large area for trajectories, and the ease of participant self-securement. The guided user interface effectively showed participants how to adjust and secure themselves in the device using videos and written descriptions. The arm restraint device, along with the safety feature of having the arm extended, allowed a large surface area of potential trajectories to be chosen, particularly near the opposite of the elbow, where there is a cluster of vasculature before spreading along the forearm.[25]

D. Human Robot Interaction and Experience

Limited work has been done for HRI studies for applied medical robotic systems, especially when the participant is asked to secure themselves with force applied by the system

(in this case, robotic arm) throughout the procedure. The participant population for this study was even distributed males/females with a range of age from 20-60 years old. With only two participants having controlled a robot arm before, it is likely this experiment was many participants initial experience with a robot arm and its capabilities.

As assurances have been found to have lingering effects on trust,[16] it was good to see participants felt more safe, post-survey average of 4.8 or "Very Safe" for both the robot procedure and arm securement mechanism, with significant change to safer pre to post survey, as shown in Fig. 5.

As described before, participants found the arm restraint mechanism and the blood pressure cuff used more uncomfortable than expected (post survey average 3.4, "Neutral"), especially males (post survey average 2.8, Neutral). This could be because some of the male participants were at the edge of 95-99% size the system was designed for, with larger arms than expected. Additionally, some participants noted having their arm outstretched for the procedure was uncomfortable. There was no significant difference seen in comfort for the robotic procedure pre to post survey, with a post-survey mean of 4.3 "A Little comfortable", as shown in Fig. 6.

Trust is necessary for adoption of any robotic system, especially in medicine where efficacy of the system is critical. Participants were asked directly if they trusted the robotic system was capable and separately, reliable at collecting vein US images. Mean participant perception significantly changed from 3.8, "Most of the Time" to 5, "All of the Time" as shown in Fig. 8. As assurances have been shown to influence trust in robotic systems,[16] it is very encouraging that the design of the experiment and procedure increased trust, as measured by the change in survey data, in our participants.

These positive findings of increased trust and perception of safety suggest that careful attention to patient comfort and well-designed patient/robot interactions can positively affect the HRI and potentially change in perception of robotic systems. As we are unable to find equivalent human testing of medical robotic systems where the awake participant self-secures and approves a procedure done on themselves, it is particularly meaningful to see this increase in trust of the medical robotic system through this experiment.

E. Limitations

1) Robotic System: This system required participants stay still throughout the procedure, as the trajectory was developed by initial RGB-D imaging. Non-contact US sensors and a novel arm restraint device were used in the securement device, as shown in Fig. 1, to try to ensure these conditions were met for both safety and efficacy.

Collecting ground truth clinical assessment of vasculature in US images is difficult. Typical clinical workflow has clinicians manually search for one vascular target for procedures such as placing peripheral IVs, rather than being shown prior still imaging and asking to find all vascular targets. This was addressed by having videos surrounding each still image given to clinicians and encouraging them to watch multiple times to find as many targets as possible. Vasculature was identified for 100% of participants, but it is difficult to know if all vasculature present was identified. Optimizing this labeling process for efficacy and speed may be necessary to generate effective machine learning models for this task, as labeling images well is time consuming, but critical to develop effective systems.

While going along the preselected trajectory, 6/31 did not complete the full trajectory, as the probe hit max force. It is likely this occurred on the participants who had their arms more twisted or were particularly muscular, as the edge of the probe hit a stiffer surface (of bone or hard muscle) the system was not able to change the trajectory in time. This is because the angle (normal to the surface) and position of the probe were decided only based on the center of the probe, so the corner reaches a hard/stiffer surface, the controller can only change the position relative to the center point. This did not happen fast enough before the system reached max force. Notably, the safety system did abort the trajectory and lessened the normal force in these cases. While this did cause an incomplete trajectory, it also indicates that the safety checks in the system are functional and reliable.

2) Arm Restraint Mechanism: The non-contact US sensors used have inherent accuracy error (0.5 mm) and noise, which was limited by a median filter using multiple measurements for determining movement rather than just the latest measurement. Additionally, the time delay greater than 0.3s between measurements could present an issue in relaying information of the movement efficiently. Noise of sensor data led to ranges for completely still participants of over 1cm with a median filter, which did not meet not sufficient accuracy for this task. Future work could explore other sensor options more suited for this task.

3) Human Robot Interaction: Surveys have many limitations such as limited options and neglecting correlated variables that could account for changes in answer. The online survey did not permit submission of incomplete surveys, so all surveys were 100% filled out. Future work could include physiological data, as different aspects of the procedure could potentially be assessed for trust and anxiety. Additionally, it would be logical to assume that only people who had some basic trust in the system to be safe/effective would be willing participants in the study.

V. Conclusions

This experiment showed that clinically meaningful US images of human vasculature in the peripheral forearm can be collected safely and autonomously with a custom restraint mechanism and robotic arm, guided by RGB-D imaging. All initial presses (31/31) of the robotic arm and 25/31 full trajectories were completed. Variance in the force during the procedure was 3.09+/-0.26N and all experiments respected the 13N force safety threshold, including the six trajectories that self-terminated when the normal force approached the safety threshold.

The arm securement system allowed a large area for scanning with the arm still but was limited in comfort. The blood pressure cuff acting as a tourniquet for half of the participants may have additionally reduced comfort. However, no participant indicated excessive discomfort during the procedure. More accurate and faster sensing modalities would add to the potential responsiveness of the system if a participant were to move too much for the procedure to continue.

From pre to post survey data, trust in the capability and reliability in the robotic system to collect US vasculature data was significantly increased as an effect of the procedure. Additionally, participants felt relaxed, calmer and more still after the procedure. Participants expected the comfort of the robotic procedure, but males, on average, found the arm restraint mechanism less comfortable than expected, while females had no significant difference in arm restraint comfort measured.

The positive findings of increased trust and perception of safety suggest that careful attention to patient comfort and well-designed patient/robot interactions can positively affect the HRI and potentially change in perception of robotic systems. As we are unable to find equivalent human testing of medical robotic systems where the awake participant self-secures and approves a procedure done on themselves, it is particularly meaningful to see this increase in trust of the medical robotic system through this experiment.

Future work involves developing controllers and trajectories that are more adaptive to stiffer tissues and varied geometry. Additionally, generating models of detection and tracking and deciphering veins versus arteries autonomously using force and US imaging sensor fusion will be the next steps in creating a fully autonomous system. For the arm system, future work could explore ways to make this restraint more comfortable without losing the safety and securement efficacy.

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