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Stereotactic Neurosurgical Robotics With Real-Time Patient Tracking: A Cadaveric Study

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BACKGROUND: Robotic neurosurgery may improve the accuracy, speed, and availability of stereotactic procedures. We recently developed a computer vision and artificial intelligence–driven frameless stereotaxy for nonimmobilized patients, creating an opportunity to develop accurate and rapidly deployable robots for bedside cranial intervention.

OBJECTIVE: To validate a portable stereotactic surgical robot capable of frameless registration, real-time tracking, and accurate bedside catheter placement.

METHODS: Four human cadavers were used to evaluate the robot's ability to maintain low surface registration and targeting error for 72 intracranial targets during head motion, ie, without rigid cranial fixation. Twenty-four intracranial catheters were placed robotically at predetermined targets. Placement accuracy was verified by computed tomography imaging.

RESULTS: Robotic tracking of the moving cadaver heads occurred with a program runtime of 0.111 ± 0.013 seconds, and the movement command latency was only 0.002 ± 0.003 seconds. For surface error tracking, the robot sustained a 0.588 ± 0.105 mm registration accuracy during dynamic head motions (velocity of 6.647 ± 2.360 cm/s). For the 24 robotic-assisted intracranial catheter placements, the target registration error was 0.848 ± 0.590 mm, providing a user error of 0.339 ± 0.179 mm.

CONCLUSION: Robotic-assisted stereotactic procedures on mobile subjects were feasible with this robot and computer vision image guidance technology. Frameless robotic neurosurgery potentiates surgery on nonimmobilized and awake patients both in the operating room and at the bedside. It can affect the field through improving the safety and ability to perform procedures such as ventriculostomy, stereo electroencephalography, biopsy, and potentially other novel procedures. If we envision catheter misplacement as a "never event," robotics can facilitate that reality.

KEY WORDS: Computer vision, Image guidance, Surgical robotics, Neuronavigation, Stereotactic surgery, Computer-assisted surgery, Artificial intelligence

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The ability of robots to provide accurate positioning of instruments in 3-dimensional (3D) space with high reliability, agility, and awareness of surroundings makes them an ideal platform for stereotactic neurosurgery. Since the introduction of the Programmable Universal Machine for Assembly robot in 1988,[1] robotic assistants have progressively become more facile, and neurosurgical indications are expanding. Cranial neurosurgical robots can add tremendous value in cases that require multiple hours, access to deep lesions, and minimal hand tremor. For example, Robotic Stereotactic Assistance (ROSA; Zimmer Biomet Holdings, Inc) and neuromate (Renishaw PLC) have facilitated fast, accurate, and minimally invasive surgeries for deep brain stimulation,[2-5] stereo electroencephalography,[6,7] stereotactic biopsy, and ventricular or endonasal endoscopy. Robotic assistance has also augmented radiosurgery, specifically the ability to orient the device's linear accelerator accurately with respect to the lesion, improving safety, and reducing off target effects.[8,9]

Given the multiple benefits of robotic surgery, it is important to understand why more neurosurgical procedures are not incorporating robotic assistance. In other surgical fields, the Da Vinci robot (Intuitive Surgical, Inc) alone has been

ABBREVIATIONS: OR, operating room; **PE,** placement error; **SRE,** surface registration error; **TE,** trajectory error; **TRE,** target registration error.

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used in more than 8.5 million interventions.[10] In neurosurgery, stereotactic neuronavigation is ubiquitous, but it is not commonly used in combination with robotics. In a 2021 review of 24 cranial robot projects and 9 cranial robot systems used in patients, the authors underscored many factors of poor adoption.[11] More specifically, robots often: (1) add significant time to the procedure because of complex setup and deployment, (2) are not usable outside of the operating room (OR) in nonfixated/nonanesthetized patients, and (3) do not integrate smoothly with current workflows.

In an attempt to address these challenges, we developed a robot for fast and accurate robotic assistance in stereotactic procedures. The robot is based on a recently developed computer vision image registration system that uses "Snap-Surface" and "Real-Track" features, which allow for fully automatic, continuous, and submillimetric image-to-patient registration. This study tests the usability and accuracy of frameless registration and continuous tracking of cadaver heads for robotic placement of intracranial catheters, with hopes of expediting workflow and enabling robotics use on nonfixated patients outside of the OR.

METHODS

Registration and Robotics Software System

The registration incorporates the surface of a patient's source computed tomography (CT) scan (or any other volumetric scan) and a 3D video of their face. The CT is segmented with a density-based filter and then transformed into a mesh and 3D point cloud consisting of more than 2 000 000 points. The 3D video of the patient's face involves a high-accuracy parallel structured light 3D camera, capturing more than 900 000 points every frame (MotionCam-3D M, Photoneo S.R.O). Both the Snap-Surface and Real-Track algorithms use artificial intelligence to identify areas of high similarity between the CT's surface model and each 3D video frame to register both images. Specifically, the algorithms calculate a descriptor for each point neighborhood in the CT surface and in each 3D video frame, which are synced to determine highly conserved areas of similarity between the two. These corresponding areas are used to coregister the images. The search of point correspondences is highly parallelized using parallel computing hardware, allowing us to perform the similarity search across more than 900 000 unique points every video frame. Although Snap-Surface performs the initial registration without additional input, Real-Track takes the previous frame's registration as a starting point, allowing for fine adjustments during patient movement.

The registration system was used to navigate our robot, enabling it to track the patient in real-time (Figure 1A). The robotic arm used was the M0609 electromechanical multijointed arm (Doosan Robotics, Inc). This robot is not yet Food and Drug Administration approved for clinical use. Robot tracking involved attaching passive spheres to the robot's arm and using Polaris Vicra optical position sensor (Northern Digital, Inc). The position sensor was colocated in the same arm as the 3D camera and both sensors were calibrated to determine the position of the robot with respect to the 3D camera and to monitor and control the robot's position.

Hardware Development

The system consisted of 2 portable carts. The first cart involved 1 arm with the 3D camera, a position sensor and drape holder, a screen to display the user interface, and the personal computer (Windows 10 64-bit operating systems on an Advanced Micro Devices Ryzen 2990WX 32 core computer processing units, Nvidia Ray Tracing Texel 3090 graphics processing unit, and 72 GB random access memory). The second cart supported the robot's arm and its controller.

Catheters and a sliding instrument track were attached directly to the robot's end effector, allowing for easy and accurate catheter placement. The custom catheters were 120 mm in length and 3 mm in diameter, made of a radiopaque material (polytetraflouroethylene inside of dragonplate carbon fiber tube). The catheter guide was tracked independently from the robot with passive spheres to determine the robot's trajectory and placement accuracy.

Specimen Preparation and Imaging

Four formalin-fixed human cadaveric heads were obtained from Science Care, following donation for scientific research. Science Care reviewed the images being published and confirmed that the anonymity is sufficient for display according to the patient consent conducted by their organization. This study was completed after Mass General Brigham Institutional Review Board approval (#2017P000499). Preoperative CT scans were obtained to plan and guide the robot through various trajectories and catheter placements. CT scans were of 0.5-mm slice thickness and 512 × 512 resolution. For each head, 18 robot trajectories were established encompassing a variety of angles and target depths. In addition, 6 trajectories and targets were calculated for the catheter placements, and 3 burr holes were constructed near the Kocher point bilaterally (**Supplementary Figure 1A**, http://links.lww.com/ONS/A616; **1B**, http://links.lww.com/ONS/A617; **1C**, http://links.lww.com/ONS/A618; and **1D**, http://links.lww.com/ONS/A619). Postoperative CTs were obtained following the same protocol.

The experiments followed a simulated sterile workflow with a custom neurosurgical drape that incorporated directly to the system's arm that held the 3D camera and position sensor (Figure 1B). This provided the 3D camera line-of-sight to the specimen's face, while simultaneously allowing the position sensor to track the robot.

Controlled Specimen Motions and Catheter Placements

To evaluate Real-Track, the heads were moved in pitch, yaw, and roll axes of motion. These motions were performed in a controlled and reproducible manner, using a Mayfield skull clamp (Integra LifeSciences Holdings Corporation), loosening the relevant axis on the clamp and moving the heads along that axis. Before each catheter placement, the specimen's CT was first processed using Snap-Surface registration, and then, Real-Track was activated for the robot to follow head movement. The specimen was moved to several new positions after loosening the Mayfield clamp and then secured in its final position. The robotic arm actively tracked the heads throughout the motion, and immediately after the motion was completed, the catheter was moved down its rail and secured in its target location. The catheter was bonded to the burr hole using cyanoacrylate cement, and the guide was retracted.

Error Calculation

To determine the device's accuracy, 4 metrics were calculated: (1) surface registration error (SRE), (2) trajectory error (TE), placement error (PE), and (4) target registration error (TRE). SRE was defined as the registration error between each point in the patient's 3D image and its corresponding point in the CT scan. TE involved the angular error between the robot's trajectory and a given intracranial target. PE was the user's error during the robotic-assisted catheter placement. TRE was the Euclidean distance between the catheter tip as seen on the CT scan and the tip position as reported by our device.

Statistical Analysis

Statistics were calculated using the SciPy Python library,[12] and plots were produced using the Seaborn and PyPlot Python libraries. SRE was calculated using the CloudCompare software and TRE using 3D Slicer. TE and PE were reported by our system.

RESULTS

SRE

SRE was calculated for the 4 specimens while draped using 72 independent registrations. The mean SRE was 0.696 ± 0.106 mm (99% CI = 0.663, 0.730 mm) (Figure 2A). Inspection of the registered images confirmed that Real-Track was able to correctly identify and use highly conserved areas between the CT scan and the 3D images and discard areas deformable regions such as eyelids and mouths (Figure 2B).

Trajectory Accuracy Across Head Surface

For each specimen, 18 intracranial targets were selected on the preoperative CT scans (Figure 3A-3D). Real-Track was used to register the CTs with the preselected targets on the specimens, and this dynamic registration was used by the robot to correctly orient itself in a trajectory that would hit the target. The average TE was 0.119° ± 0.077° (99% CI = 0.095°, 0.144°) (Figure 3E; Supplementary Table 1, http://links.lww.com/ONS/A620). The TE error was uniform across the X and Y axes (Figure 3F).

To determine Real-Track and the robot's latency, we quantified the runtime for the various computational processes (Figure 3G). The 3D image acquisition was the slowest process (0.278 ± 0.009 seconds), followed by the 3D image's import and processing (0.137 ± 0.025 seconds). The Real-Track runtime was 0.111 ± 0.013 seconds, and sending the movement command to the robot took 0.002 ± 0.003 seconds.

Trajectory Accuracy during Head Movement

Real-Track was used to control the robot's position during the pitch, roll, and yaw head motions (Surgical Video). The head velocity across the motions was 6.647 ± 2.360 cm/s. The robot was able to maintain a mean TE of 0.147° ± 0.075° during the pitch motion (Figure 4A), 0.160° ± 0.125° during the roll motion (Figure 4B), and 0.141° ± 0.077° during the yaw motion (Figure 4C). The mean SRE across motions was 0.588 ± 0.105 mm (Figure 4A-4C). The robot was able to maintain submillimetric TE (Figure 4D) and SRE (Figure 4E) across velocities, reaching 13.057 cm/s.

Robotic-Assisted Catheter Placement Accuracy

The robot guided the placement of catheters in 6 intracranial targets in each of the specimens (Figure 5A; Supplementary Figure 2A, http://links.lww.com/ONS/A621; **2B**, http://links.lww.com/ONS/A622; **2C**, http://links.lww.com/ONS/A623; and **2D**, http://links.lww.com/ONS/A624). Similar to the trajectory and motion experiments, the TE was determined for each placement, which was 0.112° ± 0.066° (99% CI = 0.068°, 0.155°). The TE error across the X and Y axes was uniform (Figure 5B). After the catheter was placed, the PE (ie, the user error) and TRE (ie, the system's accuracy) were determined (Figure 5C). The PE was 0.339 ± 0.179 mm (99% CI = 0.234, 0.444 mm) (Figure 5D), and the TRE was 0.848 ± 0.590 mm (99% CI = 0.502, 1.193 mm) (Figure 5E). The SRE was also calculated for each placement, which was 0.675 ± 0.096 mm (99% CI = 0.619, 0.731 mm; **Supplementary Table 2**, http://

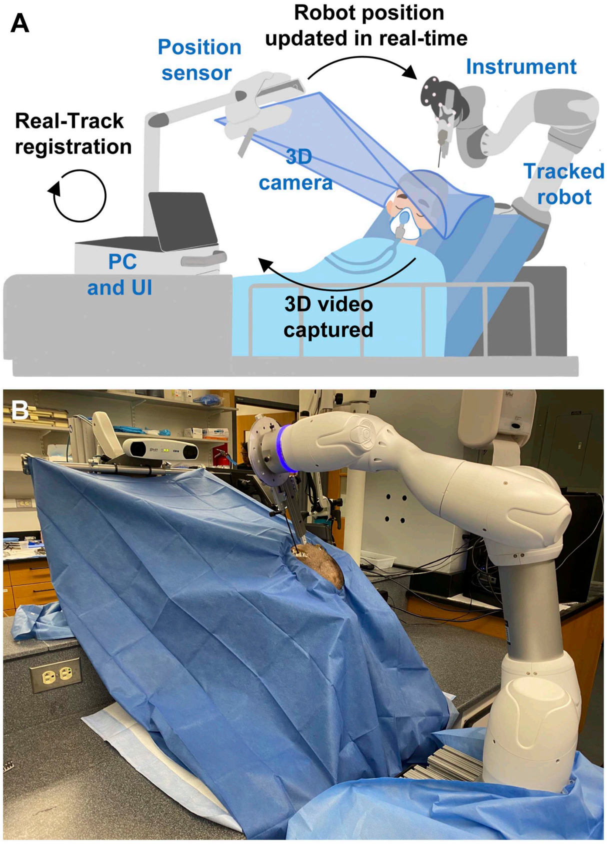

FIGURE 1. *Device overview and image.* **A**, *Diagram showing the device's workflow. The device captures a 3D video of the patient's face using a 3D camera, which is relayed to the PC. Onboard of the PC, the device registers the 3D video's frame with the surface of the CT scan using Real-Track, which may be visualized alongside preplanned intracranial targets on the device's user interface. This registration is used to update the robot's position to be aligned with the user's preselected intracranial target, by determining the robot's pose using a position sensor and updating it. This whole cycle is repeated at a rate of around 2 to 3 frames/s.* **B**, *Image of the robot and the rest of the device setup for the cadaveric procedure. 3D, 3-dimensional; CT, computed tomography.*

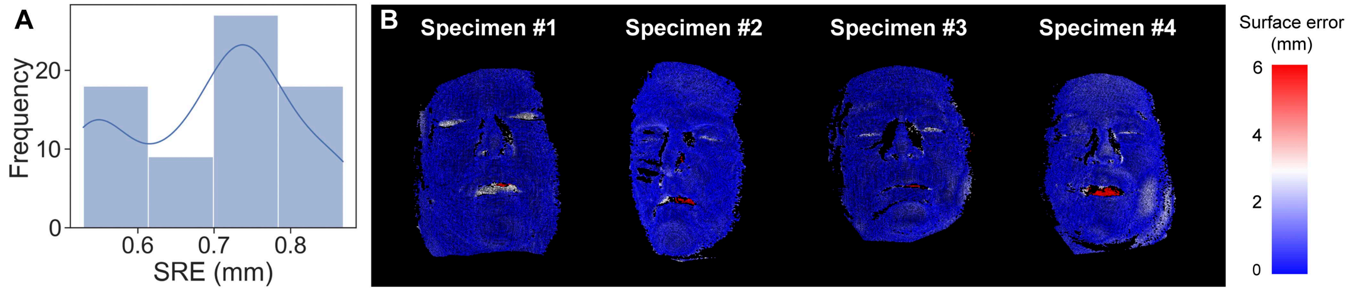

FIGURE 2. *Surface registration error.* **A**, *Distribution of SRE for 72 independent registrations.* **B**, *Heatmap displaying SRE for each facial point for each specimen. SRE, surface error.*

links.lww.com/ONS/A625). We analyzed the relationship between SRE and TRE and found no significant correlation, R^2 coefficient −0.186 (Figure 5F).

DISCUSSION

Accuracy and precision with minimal tolerance for error is a hallmark of neurological surgery, evident by the increased incorporation of stereotactic neuronavigation. The increasing use of neurosurgical robots can be attributed to their embodiment of these same principles.[13,14] In the OR, robots can perform exact movements to enact predetermined plans with a remarkable degree of safety, consistency, and accuracy. With hopes to expand robot use to nonfixed or mobile patients, we combined a computer vision–based, frameless neuronavigation technology with a robotic assistant. These characteristics subvert traditional barriers of prolonged and complex workflows, the need for rigidly affixed

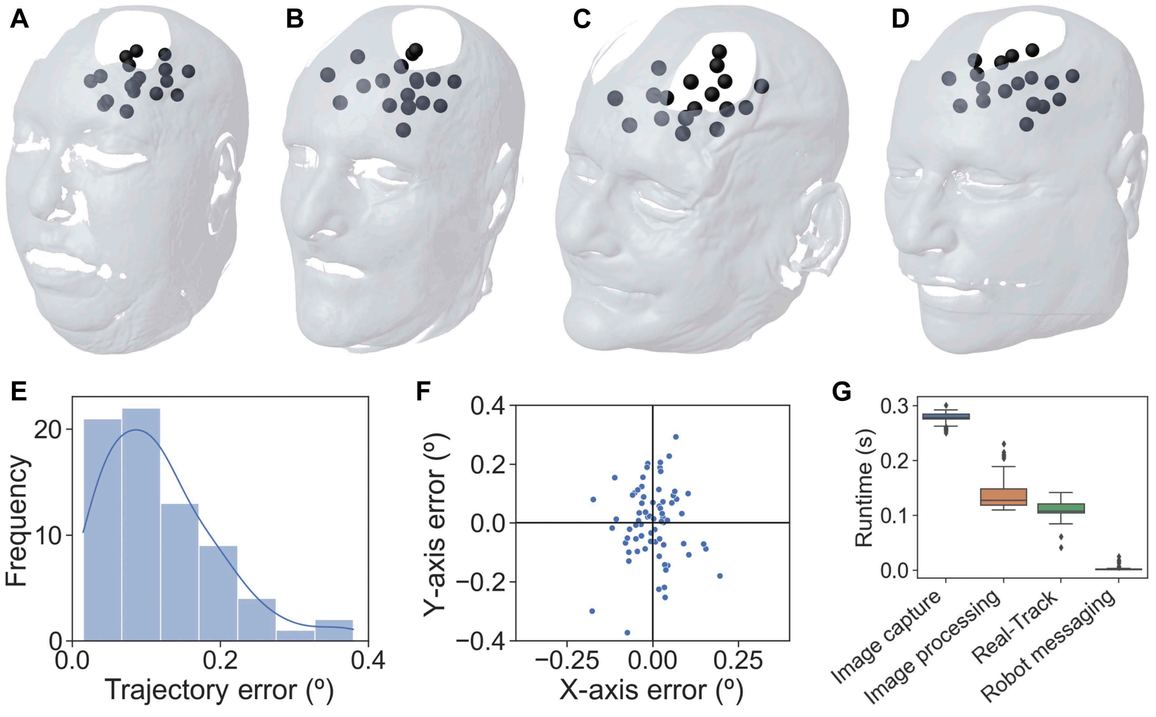

FIGURE 3. *TE and runtime. Surface of the computed tomography scan with the robot's 18 intracranial targets selected* **A**, *for specimen 1,* **B**, *specimen 2,* **C**, *specimen 3, and* **D**, *specimen 4.* **E**, *TE distribution for the robot's trajectories.* **F**, *TE for each placement broken down by X and Y axes.* **G**, *Computational runtime for the various processes controlling the robot. These images have been approved for publication by Science Care, who conducted the patient consent for image publication. TE, trajectory error.*

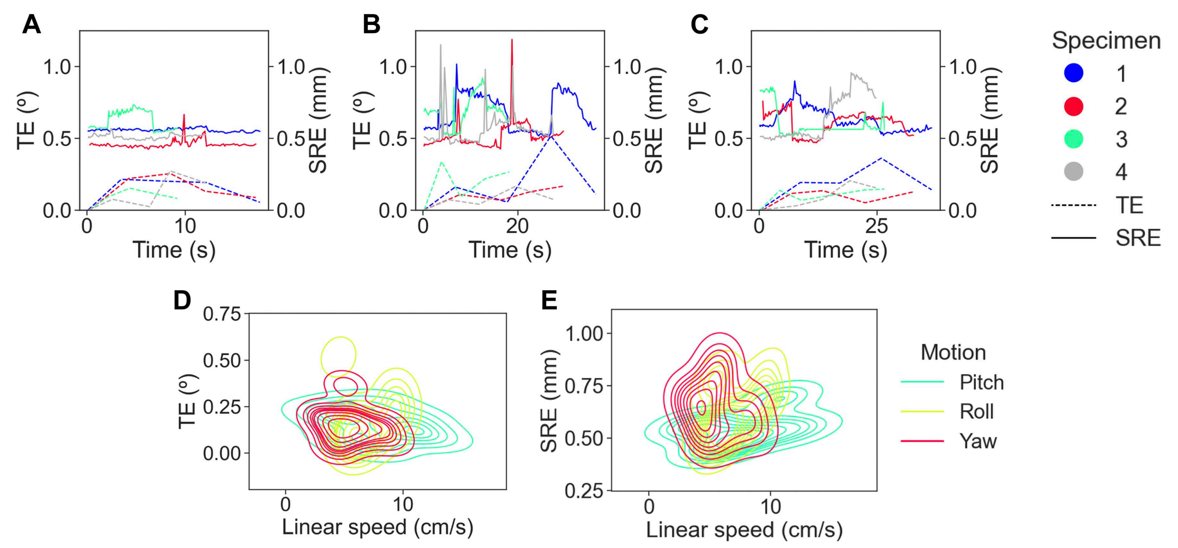

FIGURE 4. *TE and surface error during real-time robot control. TE and SRE for all specimens, during* **A**, *the pitch head motion,* **B**, *the roll head motion, and* **C**, *the yaw head motion.* **D**, *TE for all specimens relative to head velocity during the pitch, roll, and yaw and for* **E**, *SRE. SRE, surface error; TE, trajectory error.*

stereotactic frames, and neuronavigation error types IB and IIB.[15-17] We demonstrate the robot's ability to perform stereotactic catheter placements on moving subjects with submillimetric accuracy and a recalibration time of less than a quarter of 1 second.

The rapid initial registration proved accurate because of the 3D point cloud consisting of more than 2 000 000 points. For comparison, registration for BrainLab SoftTouch relies on 50 to 100 points manually selected by the operator and those are susceptible to error, differential area selection, and variation in skin deformation with pressure. This registration method is necessary in reducing time for setup, the algorithm's initial registration in 3 to 5 seconds, and recalibration time of 0.23 seconds with movement. This contrasts manual point selection registration which can take upward of 30 minutes.[18] Our method is similar to Flash registration by 7D surgical (nearly 1 million surface points for registration) as we collect 2 million surface points but is unique in that the patient does not need to be fixed in a frame.[19]

Furthermore, unlike precedent robotic frameless stereotaxy, this surgical robot automatically detects and adapts to changes in subject positioning in real time. The 3D video for Real-Track capturing more than 900 000 points every frame gives rise to the high-fidelity tracking. The ability to accommodate for patient motion and perform near instantaneous registration are unique features that improve safety and efficiency, opening myriad applications within and beyond the OR. Stereotactic procedures traditionally confined to the OR could be performed more safely and rapidly and in a wide variety of settings such as the emergency department, intensive care unit, or outpatient surgical center. Emergent lifesaving ventriculostomies, currently touting a 40% rate of catheter misplacement, could be confidently performed by an array of trained providers to achieve neurological stabilization and safe transfer to tertiary care centers. Robotic-assisted frameless neuronavigation could help reduce the rate of catheter misplacements toward 0.[20-23] Similarly, this system may create new opportunities for patients to benefit where we have failed, such as in the evacuation of intracranial hemorrhages, where rapidly deployable robotic guidance may help deliver improved outcomes.[24,25] Functional and oncologic neurosurgery are continuously evolving toward becoming less invasive and increasingly reliant on stereotaxis. Procedures such as deep brain stimulation, stereolectroencephalography lead placement, laser ablation, stereotactic biopsies, robotic-assisted neuroendoscopy, radiosurgery, or convection enhanced drug or viral delivery could be conducted more safely and economically outside of the OR under procedural sedation.[26] Currently, publications on patients undergoing frameless stereotactic biopsies using the iSYS1 robotized system had acceptable accuracy, but remain confined to the OR, and required Mayfield frame fixation to enable robot arm movement.[27] Truly becoming independent of the frame and being able to rapidly register and track is essential to improve efficiency and effectiveness of these cases.

The coupling of a surgical robot with "live" neuronavigation represents a synergistic combination of technologies that could change the immediate landscape of neurosurgical stereotaxy and the OR of the future. New technologies and innovations beget unimagined possibilities for improving patient care and outcomes. Advances such as the operating microscope, stereotactic surgical guidance, and endovascular treatments exemplify the benefits of

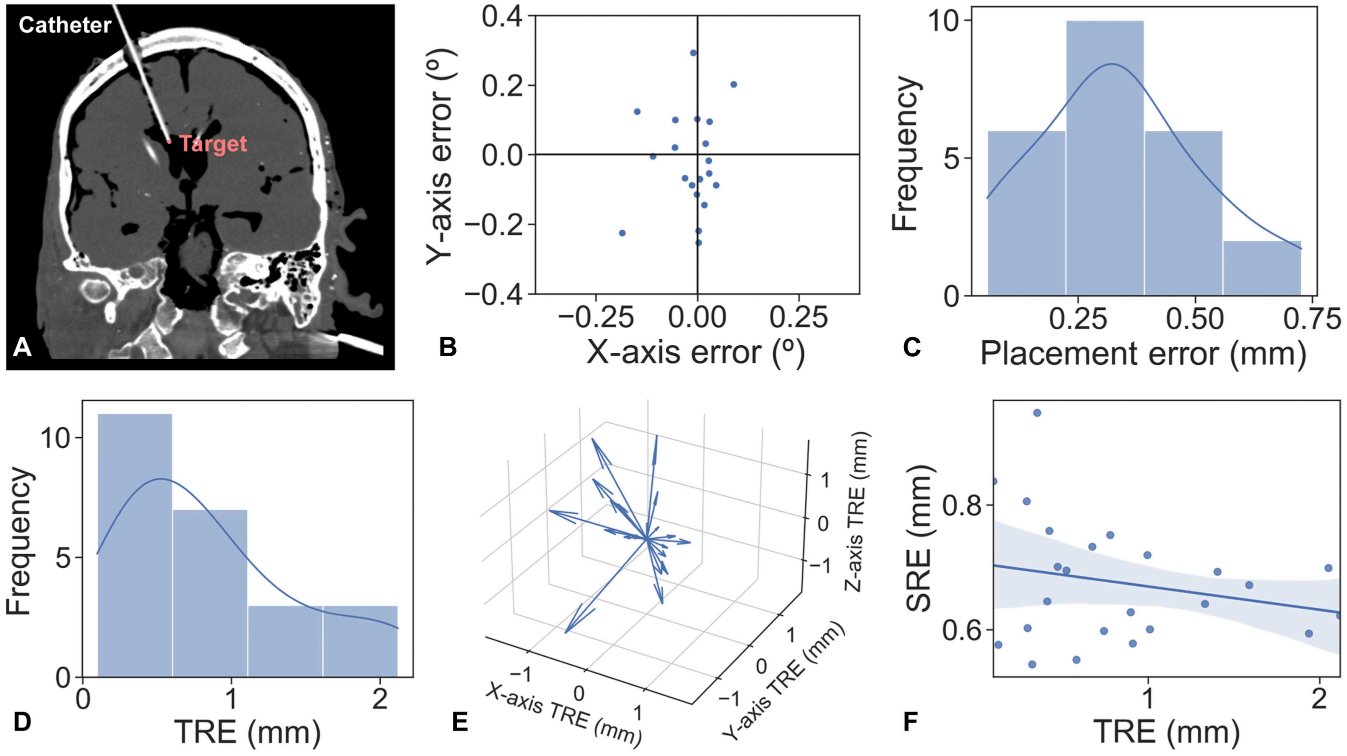

FIGURE 5. *Targeting error for the robotic-assisted catheter placements.* **A**, *CT image showing the catheter and target location. TRE is defined as the distance between the catheter's tip as seen on the CT scan and the location of the catheter's tip as determined by the device.* **B**, *Trajectory error for each placement broken down by X and Y axes.* **C**, *Placement error distribution for each placement.* **D**, *TRE distribution for each placement.* **E**, *TRE for each placement broken down by X, Y, and Z axes.* **F**, *Relationship between TRE and SRE. CT, computed tomography; SRE, surface error; TRE, target registration error.*

such evolving change. Neurosurgical innovation is occurring at an unprecedented rate. As neurosurgical procedures become less invasive and rely increasingly on stereotaxy, technologies such as this will lead the way in enabling patients to safely and consistently achieve the care that they deserve.

Limitations

Although this study demonstrates high accuracy for a novel neuronavigation robotic system with multiple positive implications, the study limitations warrant further discussion. The current registration algorithm does not specifically account for facial deformations that may occur between the time of CT acquisition and 3D image registration. However, in prior experiments, the artificial intelligence algorithm's capacity to trim low similarity areas seems to resolve these circumstances, without introducing significant error.[28] In addition, the robot's recalibration latency could be improved through several algorithmic optimizations and by combining it with a secondary sensor with highly localized but near-instantaneous capabilities, such as a torque sensor or gyroscope placed directly on the patient. Finally, this is a cadaveric study, and reproduction of these results in patients under standard clinical conditions will inevitably introduce additional variables and challenges.

CONCLUSION

Here, we present a stereotactic-guided surgical robot capable of intervening on nonimmobilized patients. The device is powered by an artificial intelligence-based registration system that rapidly recalibrates the robot's position to provide "live" tracking. This technology could enable the use of exact stereotactic robotic assistance in new clinical setting and drastically improve workflows, opening avenues for expanding future surgical interventions.

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Disclosures

Dr Sha, Mr Amich, Mr Lal, and Mr Lee are employed by Zeta Surgical Inc. Dr Robertson and Dr Gormley are advisors to Zeta Surgical Inc. with stock ownership. Zeta Surgical members underwent Harvard-administered CITI training prior to this study to facilitate Good Clinical Practice.

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Supplementary Figure 1. Position of the robotic-assisted catheter placement targets. Surface of the CT scan with the robot's 6 intracranial placement targets selected **A** for specimen 1, **B** specimen 2, **C** specimen 3, and **D** specimen 4.

Supplementary Figure 2. Postoperative CT scans for the robotic-assisted catheter placement. CTs resliced to show the catheter position and its intracranial target, with the TRE shown in each panel **A** for specimen 1, **B** specimen 2, **C** specimen 3, and **D** specimen 4. These images have been approved for publication by Science Care, who conducted the patient consent for image publication.

Supplementary Table 1. Trajectory error and surface error for the robot trajectories. TE is shown for the X and Y axes and its absolute value (all in degree). SRE is also reported for each trajectory (in mm).

Supplementary Table 2. Placement error, target registration error, and surface error for the robotic-assisted catheter placements (in mm).

VIDEO. Real-time robot control during head motion. The robot uses the Real-Track registration system to adjust its position during head movement to stay aligned with its predefined trajectory. This video shows the robot correcting for roll, pitch, and yaw motions using a phantom model. Throughout the video, the left panels show the 3D video captured by the 3D camera as a point cloud in light gray and the CT's surface in orange, which are coregistered using Real-Track in real time. The right panels show the robotic arm and tracked end effector being controlled by Real-Track to adjust their position during the head motions.

COMMENTS

The authors describe a robot capable of adjusting to real-time environmental changes, specifically motion. Given the data presented in this cadaveric study, this technology appears applicable to present-day challenges. They describe their innovation, a frameless, high-fidelity, robotic navigation system with automatic detection and adaptation. The system's patient tracking is described as instantaneous and highly accurate with mean movement command latency in the order of milliseconds and submillimeter accuracy. The system uses artificial intelligence to reconstruct and track moving anatomical targets from computed-tomographic images, and parallel structured light that can capture, recognize, and localize 3D objects in motion are used to track unfixed patients' targets.

The exceptional accuracy levels reported in this manuscript could herald potentially the end of catheter misplacements and other error-prone procedural complications in neurosurgery. Combining a frameless setup and real-time patient tracking truly makes this technology ideal for widespread adoption, and possibilities appear to abound. The success and adoption of this frameless computer navigation system are intricately linked with the results of future in-human feasibility studies and possible further miniaturization. In addition, it will be exciting to see how the system integrates with or modifies the operating room workflow and setup in live patient cases.

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I commend the authors for this technological tour de force; however, I do not see how their invention overcomes the various impediments to wider adoption of robotics in Neurosurgery- their stated goal.

1. The device is bulky, and so cannot integrate seamlessly into standard Neurosurgical practice.
2. Aside from frame-less Stereotactic Radiosurgery (which already has the CyberKnife^{TM}) when else does one require sub-millimetric accuracy on a patient who might move? EVD placements? Deep Brain Stimulation?
3. The authors compare the accuracy of their robot to that of commercially available navigation systems, but those systems are not designed for that level of accuracy and need not be.
4. This technology does not address the major issues of cost and time. Robots widely are used for stereotactic EEG and pedicle screw placements because they increase the accuracy and reduce the time required to perform these multi-trajectory procedures. But for procedures that entail just one or two trajectories and for which there are perfectly acceptable and much less expensive technologies available (stereotactic headframes, the Ghajar Guide, Neuronavigation), this device provides no real advantages and will drive up costs considerably.

In my view, robots will have to be much smaller, cheaper and easier to use before they replace the technologies that already exist for performing these latter sorts of procedures. Nevertheless, this is an impressive engineering feat.

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