Robotic external ventricular drain placement for acute neurosurgical care in low-resource settings: feasibility considerations and a prototype design

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OBJECTIVE Emergency neurosurgical care in lower-middle-income countries faces pronounced shortages in neurosurgical personnel and infrastructure. In instances of traumatic brain injury (TBI), hydrocephalus, and subarachnoid hemorrhage, the timely placement of external ventricular drains (EVDs) strongly dictates prognosis and can provide necessary stabilization before transfer to a higher-level center of care that has access to neurosurgery. Accordingly, the authors have developed an inexpensive and portable robotic navigation tool to allow surgeons who do not have explicit neurosurgical training to place EVDs. In this article, the authors aimed to highlight income disparities in neurosurgical care, evaluate access to CT imaging around the world, and introduce a novel, inexpensive robotic navigation tool for EVD placement.

METHODS By combining the worldwide distribution of neurosurgeons, CT scanners, and gross domestic product with the incidence of TBI, meningitis, and hydrocephalus, the authors identified regions and countries where development of an inexpensive, passive robotic navigation system would be most beneficial and feasible. A prototype of the robotic navigation system was constructed using encoders, 3D-printed components, machined parts, and a printed circuit board.

RESULTS Global analysis showed Montenegro, Antigua and Barbuda, and Seychelles to be primary candidates for implementation and feasibility testing of the novel robotic navigation system. To validate the feasibility of the system for further development, its performance was analyzed through an accuracy study resulting in accuracy and repeatability within 1.53 ± 2.50 mm (mean $\pm 2 \times$ SD, 95% CI).

CONCLUSIONS By considering regions of the world that have a shortage of neurosurgeons and a high incidence of EVD placement, the authors were able to provide an analysis of where to prioritize the development of a robotic navigation system. Subsequently, a proof-of-principle prototype has been provided, with sufficient accuracy to target the ventricles for EVD placement.

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KEYWORDS neurosurgical navigation; global health; inexpensive robot; external ventricular drain; traumatic brain injury; hydrocephalus

EXTERNAL ventricular drains (EVDs) can provide lifesaving stabilization in patients with acute brain injury, including traumatic brain injury (TBI), acute hydrocephalus, and intracranial hemorrhage.¹ EVDs allow for the measurement and management of increased intracranial pressure (ICP) caused by obstruction of CSF outflow. Additionally, EVD placement is indicated for temporary diversion of CSF, such as in acute hydrocephalus, when a permanent shunt cannot yet be placed; in the case

of an infected preexisting shunt; or in meningitis, when repeated lumbar punctures do not provide adequate relief. EVDs can also be used for intrathecal medication administration.²

In many conditions, placement of an EVD is a time-critical and necessary procedure. In TBI, EVDs drain CSF and any ventricular hemorrhage to lower ICP promptly and, later, serve as monitors of ICP, guiding future medical therapy.³ TBI affects up to 69 million individuals world-

ABBREVIATIONS EVD = external ventricular drain; GDP = gross domestic product; HIC = high-income country; ICP = intracranial pressure; LMIC = lower-middle-income country; ROS = Robot Operating System; TBI = traumatic brain injury.

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wide every year with mild, moderate, and severe degrees of severity.⁴ An estimated 1.6 million cases of TBI that require neurosurgery occur in high-income countries (HICs) per year, whereas an estimated 4.5 million cases occur in lower-middle-income countries (LMICs) per year.⁵

EVDs also provide benefits in the treatment of acute hydrocephalus. There are approximately 30,000 cases of hydrocephalus requiring neurosurgery in HICs and 740,000 cases in LMICs per year.⁵ In LMICs, EVDs are commonly placed for acute hydrocephalus secondary to CNS infections, which has repeatedly shown benefits.^{6–9} In infants, the most common cause of acquired hydrocephalus is intraventricular hemorrhage, and studies have shown that early intervention (at the age of 25 days or younger) with an EVD leads to better neurological outcomes.^{10,11} Improvements in cognitive, communicative, and social functioning have demonstrated that the timeliness of EVD placement can have a profound effect on outcomes.^{10,11}

Accompanying the global need for timely EVD placement is a shortage of neurosurgeons. In the United States alone, there is approximately 1 neurosurgeon per 61,000 people; however, in 44 states, there are fewer than 2 neurosurgeons per 100,000 people.¹² Additionally, in the United States there is not only a shortage of neurosurgeons, but also a predicted overall shortage of 130,600 physicians by 2025. In LMICs, the shortage of physicians and surgical care is exacerbated by increased delays in seeking, reaching, and receiving care. In these regions, there are deficiencies in access to neurosurgical care. For example, in sub-Saharan Africa, there is 1 neurosurgeon for every 3.1 to 6.4 million people.¹³ Studies have shown that only 11.8% of necessary neurosurgical care is met in LMICs.¹⁴

There are limitations in access not only to neurosurgeons but also to CT scanners in many parts of the world. In sub-Saharan Africa, only 20.3% of the population lives within 2 hours of a facility that has both a CT scanner and a neurosurgeon.¹³ In East Asia and the Pacific, this percentage decreases to 17.4%.¹³ Studies have shown that in LMICs, there is 1 CT scanner per 227,000 people, and in low-income countries, there is 1 per 1,694,000 people. This ratio differs drastically from HICs, where there is 1 per 25,000 people.¹⁵ CT scans are essential for quickly identifying the need for acute neurosurgical intervention and providing visual guidance for operations. Although placement of EVDs is often performed using a blind freehand technique, rates of misplacement are high at 20% to 40%, and incorporation of neurosurgical navigation techniques, such as CT or ultrasound guidance, can significantly increase the accuracy of EVD placement accuracy.^{16,17} Additionally, the development of robotic surgical devices has been shown to increase the accuracy of certain procedures, such as ventricular shunt placements. Lollis and Roberts demonstrated successful robotic placement of ventriculostomy catheters using preoperative imaging to plan the optimal catheter trajectory for placement.¹⁸ Robotic placement offers a unique opportunity for making EVD placement more widely available, especially in regions with limited access to a neurosurgeon. However, to allow surgeons without neurosurgical training to place EVDs, additional techniques and technology would have to be incorporated, which may rely on access to CT imaging.

In this article, we aim to highlight disparities in neurosurgical care, evaluate access to CT imaging around the world, and introduce a novel, inexpensive robotic navigation tool that has the potential to provide acute, lifesaving procedures in these underserved areas.

Methods

Heat Map

To visualize the regions in the world where a device would most benefit global neurosurgery assistive care, we compared the reported geographic concentration of neurosurgeons, CT scanners, incidence rates of indications for EVDs, and gross domestic product (GDP) on a heat map using the *rworldmap* package in R (The R Project).¹⁹

To build a heat map that superimposes the geographic concentrations of neurosurgeons, CT scanners, incidence rates of TBI-related death, meningitis, and pediatric congenital hydrocephalus, we extracted statistics from previous studies.^{20–24} Data regarding the number of neurosurgeons per country were obtained from the 2016 World Neurosurgery Workforce data published by the World Federation of Neurosurgical Societies.²⁴ The GDP of countries was also taken into consideration, as this neurosurgical navigation technology aims to provide relief to countries that cannot afford to make improvements to their neurosurgical infrastructure.²⁵ The data from these sources were aggregated, and any country without a metric in the listed sources was excluded from further analysis.

The databases were aggregated, and the minimum and maximum statistics were scaled from 0 to 1. Because this study aimed to implement an image-based neurosurgical navigation system for areas with low neurosurgical resources, despite the high incidence of EVD-indicating disease, areas dense in CT scanners and disease indications, and sparse in access to neurosurgery were compared.

Indication Metric Equation

One of the critical challenges in this study was developing a unified metric for the indication of the robotic navigation strategy incorporating CT availability, access to neurosurgeons, and medical indications for EVD placement. First, a weighted score was constructed for aggregating EVD indications based on the frequency of etiologies reported for EVD placement, labeled $\text{Place}_{\text{score}}$.²⁶ $\text{Place}_{\text{score}} = (w_1 \times \text{Meningitis}) + (w_2 \times \text{Congenital Hydrocephalus}) + (w_3 \times \text{TBI})$. Subsequently, $\text{Place}_{\text{score}}$ was combined with the weighted importance of each of the other 3 features in the model, including the GDP of the country, inverse availability of neurosurgeons (N'), and availability of CT scanners providing the indication for our system, labeled $\text{Ind}_{\text{metric}}$: $\text{Ind}_{\text{metric}} = (w_4 \times \text{GDP}) + (w_5 \times N') + (w_6 \times \text{Place}_{\text{score}}) + (w_7 \times \text{CT})$.

The weights (w_4 – w_7) were selected based on the relative incidence of the feature in describing the target population, encompassing 60% of the total weight for the unified metric (16% CT availability, 42% lack of neurosurgery, and 42% low GDP). Countries with no CT scanners were weighted substantially lower than countries with few scanners. The indications for EVD accounted for the remaining 40% of the model weight (84% for TBI, 7% for

meningitis, and 8% for hydrocephalus). These values were selected based on the relative usage of EVDs in the United States, providing a rough metric for how often EVDs would be used for certain conditions in other parts of the world.²⁶

Need Metric

To consider where robotic navigation is most urgently needed, we altered the metric by setting the weight of CT and GDP to null. While CT scans are important for the implementation of our device, the need for navigation is dependent on the concentration of neurosurgeons and the incidence of indications for EVD placement. In future technologies, overcoming the need for CT scanners to truly overcome the full breadth of need may be explored. For this reason, we made an important distinction between the need for robotic navigation and the indications for our specific device.

Robotic Implementation

With the described limitations in neurosurgeon availability and the minimal necessary presence of CT imaging in LMICs, a cost-effective, passive navigation robot was designed to allow surgeons who are not trained in neurosurgery to place emergency EVDs in patients with acute or congenital hydrocephalus (Fig. 1A). The navigation system has 4 degrees of freedom from four 14-bit rotary encoders with an angular resolution of 0.022° (CUI AMT22 Series). Mating adapters were designed with Fusion 360 (Autodesk) and 3D printed in polylactic acid with an Ender 5 3D printer (Creality). The adapters are connected to each encoder with supporting ball bearings and combined with machined aluminum rods to form the mechanical links between each robot joint. The robot base includes a stainless-steel bolt running through the bore of the base encoder that is used to securely attach the navigation system to the patient's skull.

The electrical components in the navigation system are based on a Raspberry Pi 0 WF microcontroller (Raspberry Pi Foundation) integrating the 4 rotary encoders connected by a custom-printed circuit board. The circuit board was designed in EasyEDA (EasyEDA), as shown in Fig. 2, and manufactured using the toner transfer method.²⁷ Headers for the encoder pins were soldered to the circuit board, and a wiring harness was fabricated from 28-gauge copper wire with standard terminals to connect the encoders, circuit board, and microcontroller general-purpose input/output (GPIO) header.

During the operation, the microcontroller reads encoder positions and continuously sends the values over a wireless transmission control protocol/internet protocol (TCP/IP) connection to a separate laptop computer with the Ubuntu version 20.04 (Canonical Ltd.) operating system. The laptop coordinates robotic functions through the Robot Operating System (ROS) Noetic (Open Robotics), which wraps custom Python 3.8 (Python Software Foundation) scripts, enabling real-time surgical navigation for EVD placement. These functions include managing patient imaging, instructions for clinical setup, and a real-time navigation display for use during the procedure (Fig.

FIG. 1. Navigation concept. **A:** Prototype of the robotic navigation system with wiring harness removed for visibility. **B:** ROS-generated user interface for the robotic navigation system when attached and registered to a segmented head-neck CT.

1B). All software used is obtained from open-source packages to facilitate use in low-resource settings.

With trajectory-based navigation systems, accuracy and repeatability are critical to safe and effective operation. To verify the initial robot performance, an accuracy and repeatability assessment of the end-effector position was performed (the end effector is the interactive device at the end of the robotic arm). The robot base was rigidly fixed to a precision optical breadboard (MB4545/M, Thorlabs) with five 3D-printed calibration standoffs designed to determine the zero position of all encoders (Fig. 3A). Once calibrated, six 3D-printed targets were placed at varying distances from the base of the robot (Fig. 3B). These targets were designed to rigidly mate with the robot end effector and, when placed at known positions on the breadboard, served as ground truth positions for measuring robot accuracy. For each of these targets, the robot was moved from an arbitrary pose to the target, and the robot Cartesian coordinates were recorded. This was repeated a total of 5 times at each of the 6 targets, yielding 30 separate measurements. The difference in the Cartesian position was calculated from the observed robot measurements and expected ground truth positions. The resulting accuracy in each Cartesian direction (X, Y, Z) was calculated as the average error in the given direction with repeatability calculated as the 95% CI (i.e., mean $\pm$ 2 $\times$ SD). The overall system accuracy was calculated as the average Euclidean distance error between the measured and expected robot positions, and the repeatability was calculated as the 95% CI.

Results

Heat Map Results

Our query of the aforementioned databases yielded unified results usable for 169 countries. The top 25 countries indicated for general improvement in neurosurgical access to care (Table 1 and Fig. 4) is a ranking that considers the national numbers of neurosurgeons and the incidence of

FIG. 2. Custom-printed circuit board wiring diagram. **A:** Pin-out wiring diagram with expansion port for a fifth encoder. **B:** The printed circuit board layout, which was printed using the toner transfer method.

the aforementioned indications for EVD placement. The top 25 countries indicated for the specific robotic navigation (Table 1 and Fig. 5) is a ranking that considers the national numbers of neurosurgeons, CT scanners, GDP,

and incidence of the aforementioned indications for EVD placement. We believe that this indication metric highlights environments with the capital and infrastructure to support a demonstrated need for the development of robotic navigation; the top 3 countries are Montenegro, Antigua and Barbuda, and Seychelles. Table 1 additionally demonstrates a ranking of countries based on the need metric. This need metric summarizes the general need for neurosurgical development regarding the placement of EVDs.

Robotic Navigation Results

The Cartesian position accuracy (X, Y, and Z translation) and overall accuracy of the robot were measured using the optical breadboard accuracy measurement system. The overall navigation system position accuracy was 1.53 ± 2.50 mm (95% CI). The position accuracy in X was -0.21 ± 2.04 mm (95% CI). The position accuracy in Y was 0.12 ± 1.43 mm (95% CI). The position accuracy in Z was -0.71 ± 2.78 mm (95% CI). These results are visualized in Fig. 6.

Discussion

The model used to generate the Fig. 4 heat map was designed as a minimum metric necessary to observe the need for improved access to neurosurgical care globally, and to serve as a control for the model used to generate the Fig. 5 heat map, which was designed to compare indications and prevalence of care as they relate to the robotic navigation system proposed here. This device would be

FIG. 3. Optical breadboard test setup. **A:** Calibration tool that uses the optical breadboard for setting “zero” positions of the 4 encoders. **B:** Optical breadboard targets for robotic repeatability and accuracy testing.

TABLE 1. Indications for improved access to neurosurgical care and navigated EVD placement, by country

Rank	Top 25 Countries Indicated for Neurosurgical Development	Top 25 Countries Indicated for Navigated EVD Placement
1	Montenegro	Montenegro
2	Equatorial Guinea	Antigua & Barbuda
3	The Bahamas	Seychelles
4	Suriname	The Bahamas
5	Trinidad & Tobago	Saint Vincent & the Grenadines
6	Saint Vincent & the Grenadines	Trinidad & Tobago
7	Saint Lucia	Saint Lucia
8	Antigua and Barbuda	Ireland
9	Lesotho	Suriname
10	Barbados	Bahrain
11	Comoros	Malta
12	Bahrain	Barbados
13	Seychelles	Mauritius
14	Sierra Leone	American Samoa
15	Mauritius	Samoa
16	American Samoa	Slovenia
17	Liberia	Czechia
18	Malta	Slovakia
19	Ireland	Bulgaria
20	Solomon Islands	Equatorial Guinea
21	Samoa	Poland
22	Syrian Arab Republic	Lesotho
23	Slovenia	Comoros
24	Czechia	Bosnia & Herzegovina
25	Slovakia	Sierra Leone

best utilized in a region with CT availability, a lack of neurosurgical care, and prevalent indications for placing an EVD. Countries with a lower GDP were also selected for, as we anticipated they would have a slower increase in access to care and, therefore, would benefit from a technology like this navigation system for a longer period of time.

While none of the countries are a perfect match for our device in all described metrics, some come close. Montenegro, for example, was shown to have a fairly developed medical system with many CT scanners; however, the country was in the lowest bracket for the number of neurosurgeons, despite moderate indications for EVDs. Montenegro, therefore, would be a country that could benefit from the implementation of this navigation system for lifesaving EVD indications, along with several other countries highlighted by our heat map.

This analysis demonstrates the paucity of CT scanners in areas where the indications for EVDs are high. Additionally, even in low-income countries, the presence of CT scanners is more likely to be in higher-income areas.^{14,28} Given the current necessity of CT in ascertaining the reference image for navigating the robot, this analysis demonstrates a critical limitation and restriction of implementation, which can be extrapolated to any navigation assistance technology for EVD placement.

With sufficient availability of the necessary CT scanners, lack of neurosurgical care, and a high incidence of acute TBI, there is an evidenced need for assistive technology to enable lifesaving treatment in these regions. To meet this demand, the presented navigation system was designed with a clinical workflow, which is an adaptation of the current standard of care (Fig. 7).^{29–31} This procedure begins with a preoperative CT scan that is subsequently segmented using the open-source 3D Slicer program (3D Slicer, slicer.org) to identify the skull for robot CT

FIG. 4. Heat map showing countries with a need for neurosurgeons and indications for EVD. By combining worldwide distributions of neurosurgeons and the incidence of TBI, meningitis, and hydrocephalus, this map indicates where the need for a robotic navigation system is highest, with 0 indicating low need and 1 indicating high need. Made in R using the rworldmap package.¹⁹

FIG. 5. Heat map showing indications for device trials by weighting the density of neurosurgeons, CT scanners, GDP, and the incidence of TBI-related death, meningitis, and pediatric congenital hydrocephalus. Scores range from 0 to 1, relating minor to major benefit of device trials by country. Made in R using the *rworldmap* package.¹⁹

registration and the ventricles for generating target trajectory. The surgeon then places a burr hole at Kocher's point (10–12 cm posterior to the eye and 2–3 cm lateral from the midline) where the robot attaches, using the integrated bone screw (Fig. 1A). After securely attaching the robot to the patient, a rigid registration is performed in the custom software to relate the robot and preoperative CT coordinate spaces. Once registration is complete, the user interface displays the real-time position of the robot and attached EVD, providing a continuous view of the trajectory of the EVD relative to the segmented ventricles for surgical guidance. Following the workflow, the patient will be monitored and ideally transferred to a care team that can better manage their primary neurological condition.

FIG. 6. Boxplots showing overall robotic accuracy for 30 samples with Cartesian (X, Y, and Z) coordinate accuracy for comparison.

The initial accuracy and repeatability measurements collected from the robot suggest that a low-cost approach to robotic neurosurgery is feasible. A previous study found that the average atrial diameter of fetal lateral ventricles is 7.6 mm and the ventricle size will only increase with age.³² With an overall navigation system accuracy of 1.53 ± 2.50 mm (95% CI), it will be capable of successfully guiding EVD placement, even in challenging pediatric lateral ventricles as in the case of congenital hydrocephalus. One limitation in the application of the robot is the current need for bone screws in the skull, which would render this more difficult for use in infants. Berry et al. reported depressed cranial fractures, epidural and subdural hematomas, and CSF leakage as potential complications with use in children younger than 10 years.^{33,34} To avoid undue risk, the current robotic implementation would be used in patients 10 years or older, and investigation into the use of an alternative fixation method will be required to use this technology in younger patients.

With an accurate low-cost robot that is easily modified due to its simple mechanical design and open-source software, applications can be readily expanded to include other navigation-based procedures. For example, navigation is useful for accessing lesions or cysts that reside deeper in the brain, as superficial landmarks may not be as accurate in these cases.³⁵ It may also be helpful in deep brain stimulation surgeries for certain neurological disorders, such as Parkinson's disease, dystonia, chronic pain, and seizure disorder diagnosis with stereoelectroencephalography, where imaging is required to determine the target locations for electrode lead placement.^{36,37} Accurate, low-cost robots also may be useful in placing other types of CSF shunts, such as ventriculoperitoneal and ventriculosubgaleal shunts, and ventricular access devices.³⁸ Expanding beyond neurosurgery, the passive navigation robot could be used for procedures such as percutaneous biopsies of

FIG. 7. Workflow comparison between standard-of-care EVD placement and the proposed navigation device–assisted EVD placement.

deep structures (e.g., lungs, kidney, or liver), placing pedicle screws for spine surgery, or even as a surgical training device to provide continuous trajectory feedback for novice surgeons.

Limitations of the Heat Map

In total, 169 countries were included in the heat map. The countries that were not represented in the data are represented in gray on the heat map. Additionally, although the relative weights for each component of Ind_{metric} were selected a priori, the rationale for the values for lack of access to neurosurgery, availability of CT, GDP, and the combined indications for EVD placement were dependent on subjective factors based on discussion of the device with the design and implementation team. This creates the possibility for bias in the feasibility analysis.

Limitations of the Robotic Navigation System

The navigation system was limited by several factors: the accuracy of the encoders, the rigidity of the 3D-printed parts, and the cost of the components. With the specifications of the encoders, it is theoretically estimated that the worst-case error is < 2.44 mm. If the parts were machined or cast instead of 3D printed, they could be made far more rigid, leading to further reductions in the observed errors associated with flexion and tolerance issues inherent to 3D printing. Finally, the costs associated with this robot were intentionally minimized in order to make this technology more feasible to implement in low-resource environments. The prototype cost was \$249.46, including all electronics and raw materials and excluding any tools used in production as well as the Codman Bactiseal EVD (Integra LifeSciences) and optical breadboard pictured in Fig. 2. This cost could potentially be reduced further by manufacturing the system to scale.

Future Directions

While this study informs on the feasibility of robotics in EVD navigation globally, there are important obstacles to implementation of this navigation system. Despite verifying robot accuracy and demonstrating that it meets the standard of care for technology used in HICs, the system must be deployed in a representative clinical model to validate the clinical use. First, a cadaver study will assist with quantifying the efficacy and workflow of this prototype robot for navigation in humans. This cadaver study will use Thiel's embalming method with intracerebral, ventricular formalin-injected specimens, which has been shown to be effective for EVD simulation.³⁹ Following cadaveric testing, prototype design improvements, including minimization of external wiring, creation of a disposable sterile sleeve, a battery-powered wireless implementation, and others, will be made to finalize the minimum viable product.

Additional modalities may also be investigated for navigation and imaging, including electrode placement, brain biopsy, and other trajectory-based burr hole procedures. Military or emergency medical service trauma environments will additionally be explored. The use of CT is required; however, ongoing investigations of low-

cost, noninvasive lateral ventricular imaging may serve as a valuable addition to our proposed navigation system to provide reference imaging for EVD placement.^{40,41}

Conclusions

The lack of access to EVDs may preclude a patient to any type of care for the management of hydrocephalus. While lifesaving measures are performed in some circumstances by midlevel practitioners with similar success, a navigation system could substantially improve the confidence of the practitioner in high-stress situations.⁴² We sought to create a device that bridged an important skills-associated obstacle for emergency neurosurgery for those surgeons who are without explicit neurosurgical training. Using this device's user interface, a surgeon will have the tools and guidance to safely perform EVD placement. In this feasibility study, we find that implementing such a device is feasible and may be impactful to specific countries.

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Disclosures

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Supplemental Information

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