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Critical Review: “Robotics in Neurosurgery: Evolution, Current Challenges, and Compromises”

Project Summary

Tubular retraction is used in brain surgery as a method to create a corridor in brain tissue to the site of a lesion or, more generally, the point of interest in the surgery, where the surgeon can take a biopsy, resect part of a lesion, or perform a full resection. This approach is designed to be a less traumatic alternative to using traditional methods involving metal blade retractors which can cause increased brain shear. However, tubular retractors also have safety drawbacks in that they can be shaky during manual use, as they are generally unconstrained, or free floating. This shakiness can lead to excessive rubbing against brain tissue, causing damage, and an overall less comfortable and user-friendly experience for the surgeon, increasing the likelihood of adverse effects. The goal of this project is to enhance this technique in brain surgery through automating the tubular retractor. Individual goals include creating a stabilizing component for the tubular retractor, developing hardware that allows for two degrees of freedom in retractor movement, implementing a simple control method with a focus on good surgical usability, and, as a maximum, allowing automatic retractor alignment with surgical tools by retrofitting these tools with sensors.

Paper Selection

This paper was selected to serve as an introduction to the state of technological development in the neurosurgical robotics niche of medical engineering. The paper’s elaboration of current neurosurgical robot limitations can help determine what useful aspects are missing from manual neurosurgery but are difficult to accomplish using robots. In this regard, the project aims to bridge the gap between manual and robotic neurosurgery. The project’s specific methods and organization can be adjusted based on the findings of this paper.

Problem and Key Determinations

Though the first robot applied in surgery during the 1980s falls into the neurosurgical field, surgical robots are used less in neurosurgery than in other fields of medicine, such as “urology, gynecology, gastroenterology, and orthopedics” (Doulgeris, 1). Mechanical factors and human-robot interaction are the two main categories of problems that can cause difficulty in the integration of robots into the area of neurosurgery. Mechanical obstacles are most prominent in the areas of main interaction between the robot and surgeon. This can include tools available for use with the robot, constraints of using these tools caused by the surgical operating area, and the resulting degrees of freedom that culminates from these two factors, such as force (Doulgeris, 4-5). Human-robot interaction factors in through affecting feedback, conditions, and training for the surgeon. Haptics, robotic force sensing, proprioception, and visual cues all have limitations that contribute to surgeon awareness of the environment in which the operation is being performed. Conditions created by the robot can help improve the surgeon's experience through adapting to human error and enhancing basic human qualities such as "comfort, accuracy, stamina, and dexterity." Still, adoption of robotic techniques requires a learning curve, which must be fulfilled through training (Doulgeris, 5-7).

Significance

The article, through its analysis of modern neurosurgical robot benefits and drawbacks, highlights the ways in which current robotic systems are restricted from being adopted. Thus, though inexplicitly, it can be taken as a call for solutions involving automated neurosurgery. It is safe to assume because of this that, at least in the short term, a hybrid manual and mechatronic surgical solution, such as the expected end result of this project, could be useful. Additionally, the specific drawbacks this article highlights have a direct impact on the project's focuses and timeline priorities.

Background

To understand the importance of the highlighted details in this article, it is useful to know a brief history and current status of robots in the industry. The significance of the first ever neurosurgical robot in the field and deemed predecessor of surgical robots in general, called the PUMA 200, was its capability to deliver results with record speed by correctly placing a biopsy needle in the brain with the help of CT guidance (Doulgeris, 2-3). However, this robot was discontinued. The NeuroArm (Figure 1) is a particularly important current robot due to its capability to work inside of an MRI machine through telesurgery, or remote surgery. This robot was first used in 2008, and can perform "needle insertion, cutting, cauterization, and irrigation on a microscale..." (Doulgeris, 3). Though the NeuroArm is meant for procedures similar those relating to this project, there were no new plans for its commercialization after it was licensed to IMRIS Inc. (Johnson, 31), and thus the existence of this robot does not significantly reduce the importance of this project.

Other neurosurgical robots also exist, but while still relevant to this project, do not quite share enough similarities to render this project unfavorable to pursue. The Neuromate (Figure 2) and the Pathfinder (Figure 3) are both 6 degree of freedom stereotactic systems, attributes which give each system a significant advantage in capability (Doulgeris, 3). However, the Neuromate is used for “deep brain stimulation, endoscopy, and stereoencepha-lography, and…biopsies…”, functionalities which do not coincide with the scope of surgeries that this project intends to improve. There is not much current information on the Pathfinder so it is not as relevant. A robot that dominates the robotic surgery industry, Intuitive Surgical’s da Vinci Surgical System, has also been modified to allow for neurosurgical procedures. But while the da Vinci is esteemed in urology and even usable in a “supraorbital keyhole approach for skull base tumors and aneurysms,” its usefulness in brain surgery is limited due to “the limited tools available, the number of ports needed, and the manipulation room and size of the system [which] interfere with its integration into this field of neurosurgery” (Doulgeris, 3-4). Therefore, because current neurosurgical robots aren’t useful for the procedures in which tubular retractors would be used, the incentive for this project is still evident.

Author’s Work

The author’s main work involves an analysis of factors that affect the usability of and feasibility of robots in surgery which centers on mechanical factors and human-robot interaction. The author cites tools as an important mechanical factor; the most common surgical tools are rigid, and by nature depend on flexible mobility in space for six degrees of freedom. This is easy for a surgeon to accomplish, but robots are limited to moving these tools with straight-line trajectories and have less degrees of freedom because of this. Curved tools are a possible way around this, and also a way to avoid obstacles in the brain in general. However, though the location of the tip of these tools is relatively simple, the calculations for this are only accurate under the assumption that the tools will not bend – an assumption that cannot always be made. The additional sensing required to adjust for these errors largely complicates the process. Such tools can be made rigid with tension wires, but this can change the expected tool shape. Still, curved tools can have some usefulness in “suction, and in particular, brain tumor removal and biopsies” (Doulgeris, 4-5).

A big challenge that arises from the limitation of tools is fitting these tools into the workspace. Tools are largely limited because the lack of tool strength can complicate surgeries by increasing the difficulty of locating its tip from deforming the tool, and by affecting the type of required motion. A possible solution to this is to increase tool thickness and size, but this cannot be controlled much because it can cause the tools to be too large for the work area. The tool stiffness also limits the control over the force that is exerted on tissue. Force at which a motor can hold a tool can be increased through using brakes and through integrated more powerful motors, but the tool still acts as a bottleneck for force limitations (Doulgeris, 5).

A crucial aspect of less mechanically related factors is feedback in human-robot interaction. Feedback based on natural human senses, such as haptic and proprioception feedback, are especially important in a surgeon's awareness of how he is using the tool. Haptic feedback helps the surgeon feel how much force he is applying to tissue in the surgical field, which is especially important in neurosurgery, where large forces can be very harmful to nervous tissue. This perception is somewhat taken away in robotic surgery because long tools can "distort…tactile sensation." It can be mitigated through force sensing such as through strain gauges and optical measurements; however, strain gauges are difficult to sterilize, and optical measurements are undeveloped, making haptic feedback in manual surgery still better than during robotic. Proprioception helps the surgeon be aware of his limbs and body parts without seeing, which is almost a prerequisite to haptic feedback, but is limited as a surgeon is controlling tools through a robotic arm rather than his own limbs. This can be improved through training, but there is still a maximum to which this can help.

Visualization is a very important type of feedback that helps with haptics and proprioception, and overall success in surgery. This is especially prevalent in telesurgery, as other types of feedback are limited. Visualization in this case is often done through microscopes or endoscopes, the latter of which often includes stereoscopic cameras for 3D visualization. However, microscopic surgery can be limited because the microscope can obstruct the surgeon's view, and endoscopic cameras can be obstructed with the lens and with blood clouding. Augmented reality can help overcome this by visualizing obstructed structures. Other visualization techniques include the use of CT, MRI, useful in autonomous procedures as they require 3D workspace models, and fluoroscopy (Doulgeris, 6-7).

All of the mentioned feedback mechanisms are affected by the conditions they cause for the surgeon and the prior training that the surgeon has had the chance to undergo. Something like remote surgery can provide surgeon advantages in comfort, and the fact that the surgery is robotically assisted can help with accuracy, stamina, dexterity, and motion filtering. However, to take advantage of these benefits, the surgeon must go through training, which can be a challenge. The most effective type of training is on cadavers, but this is expensive. Virtual reality can be a way around this, but it is not as effective because there is no provided haptic feedback (Doulgeris, 6-7).

Assessment

This paper gives a high quality and well-structured overview of current robotic neurosurgery and helps form a broad opinion on the strengths and weaknesses of neurosurgical robots. The paper is written concisely and is easy to understand. The paper's scope is broad and touches on many important characteristics such as types of robotic tools, mechanical compromises, and drawbacks of human-robot interaction. However, the paper would have done well to more deeply elaborate about current robot applications with other examples of relevant procedures or conditions. Additionally, instead of, for the most part, just citing results of papers, it would have been useful to directly explain what kind of trials past studies have focused on. This was done to an extent, but in an overviewing fashion.

Relevance and Next Steps

The insight from this paper directly affects the team's maximum deliverables and priorities relating to force monitoring and tool usage. It is clear the team should prioritize monitoring and limiting force – tubular retractors can act as an obstruction, and it may limit haptic feedback of force applied on brain tissue on the other side of the retractor as the surgeon's tool will be pressing against a rigid wall rather than directly on brain tissue. As haptic feedback is a problem in robotic systems, overcoming this issue can serve well to improve the attractiveness of this project's solution. This is feasible as the solution can be regulated electromechanically. A possible mechanism for this is to allow the surgeon to gently push against the retractor wall to move it, instead of allowing motion strictly through remote input, such as buttons or coordinates. A mechanical boundary can be applied to velocity to resist strong forces when a surgeon pushes too quickly.

Since the paper highlights limitations of straight tools which are commonly used in brain surgery, it is important that this project does not pose its own such limitations. If such limitations are avoided, the value proposition of this project over robotic surgery is clearer. It is therefore important to test the usability of surgical tools that are integrated with this project's technology. This can be done by retrofitting surgical tools with sensors and testing them, rather than just testing automatic alignment functionality with a mock tool that doesn't hold any real surgical value. It would be useful to test a comprehensive variety of tools and to select most commonly used tools in tubular retraction.

Conclusions

It can be drawn from analyzing this article that current robots in neurosurgery are not developed enough to be used in a significant portion of surgeries. This suggests that the project will not be rendered useless; thus, this project has a clear purpose and is relevant to brain surgery. Insight from this paper helps direct the team to choosing priorities for maximum project deliverables. A crucial part of this is implementing force control and limiting. A less heavy but still important task is surgical instrument sensor integration.

Appendix

Figure 1: NeuroMate (Doulgeris, 3)

Figure 2: Neuroarm (Doulgeris, 3)

Figure 3: The Pathfinder (Deacon)

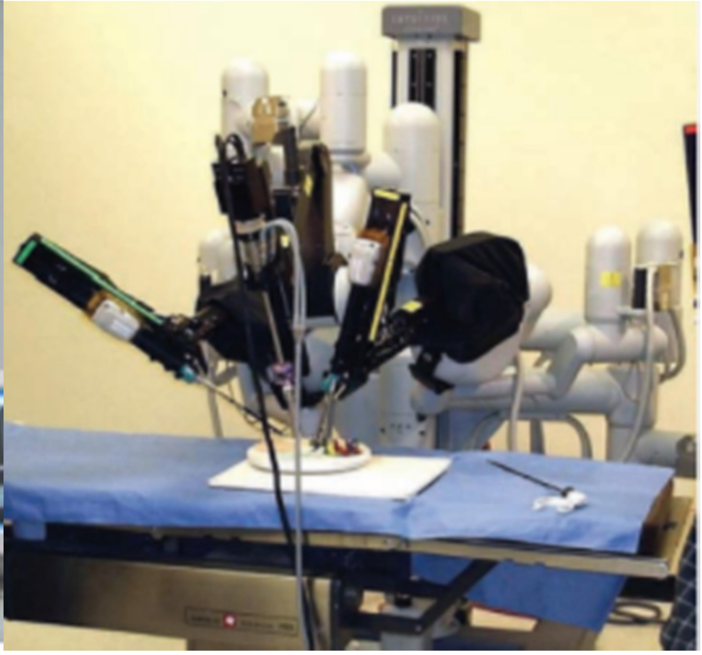

Figure 4: da Vinci Surgical System (Doulgeris, 4)

Works Cited

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