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Comparing Manual and Robotic-Assisted Carotid Artery Stenting Using Motion-Based Performance Metrics

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Abstract— **Carotid artery stenting (CAS) is a minimally invasive endovascular procedure used to treat carotid artery disease and is an alternative treatment option for carotid artery stenosis. Robotic assistance is becoming increasingly widespread in these procedures and can provide potential benefits over manual intervention, including decreasing peri- and post-operative risks associated with CAS. However, the benefits of robotic assistance in CAS procedures have not been quantitatively verified at the level of surgical tool motions. In this work, we compare manual and robot-assisted navigation in CAS procedures using performance metrics that reliably indicate surgical navigation proficiency. After extracting guidewire tip motion profiles from recorded procedure videos, we computed spectral arc length (SPARC), a frequency-domain metric of movement smoothness, average guidewire velocity, and amount of idle tool motion (idle time) for a set of CAS procedures performed on a commercial endovascular surgical simulator. We analyzed the metrics for two procedural steps that influence post-operative outcomes. Our results indicate that during advancement of the sheath to the distal common carotid artery, there are significant differences in SPARC ($F(1, 22.3) = 6.12$, $p = .021$) and idle time ($F(1, 22.6) = 6.26$, $p = .02$) between manual and robot-assisted navigation, as well as a general trend of lower SPARC, lower average velocity, and higher idle time values associated with robot-assisted navigation for both procedural steps. Our findings indicate that significant differences exist between manual and robot-assisted CAS procedures. These are quantitatively detectable at the granular-level of physical tool motion, improving the ability to evaluate robotic assistance as it grows in clinical use.**

I. INTRODUCTION

Carotid artery stenting (CAS) is a minimally-invasive endovascular technique and an alternative treatment option of carotid artery stenosis in select patient groups. Compared to open surgery, CAS procedures are associated with faster recovery without excessive hospitalization [1], [2], and when compared to carotid endarterectomy, it is associated with a lower rate of periprocedural death and myocardial infarction [3]. CAS procedures are performed using endovascular interventional tools, including catheters, sheaths, and guidewires, which are inserted via percutaneous access at the radial, brachial, or femoral artery [2]. During the procedure, the interventionalist uses a stent in the treated carotid artery and implants at the stenosed segment in order to restore normal blood flow to the brain and prevent stroke. Dilation of the vessel can be performed by inflating a balloon at the diseased segment [4]. Previous studies have described increased embolization with certain procedural steps of CAS, such as aortic arch navigation, common carotid artery navigation, lesion crossing and balloon angioplasty [5]. Eliminating the operator's natural hand movements with the use of robotic assistance may help to reduce this iatrogenic embolization.

Advances in robotic assistance have led to its adopted use in various surgical domains [6], [7]. For endovascular catheterization procedures, devices such as the Corpath GRX Vascular Robotic System (Corindus, Waltham MA, USA) can provide robotic assistance for interventions ranging from percutaneous coronary intervention procedures to pulmonary vein isolation. The Corpath GRX can provide robotic assistance in the form of improved control of surgical tools, increased precision when positioning stents, and clear visualization of the anatomy [8]. For CAS procedures, robotic devices can provide automatic assistance to surgeons as they navigate the sheath through the common carotid artery, potentially decreasing the peri- and post-operative risks associated with the procedure [4]. Previous work has highlighted the effectiveness of robotic assistance in CAS procedures using outcome-based measures, including technical success, occurrence of complications, fluoroscopy time, stroke, and mortality [9]. While robot-assisted navigation shows promise for CAS procedures, these purported advantages have not been quantitatively verified using surgical tool motions, as granular differences in motion quality at the tool tip level may cascade upward to influence post-operative outcomes.

There are various methods of analyzing surgical navigation proficiency that may be applied to comparing manual and robot-assisted navigation techniques in CAS procedures. While surgical performance evaluation has traditionally relied on structured rating scales and checklists, such as the Global Rating Assessment Device for Endovascular Skill (GRADES) [10], objective evaluation techniques using time- and frequency-domain measures derived from surgical tool tip velocity profiles have recently shown promise as indicators of endovascular navigation proficiency. These metrics are also well-suited for comparing different endovascular navigation modalities [11]. In particular, spectral arc length (SPARC), a frequency-domain measure of motion smoothness, has been considered to be the gold standard measure of movement smoothness and has been previously shown to correlate with surgical experience level for endovascular navigation performed manually [12], [13] and robotically

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[14]. Average velocity and idle time (the amount of time the tool remains stationary), have also been shown to be valid performance measures for endovascular surgical proficiency, and serve as complementary measures of movement smoothness to SPARC [15].

In this study, our contributions are two-fold. First, we extend our previous application of SPARC, average velocity, and idle time from evaluating surgeons' endovascular navigation proficiency to comparing different surgical modalities for carotid artery stenting procedures. From these results, we provide insight into the potential advantages of robotic assistance for CAS procedures implied from granular differences in tool tip motion quality.

II. METHOD

We instructed participants to perform a standard CAS procedure with and without robotic assistance on a commercial endovascular simulator. We developed a semi-automated image processing technique to isolate the tool trajectory of interest and extract its kinematic behavior from procedure videos. From each tool tip trajectory, we calculated SPARC, average velocity, and idle time to compare the two surgical modalities (manual vs. robot-assisted navigation).

A. Participants

Ten participants (six vascular surgery residents, four endovascular specialists) with varying experience with robot-assisted navigation were recruited to perform a set of CAS procedures. Eight had no prior experience with robot-assisted surgery, while two had prior experience. Each participant performed two navigation tasks in each of the manual and robot-assisted conditions, resulting in four videos per subject.

B. Materials

The Corindus CorPath GRX Vascular Robotic System (Corindus Vascular Robotics, Waltham MA, USA) was used by participants to perform robot-assisted CAS procedures. CorPath allows the operator to control each endovascular tool with three joysticks on the device's workstation, while a bedside unit consisting of a robotic arm, motorized drive and sterile tool cassette executes the movement of catheters, guidewires, balloons, and stents [8]. The CAS procedures were performed on a high-fidelity commercial endovascular simulator (AngioMentor, 3D systems, Littleton CO, USA), allowing for the recording of each case for further evaluation. We used OpenCV in Python for image processing, MATLAB for data preprocessing, and R for statistical analysis.

C. Procedure

All participants received training for the endovascular simulator and the robotic system, and each of them performed a training case before the study. Participants were then asked to complete two tasks. The first task was a left internal carotid artery (L-ICA) stenosis for a type I aortic arch (Fig. 1). The second task was an L-ICA stenosis for a type II aortic arch. Each task consisted of six steps: 1) aortic arch navigation, 2) L-CCA (left common carotid artery) catheterization, 3) advancement of sheath to the distal common carotid artery, 4) L-ICA catheterization with filter, 5) stent deployment, and 6) post dilation. The first two steps were performed manually, while the other four steps were performed with or without robotic assistance. For our comparison of manual and robot-assisted navigation, we evaluated only steps 3 (Fig. 1a) and 4 (Fig. 1b). Proper tool navigation during these two steps is important for avoiding intraprocedural cerebral embolization and can be performed either manually or with robotic assistance [16], [5]. Video of each procedure was recorded in its entirety and downloaded for post-processing.

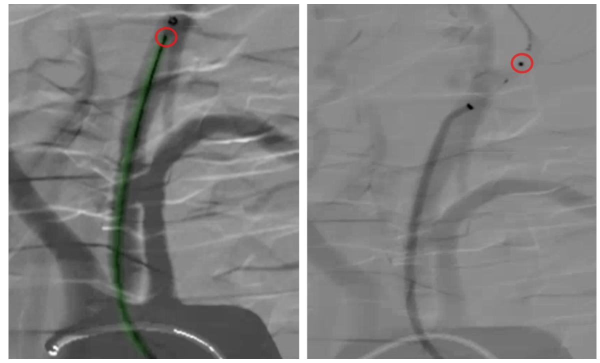

Fig. 1. Case recordings of CAS procedures with tool tip circled in red. a) Advancement of sheath to the distal common carotid artery with guidewire highlighted in green. b) L-ICA catheterization with filter.

D. Performance Metrics

From the tangential velocity profile of the guidewire tool tip, we calculated SPARC, average velocity, and idle time. SPARC is a frequency-domain measure of movement smoothness and has been shown to be a robust indicator of performance in other endovascular tasks [12], [13], [14]. Lower SPARC values have been shown to correlate to greater experience levels during endovascular navigation [15]. Average velocity represents the speed of tool motion, and similar to SPARC, provides an accurate measurement of surgical performance [15]. Idle time, the amount of time the tool tip remains stationary during a navigation task, has also been shown to be a promising measure of navigation proficiency [15], [17]. Similar to average velocity, idle time provides a measure of cognitive engagement, as higher average velocities and lower idle time values correspond to surgical experience level and lower SPARC values [15], [17].

E. Extraction of Tool Tip Data

We developed a semi-automated image processing technique to obtain guidewire tool tip kinematic data from each procedure video using OpenCV Python. Given the presence of background noise from the simulated fluoroscopic display in each case recording, we first performed manual selection of rectangular regions that cropped the size of the video to a selected subregion, which allowed for an automated tracking routine to accurately detect the guidewire tip location. These subregions could be reselected every 10 frames of the video to follow the guidewire throughout the recording.

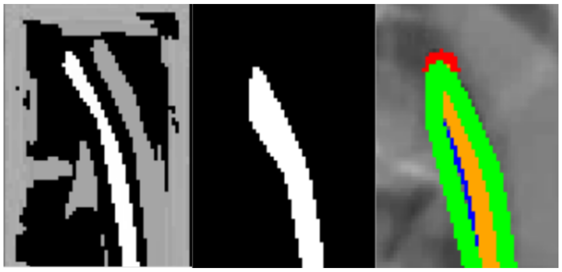

Fig. 2. Frangi filter, thresholding, and convex hull applied to CAS video. a) Frangi filter. b) Binary image after thresholding and dilation. c) Convex hull and polynomial fitting functions. Green line is convex hull contour. Orange line is fitted curve. Red point positioned at tip of guidewire.

After selecting these subregions, we applied a filter that enhances wirelike objects in each video frame to identify the guidewire and catheter (Fig. 2a) [18]. A blurring operation was performed to smooth out smaller background artifacts, followed by image thresholding using Otsu's binarization and a morphological dilation operation to thicken and eliminate any gaps in the guidewire profile (Fig. 2b).

To identify the guidewire tool tip and extract its kinematic data, we traced a polygonal contour around the guidewire profile using a convex hull function. We then applied a polynomial fitting function to plot a curve from one edge of the contour to the other and identify the end points of the curve, and thus the position of the tool tip (Fig. 2c).

Due to data collection errors, 6 out of the 40 recorded case videos were not usable for analysis.

F. Post-Processing of Tool Tip Coordinates

Following extraction of guidewire tool tip position from the procedure videos, post-processing of the tool tip data files was necessary, as some frames contained multiple convex hull contours due to unfiltered noise. To achieve this, we implemented a distance-based filtering function in MATLAB that ranked candidate tool tip coordinates by the distance between the current point and the tool tip position coordinates from the previous frame, and selected the point with the smallest distance. This process resulted in the identification of the correct tool tip coordinates for each frame. These coordinates were then used to calculate the motion-based performance metrics for each procedural video.

G. Statistical Analysis

Following the calculation of performance metrics for each case recording, we performed separate statistical analyses for the two procedural steps of interest from the case recordings. We applied a linear mixed effects model using the calculated values of SPARC, average velocity, and idle time, using manual and robot-assisted navigation as the fixed-effect factor of interest. Degrees of freedom were approximated using the Kenward-Roger method.

III. RESULTS

For each of the motion-based performance metrics calculated from guidewire tool tip kinematic data extracted from each case recording, we applied a linear mixed effects model to analyze the differences between manual and robot-assisted navigation in CAS. The results for both procedural steps are summarized in Table I. For performance metrics calculated during advancement of the sheath to the distal common carotid artery, tasks performed with robotic assistance displayed significantly lower values of SPARC than those performed manually ($F(1,22.3) = 6.12, p = .021$), as well as significantly higher values of idle time ($F(1,22.6) = 6.26, p = .02$). Average velocity was lower for robotic navigation than manual navigation, but not significantly. From Table I, none of the performance metrics showed significant differences between manual and robotic-assisted guidewire navigation during filter advancement across the internal carotid artery. However, we observed the same trends in lower SPARC and average velocity values associated with robotic-assisted navigation, as well as higher idle time values.

TABLE I

RESULTS FROM LINEAR MIXED EFFECTS MODEL FOR MANUAL VS. ROBOTIC. STATISTICALLY SIGNIFICANT VALUES IN BOLD.

Metric	Sheath Advancement	Filter Advancement
SPARC	**F = 6.12; p = .021**	F = 2.61; p = .12
Idle Time	**F = 6.26; p = .02**	F = 1.06; p = .31
Average Velocity	F = 2.55; p = .12	F = 2.35; p = .14

IV. DISCUSSION

Robot-assisted endovascular surgery promises several advantages over conventional manual techniques, though this surgical modality has not been quantitatively compared with interventional techniques. In this paper, we used a set of time- and frequency-domain performance metrics to compare manual and robot-assisted navigation during carotid artery stenting procedures. We examined guidewire tool tip motion extracted from case recordings during two procedural steps known to influence post-operative recovery. Using linear mixed effects modeling, we explored whether robotic assistance results in differences in tool tip motion quality.

During advancement of the sheath to the distal common carotid artery, we observed significant differences in SPARC and idle time between manual and robot-assisted navigation. The lower SPARC values associated with robotic assistance indicate smoother guidewire motion, which supports the objective of devices like Corpath to stabilize the surgeon's motions. Robotic assistance resulted in longer amounts of idle time, suggesting that while using CorPath led to smoother motions, surgeons spent more time keeping the guidewire stationary. This inverse relationship between SPARC and idle time differs from the linear relationship observed in Murali et al. [15], and can be explained by the participants' unfamiliarity with the robotic navigation system. Idle time is also an indicator of a surgeon's cognitive engagement during tool navigation [15]. As 80% of the participants had no prior experience with robot-assisted endovascular surgery, a lack of practice with CorPath would likely result in a tendency to have multiple stopping points throughout the procedure and to contemplate their navigation strategy. Additionally, while average velocity did not show significant differences between conditions, lower values were associated with robot-assisted navigation. Similar to the higher idle time values, slower movement of the guidewire is likely due to the participants' lack of experience with the robotic system.

None of the performance metrics showed significant differences between manual and robot-assisted navigation during filter advancement across the internal carotid artery. However, we still observed the same trends of lower SPARC, lower average velocity, and higher idle time values for robotic assistance. The lack of statistical significance during the filter advancement segment is largely attributed to our small sample size. Assuming future participants would behave the same as those measured, and given the similar trends observed during both procedural steps, a larger number of participants would give more statistical power and may result in statistically significant differences between SPARC, average velocity, and idle time, though this is obviously speculative. Additionally, compared to SPARC, which performs an inherent filtering operation [13], average velocity may be more susceptible to noise. For instance, if a sufficiently close noise point (point other than the tool tip coordinate) was identified as the tool tip by the distance-based filtering function, a spike in the velocity profile would occur and affect the computed average velocity.

Overall, motion-based performance measures demonstrate the capability of providing a more holistic picture of a surgical procedure, namely by providing an ability to quantitatively describe specific observations about tool smoothness and speed. These results have broader implications, as similar observations between different surgical modalities can be made at the tool tip level across various domains, providing more insight into the evaluation of robotic-assistance.

V. CONCLUSION

We compared manual and robot-assisted navigation during two critical steps within a pair of carotid artery stenting procedures. Using three motion-based performance metrics calculated from surgical tool tip velocities, we identified that for both steps of the CAS procedure, robot-assisted navigation was associated with lower SPARC, lower average velocity, and higher idle time values, though we only observed significant differences in SPARC and idle time during advancement of the sheath to the distal common carotid artery. These findings provide quantitative evidence that robot-assisted endovascular navigation systems are able to provide precise positioning and motion-stabilizing capabilities to surgeons during guidewire movement. Smoother guidewire tool tip motion provided by robotic assistance is also accompanied by a corresponding increase in idle tool motions and decrease in tool movement speeds, which highlights a probable lack of familiarity with the robotic system. As robotic assistance continues to be adopted and evaluated for different surgical procedures, we believe that our technique relying on performance measures derived from tool tip kinematics will allow for a more granular comparison of different surgical techniques and technologies, and will complement existing outcome-based measures.

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