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Foot-Controlled Robotic-Enabled Endoscope Holder for Endoscopic Sinus Surgery: A Cadaveric Feasibility Study

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Objectives/Hypothesis: To evaluate the feasibility of a unique prototype foot-controlled robotic-enabled endoscope holder (FREE) in functional endoscopic sinus surgery.

Study Design: Cadaveric study.

Methods: Using human cadavers, we investigated the feasibility, advantages, and disadvantages of the robotic endoscope holder in performing endoscopic sinus surgery with two hands in five cadaver heads, mimicking a single nostril three-handed technique.

Results: The FREE robot is relatively easy to use. Setup was quick, taking less than 3 minutes from docking the robot at the head of the bed to visualizing the middle meatus. The unit is also relatively small, takes up little space, and currently has four degrees of freedom. The learning curve for using the foot control was short. The use of both hands was not hindered by the presence of the endoscope in the nasal cavity. The tremor filtration also aided in the smooth movement of the endoscope, with minimal collisions.

Conclusion: The FREE endoscope holder in an ex-vivo cadaver test corroborated the feasibility of the robotic prototype, which allows for a two-handed approach to surgery equal to a single nostril three-handed technique without the holder that may reduce operating time. Further studies will be needed to evaluate its safety profile and use in other areas of endoscopic surgery.

Key Words: Robotic surgical procedures, robotics, endoscopes, paranasal sinus.

Level of Evidence: NA.

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INTRODUCTION

Endonasal endoscopic sinus surgery is one of the most commonly performed procedures in otolaryngology, initially pioneered by the Austrian surgeons Stammberger and Messerklinger. The surgery requires the surgeon to hold the endoscope in one hand at all times, leaving only one hand to manipulate surgical instruments in performing sinus surgery. This two-handed technique is more time-consuming than a four-handed technique previously described in endonasal surgery by Briner et al.[2] However, a four-handed technique is neither ergonomic nor cost effective because it requires two surgeons to be operating in the same small workspace. Thus, there is a need for a controllable endoscope holder than can relieve a hand for the surgeon to manipulate instruments.

The da Vinci robot (Intuitive Surgical, Inc., Sunnyvale, CA) has been used extensively in transoral robotic surgery of the oropharynx; however, it has been sparsely used in endonasal surgery.[3–5] This is because the da Vinci robot (Intuitive Surgical, Inc., Sunnyvale, CA) was primarily designed with opposing arms via widely spaced ports for abdominal and thoracic surgery, which is very different from the coaxial manipulation and entry through the narrow nostril for endonasal surgery.[6] To use the da Vinci robot (Intuitive Surgical, Inc., Sunnyvale, CA) to operate within the nasal cavity would therefore require external incisions, rendering the use of this system relatively invasive.

In this regard, there have been attempts at designing robotic endoscope holders, including the joystick-controlled Evolution 1 (Universal Robot Systems, Schwerin, Germany), A-73 (University Erlangen-Nuremberg, Erlangen, Germany), and Tx40 (Staubli, Pfäffikon, Switzerland),[7–9] and the voice-controlled Automated Endoscopic System for Optimal Positioning (AESOP) robot (Intuitive Surgical, Inc., Sunnyvale, CA).[10] However, none of these systems have yet gained traction in endonasal surgery, possibly related to the robot's dimensions and the continued requirement of a separate hand to manipulate the joystick. To improve on these previous designs, we describe the use of a prototype foot-controlled robotic endoscope holder and its feasibility in performing endoscopic sinus surgery.

Additional Supporting Information may be found in the online version of this article.

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Fig. 1. Model of the robotic endoscope holder with the control unit, light box, and camera mounted on the metallic unit above the wheels. The robotic endoscope holder arm is shown extending across.

MATERIALS AND METHODS

A robotic endoscope holder was designed to hold different sized rigid endoscopes (Fig. 1). The base of the robot houses the control unit and light source with the base measurements of 37 $\times$ 45 $\times$ 51 cm. The 4-mm 0-degree Storz (Tuttlingen, Germany) endoscope was used for these experiments. To provide adequate control of the rigid endoscope, the robotic arm provides four degrees of freedom (see Fig. 2). These four joints are powered by brushed DC motors, and have a range of motion of 13 cm, 100 degrees, 360 degrees, and 12 cm, respectively.

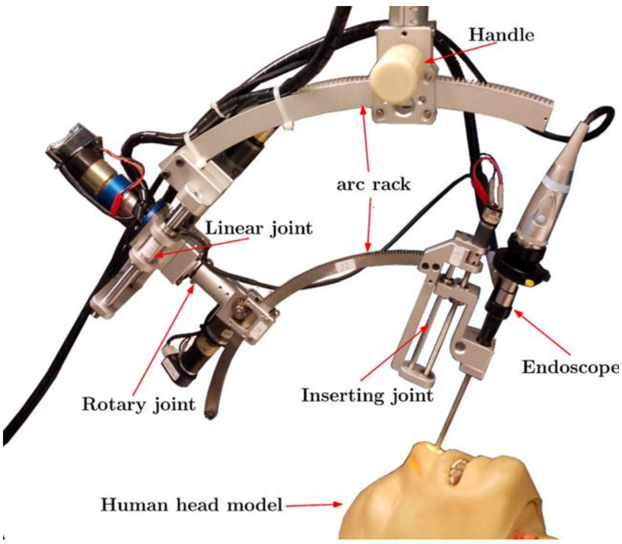

Fig. 2. Active part of the robotic arm in detail.

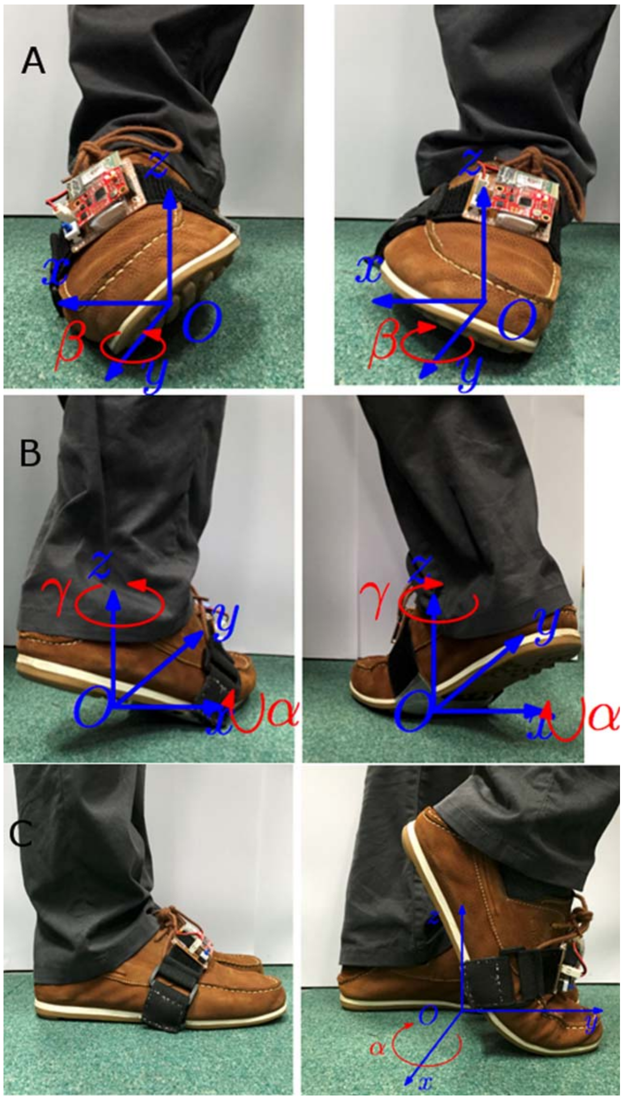

Fig. 3. Foot movements. (A) Inversion or eversion to change joints. (B) With the heel elevated to 15 degrees or more, the foot is moved left or right to move a particular joint. (C) Heel movements off the ground to start or stop the robot.

The foot control interface consists of an IMU (inertial measurement unit) module that is attached to the surgeon's foot; this setup allows the measurement of the foot's relative orientation in real time. The IMU module communicates with the servo control unit via Bluetooth. Briefly, two quick heel movements off the ground, orientated in an inferior to superior direction of more than 15 degrees (with respect to the ground) either activate or deactivate the controller; the unit also verbalizes "start" and "stop." Eversion or inversion of the foot changes the active joint in an increasing or decreasing manner; for example, eversion switches from joint 2 to joint 3 and inversion from joint 2 to joint 1. The current joint that is engaged to function is verbalized by the unit as "joint 1," "joint 2," "joint 3," or "joint 4." To provide the desired motion command to the active joint, the

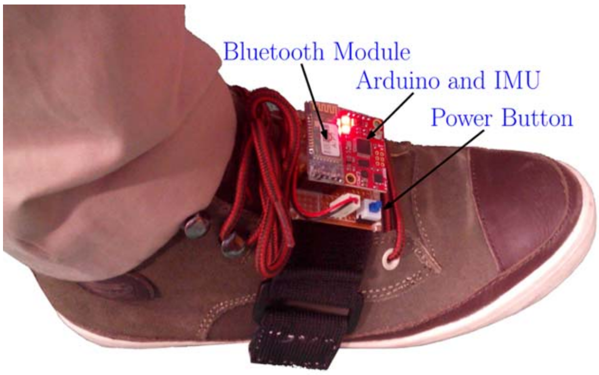

Fig. 4. The foot control with elastic strap around the foot and constituent components demonstrated.
IMU = inertial measurement unit.

heel of the foot is raised to 15 degrees (or more) from the ground and moved left or right. These movements are shown in Figure 3. Figure 4 provides a conceptual representation of this foot-controlled interface, and the accompanying video (Supp. Video 1) provides an overview of the robotic movements and functions.

Clinical Validation

Procedures were performed on five fresh cadavers in the dissecting laboratory, School of Biomedical Sciences, The Chinese University of Hong Kong, SAR, China. Each cadaver head was placed on the dissecting table and then secured with headrest blocks and taped to the table. First, to demonstrate the ease of setup for the robot, we evaluated the time that it took to have the control unit adjacent to the head of the bed until the visualization of the middle meatus. Next, we evaluated the use of the foot-controlled robotic-enabled endoscope holder (FREE) in performing a maxillary antrostomy, total ethmoidectomy, and sphenoidotomy, with the goal of evaluating the use of three instruments in one common nasal cavity to perform sinus surgery.

Fig. 5. Demonstration of the single nostril three-handed technique utilizing the foot-controlled robotic-enabled endoscopic holder robot and one surgeon.

RESULTS

The FREE robot was easy to set up, with a mean setup time of 2.39 minutes (range 1.92–3.00 minutes); the time to set up improved with each trial, from an initial 3 minutes to 2 minutes by the third trial. The movement across all four degrees of freedom was smooth, precise, consistent, and reproducible. The speed of movement was constant regardless of the degree of movement of the foot. There were no sudden jerks or erratic movements. There was a learning curve in use of the interface to manipulate the endoscope; however, this improved quickly with experience. Furthermore, the FREE robot was used continuously for a period of ~4 hours without any change in dexterity or discomfort in using the foot control. The endoscope was easily removed directly from the mount and reinserted for cleaning of the lens. The mount can also be customized to accommodate for a lens cleaner and different endoscopes.

The mean time to perform a maxillary antrostomy, from medializing the middle turbinate to excising the uncinate with a sickle knife to widening the antrostomy, was 6.83 minutes (range 4.02–9.05 minutes) by a surgeon experienced in sinus surgery. Initially, this took around 8.8 minutes but improved to 4.02 minutes by the fourth maxillary antrostomy in the cadaver heads. Visualization and performance of the maxillary antrostomy and total ethmoidectomy were smooth, with the lamina papyracea clearly defined. The sphenoidotomy was easily performed and the opticocarotid recess and sella seen. Finally, there was ample room with the endoscope in a single nostril to effectively perform a single nostril three-handed surgery with one surgeon, as seen in Figure 5.

DISCUSSION

In this study, we have demonstrated the feasibility and advantages of using this unique foot-controlled FREE robot as an endoscope holder in endonasal sinus surgery, thereby effectively permitting a single nostril three-handed technique with one surgeon. This overcomes an inherent problem in endonasal surgery, which requires the surgeon to hold the endoscope in the nondominant hand and the handle instruments with the other hand. Furthermore, this is more ergonomic and cost-effective than having a second surgeon acting as the third hand, if needed.

Static scope-holding devices are available, including the Karl Storz Endoscopy-America Point Setter (Karl Storz Endoscopy-America, Culver City, CA), Invotec Flexible Tension Arm (Invotec International, Jacksonville, FL), and Fukashima Flexible Retractor Arm (Paugh Surgical, Richmond, VA).[11] However, because of their static nature, the need for the surgeon to manually position the scope holder for image adjustments or to clean the lens, and the relatively high cost of these devices, the devices have not been widely adopted. Therefore, the developed hands-free robot provides a feasible solution to the active endoscope manipulation problem in sinus surgery.

There have also been descriptions of a number of experimental robotic endoscope holders over the last decade. Among the earliest was the Evolution 1, a hexapod robot described initially for neurosurgical procedures by Nimsky et al.,[7] which was joystick-controlled. However, this robot was cumbersome, required a setup time of 30 minutes, and had a maximal force of 250 Newton—much higher than the maximal forces suggested to fracture the lamina papyracea and carotid canal during functional endoscopic sinus surgery.[12] Subsequently, a voice-controlled AESOP (Intuitive Surgical, Inc.) was also described with seven degrees of freedom; however, its high cost and large working space were preventative of its widespread use.[10,13] More recently, the Tx40 robot was described by Eichhorn and Bootz[9]; it was capable of visual servoing and automatic lens cleaning, but the dimensions still affected the ergonomics of the operating surgeon. Nonetheless, despite these advances in robotic endoscope holders, they have not achieved widespread use due to multiple factors, including cost; robotic dimensions; and in the majority, the continued requirement of a separate hand to drive the endoscope with a joystick.

To this end, we have been collaborating closely with robotic engineers in developing the current FREE robot to meet safety and ergonomic requirements in endonasal surgery to both enhance the surgeon's capabilities and save time at a reasonable cost. We believe that the FREE is ergonomic, requires a relatively small amount of space in the operating room, has a short learning curve, is safe and precise, and can be easily adapted to different endoscopes. Furthermore, in the future the FREE can potentially be integrated with navigation, image overlay, three-dimensional endoscopes, narrow band imaging, and optical coherence tomography, further expanding its application. Refinements of the FREE to enhance its capabilities and safety features, such as haptic feedback and integration of active visual perception, will be pursued in the future.

CONCLUSION

In this article, we have presented and experimentally validated a new foot-controlled robotic endoscope holder prototype that allows the surgeon to directly manipulate surgical instruments with both hands at all times. The conducted ex-vivo cadaver test corroborated the feasibility of the robotic prototype. Further studies are needed to explore its capabilities in other endonasal surgical approaches, and subsequently, its use in the clinical setting.

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