Design of a Bone-Attached Robot for Mastoidectomy

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INTRODUCTION

The mastoidectomy is a common otologic procedure performed as a component of other surgeries such as cochlear implantation and acoustic neuroma tumor removal as well as to treat infections in the mastoid. Sub-millimetric accuracy is required to avoid damage to critical anatomic structures embedded in bone such as the facial nerve, sigmoid sinus, external auditory canal, and carotid artery [1]. This accuracy requirement and the fact that many of the critical structures are hidden within the bone, makes it a strong candidate for image-guided robotic surgery.

Several research groups have investigated the feasibility of robotic mastoidectomy using a serial, industrial robot with a surgical drill attached to its end-effector (e.g. [2-3]), an approach similar to the commercial Mako RIO robot typically used for joint repair/replacement surgeries (Mako Surgical Corp., Ft. Lauderdale, FL, USA). Using this approach, patient motion must be monitored so that the drill tip remains correctly registered with the target anatomy at all times. This registration process introduces an additional uncertainty in the overall system, and requires cumbersome error checking to prevent failure of the patient motion monitoring system. To mitigate this added uncertainty and reduce error checking burden, we propose to use a bone-attached robot.

While such a system may be beneficial for registering the robot to the patient anatomy, it also presents an additional set of design challenges. The size constraint of a robot that can be attached directly to the patient restricts the power of the actuators and the stiffness of the entire robot. The workspace of the robot is also limited with the bone-attached approach. Along with the general requirements of traditional mastoidectomy, these constraints must be accounted for in the design of a bone-attached system. This paper outlines several of these design considerations and presents the first version of the robot.

MATERIALS AND METHODS

The forces required for robotic mastoidectomy were evaluated experimentally by milling formalin-fixed temporal bone specimens using an industrial robot under various cutting conditions. A standard otologic drill and cutting burrs were used and the experiments tested different cutting burr sizes and types, drill angles, cutting depths and velocities, and different bone types (cortical/surface bone and pneumatized bone of the mastoid). The full details of this study are given in [4].

The required workspace for a mastoidectomy robot was evaluated in terms of overall size and the angular requirements of the drill shaft so that all target points are safely reached without removing any unnecessary bone or violating critical anatomy. Ten temporal bone specimens were used in this study. The specimens were formalin-fixed bones previously used by residents in the department of Otolaryngology at Vanderbilt University Medical Center for training purposes. The set of ten was selected by an experienced surgeon who verified the mastoidectomy procedures of each and that the set of bones were representative of a broad range of patient anatomy. The bones were scanned using a Xoran xCAT ENT portable CT scanner (Xoran Technologies, Inc., Ann Arbor, MI, USA). The removed volume of bone for each mastoidectomy was segmented using custom software with a semi-automated approach. The outermost surfaces of the removed volume for each specimen (i.e. the open face of the cavity) were aligned since this is the location where a bone-attached robot would attach to the patient. An overall workspace size was calculated from this aligned set of specimens.

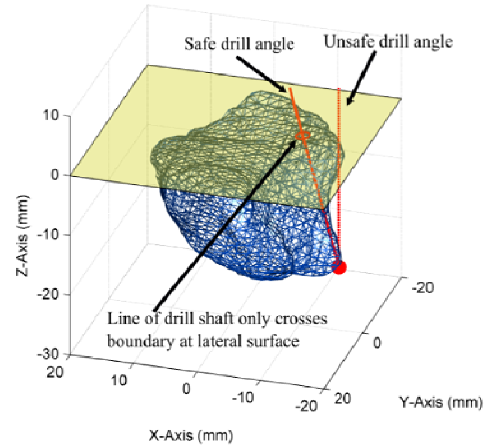

Fig. 1 One safe and one unsafe drill orientation for a given target point. In the unsafe case, the drill shaft passes through bone outside of the target volume.

The angular workspace was calculated by examining the allowable drill angles for each specimen. The removed volume of bone was discretized into a series of target points (1 point for each voxel of the 0.4 mm x 0.4 mm x 0.4 mm scan) and each individual point was checked to determine the angles required to reach the point without the drill crossing out of the target volume at any point along its shaft (see Figure 1). Two cases were examined: 4 total degrees-of-freedom (1 angular DOF) and 5 total DOF (2 angular DOF). Figure 2 shows the orientation angles of the drill shaft relative to the top surface of the target volume (lateral surface of skull where the robot is attached). In the 4 DOF case it was assumed that the robot could be attached to the patient at various orientations of its base (φ angle); however, this angle is fixed once the robot is attached. In the 5 DOF case, the drill was free to rotate about φ as well as θ. For each specimen, the range of angles required for the target points to be safely reached was calculated.

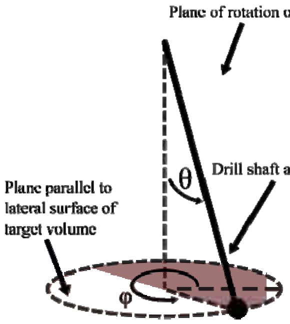

Fig. 2 Drill orientation angles relative to the patient.

RESULTS

The mean forces for various cutting conditions ranged from 0.4 N to 3.4 N with maximum force spikes up to 13.1 N. It was determined that larger burrs can remove a specified volume of bone in a given time with lower forces than smaller burrs and utilizing the side of the spherical burr (rather than the distal tip) by adjusting the drill angle relative to the bone surface reduced the transient force spikes. Lower forces were observed in pneumatized mastoid bone versus cortical/surface bone; however, higher variation was observed in the pneumatized bone. Finally, lower forces were observed for a given bone removal rate under cutting conditions that utilized higher cutting velocities and shallower depths rather than slower/deeper cuts.

The required workspace of the robot was calculated to be 41 mm deep with a maximum cross-sectional area at the lateral surface of the skull. The workspace at this surface can be approximated by an ellipse with major diameter of 52 mm and minor diameter of 45 mm. The cross-section decreases as the depth into the skull increases. In the angular workspace analysis, it was determined that at least 98.3% of the target points in each specimen could be reached with a 4 DOF robot (7 of 10 specimens were completely reachable). A drill tilt angle range of 45° was the maximum range required. Additionally, in our opinion, the few target points that were unreachable were not required to perform the surgical procedure. The 5 DOF case allowed for 100% of the target points to be reached for each specimen and reduced the required tilt angle to 35°.

The prototype of this robot (see Fig. 3A) utilizes four SmarAct piezoelectric linear positioners (SmarAct GmbH, Oldenburg, Germany) with a repeatability of approximately one micrometer, travel length of 46 mm, and maximum velocity of 15 mm/s. Additionally, these actuators are available in autoclavable versions, allowing for the entire robot to be sterilized without being disassembled. Three of the actuators control motion in the x-, y- and z-directions, while a fourth actuator controls the tilt in the drill (range of -40° to +40°) through a rack and pinion and worm-wheel gear set. The worm-wheel setup is necessitated by the fact that the torque about the shaft controlling the tilt imposes a higher than allowable force along the axis of that actuator due to the forces at the drill tip and makes this joint non-backdrivable. In a future version, the rack and pinion could be replaced by a rotary positioner. The base plate has three attachment points that allow it to be positioned at several different orientations relative to the patient through a positioning frame that is anchored to the patient and scanned pre-operatively (see Fig. 3B).

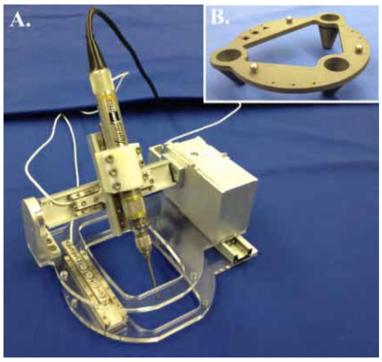

Fig. 3 Photograph of robot prototype (A) and positioning frame (B) which attaches rigidly to the skull and connects to the robot.

DISCUSSION

The first prototype for a bone-attached robot for mastoidectomy is discussed in this paper along with several of the design considerations. A 4 DOF robot was chosen to maximize the accuracy and stiffness of the robot while keeping the overall robot as small, light and stiff as possible. The results of the force experiments are important in both robot design and motion planning and were combined with a mastoidectomy workspace analysis to aid in the design process. Future work on this project will include verification that the accuracy of this robot meets the surgical requirements, motion planning for optimal mastoidectomy volume removal, and testing on cadaver temporal bone specimens.

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