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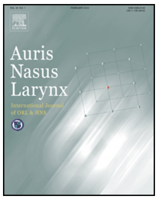

Semi-manual mastoidectomy assisted by human–robot collaborative control – A temporal bone replica study

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ABSTRACT

Objective: To develop an otological robot that can protect important organs from being injured.
Methods: We developed a five degree-of-freedom robot for otological surgery. Unlike the other robots that were reported previously, our robot does not replace surgeon's procedures, but instead utilizes human–robot collaborative control. The robot basically releases all of the actuators so that the surgeon can manipulate the drill within the robot's working area with minimal restriction. When the drill reaches a forbidden area, the surgeon feels as if the drill hits a wall.
Results: When an engineer performed mastoidectomy using the robot for assistance, the facial nerve in the segmented region was always protected with a more than 2.5 mm margin, which was almost the same as the pre-set safety margin of 3 mm.
Conclusion: Semi-manual drilling using human–robot collaborative control was feasible, and may hold a realistic prospect of clinical use in the near future.

1. Introduction

Otological surgery is performed to remove infection in cases with chronic otitis media, to remove benign or malignant tumors, or to restore hearing in patients with ear troubles. Most procedures require drilling of the temporal bone. Because the temporal bone has three-dimensionally located complex anatomy, drilling the temporal bone has always been a demanding task requiring knowledge of the precise anatomy, as well as submillimetric accuracy of the drilling hand. Robotic surgery in the field of otology has been a target of research to achieve a level of accuracy and stability that have not been possible during manual surgery [1].

One example of an otological surgical robot for a specific surgical target is a newly developed robot designed for cochlear implantation, which precisely drills along a predetermined trajectory line from the bone surface to the cochlea [2–5]. The image-guided, robotic approach enabled successful cochlear implantation into a patient with a completely ossified cochlea whose surgery was previously aborted because of this problem [6]. Another example with broader potential applications is a robot for mastoidectomy [7,8].

Mastoidectomy is a surgical procedure involving the drilling of the mastoid portion of the temporal bone, and it is one of the most basic and important surgical procedures performed during many otological surgeries. As new otologists start their training with mastoidectomy on cadavers, it is natural to choose mastoidectomy as the first research target for robots in the field of otology. However, mastoidectomy is seldom the goal of the otological surgery. The surgeon must further drill toward the surgical target to accomplish the objectives of the surgery. Therefore, automatic or robotic mastoidectomy only replaces a small, and relatively easier, part of the surgical procedure, during which surgeons usually feel a lower need for the assistance of computers or robots. It is therefore necessary to develop a robot that supports the surgeon during the entire course of the temporal bone surgery, without restricting the use to specific procedures.

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In addition, surgeons are less attracted to forms of surgical assistance that restrict the freedom of the manual procedure in any form. It is widely believed that a trained surgeon without restriction can perform a safer surgery than the same surgeon restricted by "safety features" of image or robot guidance [9]. Thus, surgeons would perceive such safety features better if the features were inactivated while the patient is not in danger of surgical complications.

We have developed a surgical robot that physically protects the pre-set structures in the temporal bone using image guidance and robotic control. Our newly developed robot with human–robot collaborative control basically does nothing while the surgeon manually drills the bone. However, once the drill approaches one of the pre-set structures, the robot then activates the actuators on the arm to restrict the movement and protect the structure. In this study, we set the facial nerve as the structure to be protected and tested the usability of the robot while drilling temporal bone replicas. We herein report the results of an initial feasibility study of the robot-assisted manual surgery on the temporal bone.

2. Materials and methods

2.1. Robot design

A five degree-of-freedom robot was designed, paying particular attention to the feasibility of mount the robot on the surgical bed and the ability of the robot to be manipulated by the surgeon. The robot consists of three actuators for linear movement along three orthogonal axes, and two revolute actuators (Fig. 1A). The tip of the surgical drill (a Saber drill connected to a Core console, Stryker Japan, Tokyo, Japan) was set near the crossing point of the two revolute axes (fulcrum point, Fig. 1A) so that movement at the revolute joints results in changes in drill direction, but leads to a much smaller change in the tip location. The workspace of the robot-mounted drill was large enough to perform complete mastoidectomy (Fig. 1B), and there was enough room to place the patient's head under the drill. The drill can be detached for sterilization, and the rest of the robot can be draped. The robot was controlled through a Windows-based controller PC. An active marker and a force/torque (F/T) sensor were attached at the rear of the drill to detect the location and the intended direction of the surgeon's drilling. The controller PC collects the location of the drill tip from the image-guided surgery (IGS) computer, along with the direction of the force from the F/T sensor. For example, if the active marker detected the drill tip that is not moving, and the F/T sensor detected a force toward left, the computer understood that the surgeon is trying to rotate the drill to the right (clockwise if seen from top) instead of trying to drill to the left. The measured surgeon's intention is converted as the same motion command to the five actuators of the robot so that the surgeon felt as if all the actuators are released. If the drill tip approaches the forbidden area (described below), the computer sends signals to the actuators to gradually restrict the joint movement so that the surgeon feels growing resistance related to the proximity to the area. When the drill tip reaches the forbidden area, the actuators block the movement from entering the area (virtual fixture) [10,11]. At the same time, the warning system is activated so that the surgeon can understand the reason for the restriction [12]. The virtual fixture function can be turned off at any time to abort the robotic control.

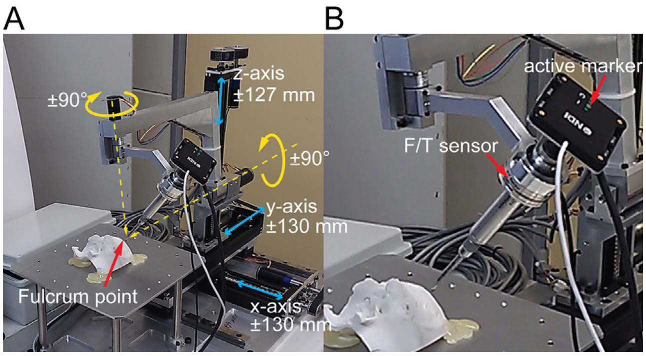

Fig. 1. The robot. (A) The experimental setup. (B) A close-up view of the drill and the temporal bone replica. F/T sensor: force/torque sensor.

2.2. Experiment

Commercially available temporal bone replicas for surgical training (KEZLEX, Ono and Co., Tokyo, Japan) were used for the experimental evaluation of the system. A preoperative CT dataset of the replica was installed in an open-source software program for image guidance (3DSlicer, www.slicer.org). The region of the facial nerve in the temporal bone, from the first genu to the level of the cochlea (Fig. 2A), was segmented and extracted as a model consisting of a finite number of spheres (Fig. 2B). This range of segmentation was our clinical routine while preparing for image-guided temporal bone surgery. Then, this volume data of the segmented facial nerve were covered with a 3-mm-thick safety margin and set as a forbidden area (Fig. 2C). We used the paired point method to register the temporal bone replica to the IGS computer.

The engineer (HL), who had no background of clinical training in otolaryngology and no surgical experience, drilled the mastoid portion of the temporal bone. The engineer's task was to skeletonize the facial canal and complete the mastoidectomy. The engineer had experience in analyzing the drill movement during otologist's mastoidectomy, segmenting the facial nerve, cochlea, semicircular canal, sigmoid sinus, jugular vein, middle and posterior cranial fossa plate. The surgeon showed the engineer an example of temporal bone model after complete mastoidectomy. No other surgical or anatomical instruction was given to the engineer. When the drill reached the forbidden area, the alarm sounded, the virtual fixture function of the robot was activated, and further drilling toward the facial nerve was blocked (Fig. 2D).

2.3. Analysis

We performed a CT scan of the temporal bone replica after drilling (Fig. 3A and B). The surgeon (NM) checked the CT data and determined whether anatomical structures were injured. The pre- and postoperative CT data were overlaid (Fig. 3C). The original and drilled surfaces were distinguished using the Mimics software program (Materialise Japan, Yokohama, Japan). Then, the closest distance from the drilled surface to the surface of the facial nerve was measured in each slice of the original CT (Fig. 3D). The data were collected from five temporal bone replicas fabricated from the same CT dataset.

3. Results

Table 1 shows the results of the robot-assisted mastoidectomy. Although some of the external ear canal, sigmoid sinus, and middle or posterior cranial fossa bones were damaged during the five mastoidectomy procedures, the engineer never injured the facial nerve at the segmented area. In the analysis of the postoperative CT data, there was always a margin of at least 2.5 mm from the facial nerve of the segmented region to the drilled surface, indicating that the human–robot collaboration with the virtual fixture had protected the structure. The facial nerve was injured in three of

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