Performance Evaluation of a Cooperative Manipulation Microsurgical Assistant Robot Applied to Stapedotomy

Peter J. Berkelman*, Daniel L. Rothbaum M.D., Jaydeep Roy, Sam Lang,
Louis L. Whitcomb, Greg Hager, Patrick S. Jensen, Eugene de Juan,
Russell H. Taylor, and John K. Niparko M.D.**

Johns Hopkins University

Abstract. This paper reports the development of a full-scale instrumented model of the human ear that permits quantitative evaluation of the utility of a microsurgical assistant robot in the surgical procedure of stapedotomy.

1 Introduction

The need for microsurgical assistants arises from the normal limitations of human dexterity resulting from tremor, jerk, drift, and overshoot [1, 2]. Recently developed robotic assistant devices offer the possibility of extending human performance to permit fine manipulation tasks that are normally considered difficult orimpossible[3, 4, 5, 6, 7, 8, 9]. The "steady-hand" robot employed in these experiments cooperatively assists a surgeon to manipulate microsurgical tools [9]. In this paradigm, both the user and the robot cooperatively hold and manipulate the surgical instrument [8]. This paper reports the development of a full-scale instrumented model of the human ear that permits quantitative evaluation of the utility of the "steady-hand" robot in the surgical procedure of stapedotomy. The model enables direct measurement of intra-operative parameters for two important steps in the stapedotomy operation: (i) fenestration and (ii) prosthesis crimping. Using this instrumented surgical model, we plan to compare performance measures of stapedotomy performed (a) manually and (b) with robotic assistance and, further, to evaluate the effect of expert/novice differences in the comparative performance of human-robotic augmentation.

Otosclerosis, a disorder of the middle ear that causes conductive progressive hearing loss, occurs when bony deposits cause the stapes-the innermost bone of the middle ear-to become immobilized. In consequence, sound vibrations cannot propagate to the inner ear. In stapedotomy, part of the immobilized stapes bone is removed and replaced by a small piston-shaped prosthesis. To achieve contact

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between the stapes prosthesis and inner ear, the footplate is fenestrated with a micro-pick. After the prosthesis has been placed within the fenestration, it is attached by crimping an integral wire to the long process of the incus, the second of the three bones of the middle ear.

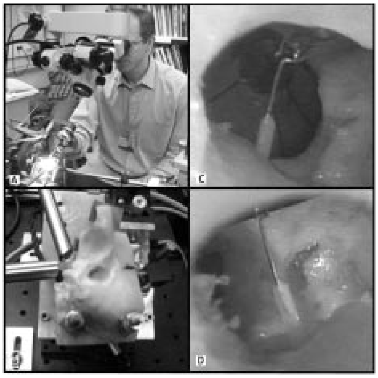

Fig. 1. (A) Dr. Larry Lustig using the stapedotomy surgical station. (B) View of the temporal bone and endoscopes. (C) and (D) View from the endoscopic cameras.

2 Experimental Methodology

Our goal is to compare the performance of otologic surgeons with and without robotic assistance. Using the instrumented model ear, we are able to compare performance variables during both the fenestration and crimping steps of stapedotomy. Performance variables will be measured for skilled operators performing multiple repetitions of a procedure both with and without robotic assistance. To replicate closely actual operative conditions, the procedures reported herein are performed in a prepared human temporal bone. The temporal bone has been drilled to permit 1) visual access to two endoscopic cameras mounted nearly-orthogonal to one another and 2) positioning of an artificial stapes bone mounted on a load cell. To ensure authentic yet repeatable experimental trials, we employ synthetic artificial stapes bone samples exhibiting mechanical properties typical of actual stapes footplates. The experimental setup is pictured in Figure 1.

We measure performance variables for fenestration of the stapes footplate as follows: (i) To measure perforation diameter, we photograph the fenestrated stapes footplate, and analyze the image digitally to measure the actual fenestration diameter. (ii) To measure the perforation placement around a desired point, we employ the same digital imaging technique of the previous step. (iii) To measure force applied to the stapes footplate, we record forces on the load cell upon which the stapes bone is mounted.

We measure performance variables for crimping of the stapes prosthesis to the incus bone as follows: (i) To measure the degree of circumferential contact between the prosthesis wire and incus bone, we employ a sensitive high-impedence op-amp circuit to measure electrical continuity between the each of the electrodes on the artificial incus and the prosthesis wire. The number of incus electrodes exhibiting continuity reveals the extent of mechanical contact between prosthesis wire and incus bone. (ii) To measure crimp quality, experienced otologists judge post-crimping frame-grabbed images from the endoscopic cameras. (iii) To measure force applied to the oval window during crimping, we use the load cell upon which the stapes bone is mounted. (iv) To measure movement of the prosthesis during crimping, we film the crimping procedure with two endoscopic cameras. By moving the robot in a pre-defined trajectory, we are able to calculate the exact angle between the cameras. Thus, after optically tracking the images on each camera, we can reconstruct the movement of the piston prosthesis in three-dimensional space.

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