Toward Robot-Assisted Stapes Fenestration with a Handheld Micromanipulator

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***Abstract*—Stapedectomy is a delicate surgical procedure of the middle ear to improve hearing. In the middle ear there are anatomical structures that can be damaged during the surgery. Suppression of tremor during the procedure may reduce the likelihood of damage. This paper reports on a study of the feasibility of using Micron, a fully handheld micromanipulator, in stapedectomy. An ergonomic handle, a special tip, and a brace attachment were designed for this purpose and tested in a perforation task through a fixed speculum. Fenestration area and time in forbidden zones were analyzed in a penetration task under two conditions: unaided, and aided by tremor compensation. Preliminary results show a statistically significant improvement in cross-sectional area of fenestration and in time spent in forbidden zones.**

I. Introduction

In otolaryngology one of the most complicated procedures is stapedectomy [1]. During stapedectomy part of the stapes footplate is removed in order to place a prosthesis. Several perforations are made in the stapes footplate to enable this removal. Around the workspace there are soft tissues that can be easily damaged. The region medial to the stapes footplate contains the inner ear which provides hearing and balance to that side. Accordingly, imprecise fenestrations carry considerable risk to these sensitive tissues. The surgery is done through a fixed speculum that is also often used by the surgeons as a brace, since that provides some mechanical suppression of the tremor.

Some robotic systems have been investigated for application to stapedectomy, including the SteadyHand robot [2], which is a cooperatively-controlled system, and the RobOtol [3], a teleoperated system. We investigated the feasibility of Micron [4], a fully handheld active robotic instrument, for stapedectomy, since it has previously demonstrated successful tremor reduction, and its light weight and handheld operation may be advantageous for the purpose [5].

The purpose of this work, therefore, is to test the performance of Micron in a perforation task carried out in a confined workspace. With this goal in mind, some special adaptations were modeled to enhance the suitability of the system for otologic use.

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II. Methods

Several modifications were made to Micron in order to improve its applicability to otologic surgery (see Fig. 1). A specially-designed end-effector was added, ending in a 0.127-mm superelastic nitinol needle, with similar shape to the micropicks used in otologic surgery. A custom brace attachment was also designed, conforming to the curvature of the speculum, to allow the surgeon to brace against the speculum for mechanical reduction of tremor. Both tip and brace were fashioned from aluminum tubing. An ergonomic handle was also designed and fabricated via rapid prototyping. The new handle was designed to provide better grip, and to tilt the tip manipulator to avoid blocking the sight-line of the user.

The feasibility experiment was performed under a Zeiss® OPMI-1™ surgical microscope through a fixed speculum, simulating real conditions. Position information regarding the hand motion and the tip of the tool was measured by a custom optical micro-tracker system developed in our laboratory [6]. The experimental task consisted of penetration of a thin material layer, simulating fenestration of the stapes footplate. The testbed apparatus was formed by three parts: a metal grid, with holes 0.51 mm in diameter and 0.76 mm between centers, to indicate where fenestrations must be done and to delimit areas that are forbidden, simulating zones of delicate tissue; a clay film roughly 1 mm thick, simulating the stapes footplate; and a metal plate, to detect any penetration that went all the way through the clay layer. The desired depth to reach was indicated by a mark in the needle (approximately 0.9 mm). The tool tip and the test apparatus were equipped with a circuit that detects any contact between the tool and the side of a hole or the underlying metal plate. The output of this circuit was recorded by computer at 2 kHz throughout each trial. This task was completed 12 times, under two test conditions: 6

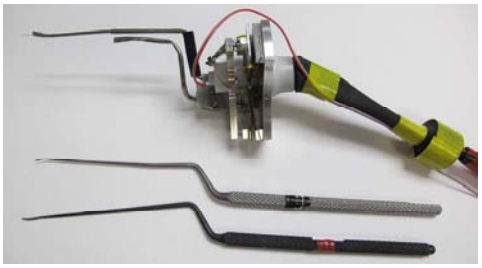

Fig. 1. Micron device (top) outfitted with end-effector similar to micropicks currently used in stapedectomy surgeries (bottom), brace attachment, and slanted ergonomic handle

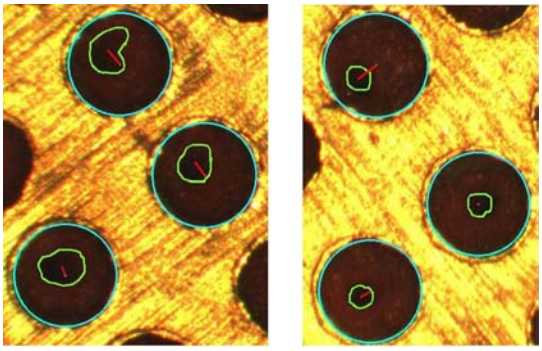

Fig. 2. (a) Unaided trial (b) aided trial. Cyan: detected test grid. Green: detected fenestration area. Red: deviation from target center

trials aided by Micron, followed by 6 trials unaided (with Micron powered off). Each trial consisted of 3 fenestrations, for a total of 18 fenestrations in each of the two test conditions. The experiment was completed by a non-surgeon, who was not experienced in the use of Micron.

During the experiment two kinds of data were recorded: (1) image video, used to measure fenestration accuracy by using a program for automatic estimation of the cross-sectional area of each hole generated (see Fig. 2); and (2) the two voltage outputs from the contact detection circuit, recorded as described earlier, from which the percentage of time that Micron was in a forbidden area (either grid or plate) was computed for each trial.

III. Results

The mean of all trials completed in each condition are shown by bar charts, with standard deviation represented by error bars. Statistical significance is assessed with a two-tailed *t*-test ($p < 0.05$). Significant results are marked with an asterisk in Figs. 3 and 4.

A. Fenestration size

Figure 3 shows a comparation of the cross-section of each fenestration with a hypothetical perfect fenestration that is exactly the cross-sectional area of the needle. Micron yielded significant reductions in both the mean and the maximum error compared to the unaided case.

B. Contact with forbidden zones

Manual positioning error affects not only fenestration size, but also the amount of time in contact with forbidden zones. Figure 4 shows the mean and maximum of the percentage of

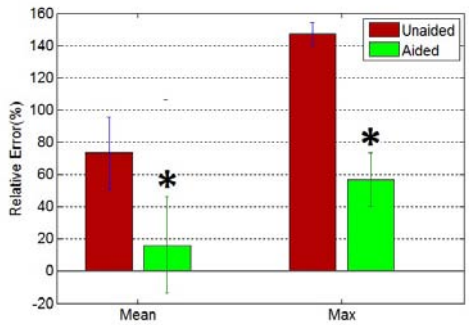

Fig. 3. Relative error in fenestration area

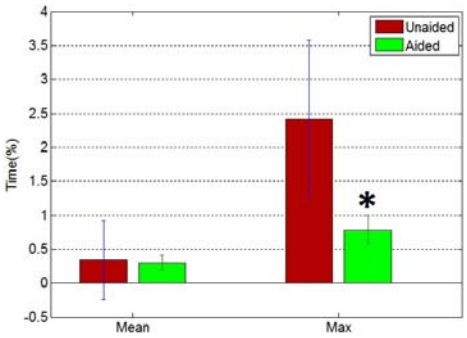

Fig. 4. Percentage of time in forbidden zones

time in which the tool was in contact with any of the defined forbidden areas. Micron produced a significant reduction in maximum percentage of time in contact with forbidden zones per trial.

IV. Discussion

These preliminary results indicate the general feasibility of using Micron, modified as described here, to reduce fenestration size and to reduce unwanted contact with vital areas. Improved fenestration placement, as indicated by the deviation of the centroid of each fenestration from the center of the circular hole in the grid, would be a useful outcome also, but placement was not improved by Micron in this experiment. This may be due to a training effect, since previous experiments with Micron indicate that performance improves with user experience [4]; further experimentation is needed in order to determine if this holds true in this case.

Future work will include more realistic experiments using artificial middle ear models or cadaver temporal bones. We also plan to incorporate patient-specific anatomical models, using stereo vision within the operating microscope, in order to improve avoidance of dangerous areas.

V. References

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