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Handheld Micromanipulator for Robot-Assisted Stapes Footplate Surgery

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Abstract— **Stapes footplate surgery is complex and delicate. This surgery is carried out in the middle ear to improve hearing. High accuracy is required to avoid critical tissues and structures near the surgical worksite. By suppressing the surgeon's tremor during the operation, accuracy can be improved. In this paper, a fully handheld active micromanipulator known as Micron is evaluated for its feasibility for this delicate operation. An ergonomic handle, a custom tip, and a brace attachment were designed for stapes footplate surgery and tested in a fenestration task through a fixed speculum. Accuracy was measured during simulated surgery in two different scenarios: Micron off (unaided) and Micron on (aided), both with image guidance. Preliminary results show that Micron significantly reduces the mean position error and the mean duration of time spent in specified dangerous zones.**

I. INTRODUCTION

OTOSCLEROSIS is an abnormal bone growth around the stapes in the middle ear. This calcification produces stapes bone entrapment that inhibits proper transport of sound to the inner ear through the oval window; moreover, it can also cause dizziness. Replacement of the immobile stapes bone with a prosthesis is the most common solution to this condition. Stapes footplate surgery is one of the most delicate procedures in otolaryngology. The incidence of complications related to work around the footplate and inner ear is about 1% [1]. The most technically challenging part of the stapedectomy procedure is the creation and subsequent enlargement of the fenestration, which may be accomplished by micropick, microdrill, or laser, and the removal of parts of the footplate [2].

Physiological tremor is an involuntary phenomenon that causes positioning error and becomes readily apparent in microsurgery [3]. Microsurgeons use bracing techniques to mitigate tremor; however, tremor cannot be completely eliminated with bracing. Robotic systems have been used for microsurgery in the middle ear to improve accuracy, including the SteadyHand [4], a cooperative system, and the RobOtol [5], a teleoperated system. Our lab has developed Micron, a previously reported fully handheld micromanipulator which has demonstrated up to 50% reduction of hand tremor in experiments [3]. Micron is based on three Thunder® piezoelectric actuators that provide tip movement independent of hand motion inside a 1.0x1.0x0.6 mm workspace centered on the handle. Tip position and handle orientation are obtained from a custom optical tracker also developed in our laboratory [6].

In a previously reported investigation of applying Micron to middle ear surgery [7, 8], Micron was adapted for stapes procedures. These modifications include mechanical changes to the tip and handle to better conform Micron to clinically used tools for the procedure. As shown in Fig. 1, a custom tip was fashioned, ending in a 450-μm diameter copper needle with a similar shape to micropicks used in stapes surgery. A custom brace attachment, shaped to conform to the speculum that is typically used in stapes surgery, allows the surgeon to brace against the speculum for mechanical support. An ergonomic oblique handle that provides better grip was designed and manufactured with rapid prototyping. The feasibility of using Micron was studied with its new adaptations in a “peg-in-hole” penetration task which was carried out in a clay environment that allowed us to compare the size of holes made with and without the aid of Micron. The results of the previous experiments suggested that the use of Micron in otologic

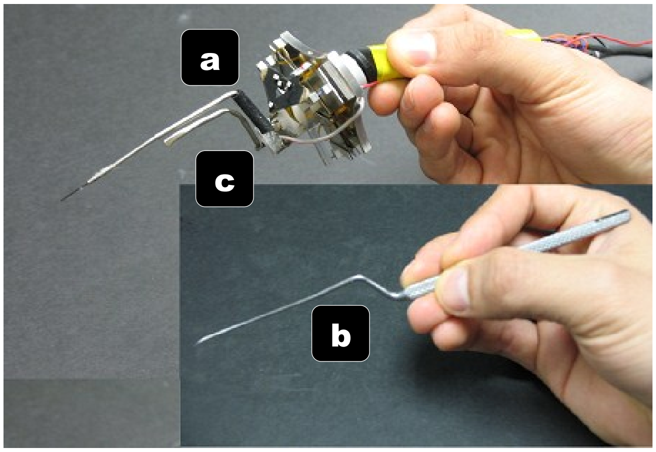

Fig. 1. (a) Micron device outfitted with end-effector similar to (b) micropicks currently used in stapedectomy surgery. (c) Brace attachment and non-perpendicular ergonomic handle developed for otologic Micron.

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microsurgery would be feasible. This paper presents the application of Micron to a procedure that simulates fenestration more realistically.

II. METHODS

In order to continue studying the viability of using Micron in fenestration operations, a penetration task was performed in a simulated stapedectomy procedure. Fig. 2 demonstrates the steps of the procedure: penetrating the first hole, moving safely between target holes, and penetrating a second hole. The goal of this experiment was to compare the accuracy of Micron making penetrations at predefined points. This task was conducted in two different situations: (1) unaided (Micron off), and (2) aided (Micron on) with position-based virtual fixtures [9].

A. *Work Environment*

For more realistic results, all operations were performed in an environment similar to real surgery (see Fig. 3). A Zeiss® OPMI™ surgical microscope, which was equipped with stereo cameras, was used to obtain visual data for image processing during the experiments. Video was captured with a resolution of 800x600 and analyzed at a frame rate of 30 Hz. All the trials were accomplished with visual cues displayed to the operator (see §II.D) via an augmented reality display [10]. This information is also duplicated on an HD monitor. All the trials carried out during the experiment were done through a fixed speculum as used by surgeons during regular ear procedures. Surgeons can brace against the speculum during the procedure for mechanical support.

B. *Visual Tracking*

While the operator performs the task, the system needs to track the tip position of Micron from the stereo cameras to generate virtual fixtures that guide the instrument. As these cameras focus on the grid, the space above it is blurred because of the narrow depth of field. This represents a challenge for the vision system, since the tip approaches the workspace almost vertically. To obtain satisfactory results and obtain sufficient depth of field without losing detail, a low magnification was used during the experiment. A dark foreground and a bright copper tip were used with carefully arranged illumination to achieve good visual tracking.

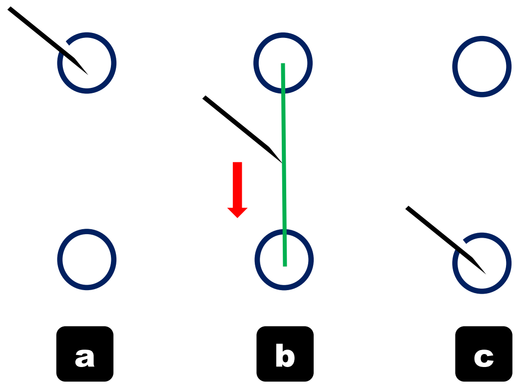

Fig 2. The selected procedure for the experiment tries to mimic the motions of the stapes fenestration procedure. The experiment steps are : (a) make one first fenestration in the first hole, (b) move from tip of Micron from the first hole to the second one, following the line defined by the center of the first and the second hole and finally (c) make a second fenestration in the second hole.

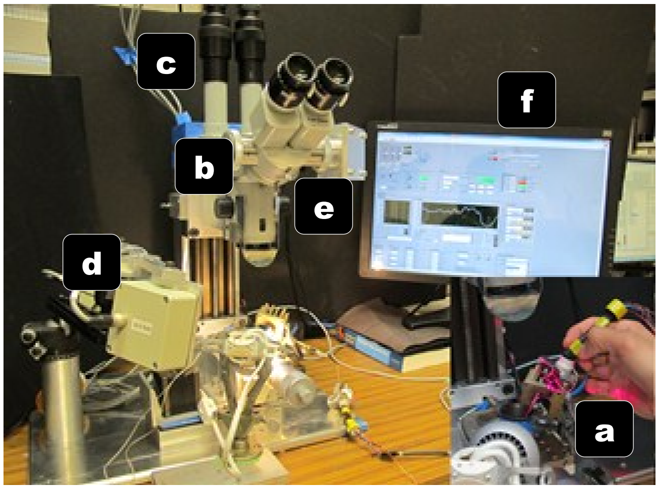

Fig. 3. Work environment: (a) Micron, (b) microscope, (c) stereo cameras, (d) ASAP optical trackers, and (e) augmented reality projector (f) HD monitor.

C. *Virtual Fixtures*

Micron has proven to enhance accuracy by suppressing hand tremor [3]. Furthermore if the sought position and the current position of the tip are known, Micron could be controlled, to reach these points [9]. The goal points during the procedure are obtained by the stereo vision system, whereas the tip position of the Micron, is provided by the combination of the optical tracking system and the visual tracking.

Once both points are acquired, goal and tip position, the tip is moved to the desired position by using its three piezoelectric actuators. However, the range of motion of Micron is limited to a few hundred microns. Therefore in order not to saturate the three actuators trying to move the tip beyond the reachable workspace, a set of boundaries surrounding the desired goal points based on tip position was defined. If the tip is too far away from the goal position, or outside the defined boundaries, Micron merely compensates the tremor, rather than trying to enforce the virtual fixture.

D. *Image Guidance*

Using a projector attached to the microscope that injects visual information directly into the right eyepiece of the microscope [10], visual cues were injected into the microscope view to improve position perception and keep the operator centered on the virtual fixtures [10]. The injected cues consisted of two circles. Fig. 4 shows a green visual cue that is centered on the goal position. A blue circle

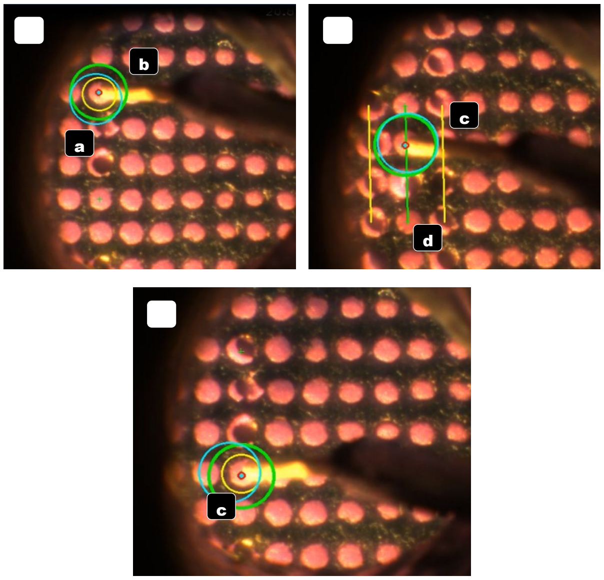

Fig. 4. Visual cues injected into the surgical microscope. (a) A green circle marks goal position and depth. (b) A blue circle shows the null position of the micromanipulator. (c) Yellow lines delimit virtual fixture work space. They change depending on tip position: (1) Aiming at the first hole, (2) moving between holes with (d) a green line to show the desired path, and (3) aiming the second hole. If the tool is too high, the blue circle grows larger than the green circle by an amount proportional to the Z-depth error; thus visual cues show guidance in 3D.

is centered at the null position of the manipulator, where the tip would be if Micron assistance were not active. The yellow lines delimit the area where virtual fixtures work. The desired path between the selected holes is depicted in green.

E. Experiment

A brass grid was used to provide a matrix of holes as workspaces where fenestration could be performed. This mesh is also used to delineate the “forbidden zones” where entry is undesired, thus simulating the critical tissues around the stapes that should be avoided (e.g., the facial nerve). The holes in the grid are 508 microns in diameter, and the selected copper needle for the experiment is 450 microns in diameter. This relation between holes and needle was chosen based on the typical sizes of fenestration tools and holes; consequently, high accuracy is needed in order to avoid touching the grid. The proposed task tries to mimic the real procedure and the need to avoid easily damaged tissues. It consists of making penetrations through the brass holes into an underlying clay substrate while avoiding the forbidden areas (see Fig. 1). To measure contact of the tip with the forbidden zones represented by the sides of the holes and the top of the grid between the holes, the tip and brass plate with holes are wired for electrical connectivity. Entering in a forbidden area is detected by a voltage output from completing an electronic circuit, which is measured and recorded at 2 kHz.

The experiment was carried out under a board-approved protocol by a novice without surgical training. A total of 48 trials was split between the two test conditions: (1) unaided (Micron off); and (2) aided (Micron on). Trials were performed randomly to alleviate ordering effects. During the experiment, data recorded included the position of the tip, measured by both optical tracking and the stereo camera tracking, and the voltage output indicating contact between the tip and the plate. Each time, the task was performed in two holes in a row in the brass grid. The holes were 2.29 mm apart, measured between centers (Fig. 4(2)). Evaluation is done by measuring deviation of the tip from the virtual fixtures and detecting tip contact with the forbidden regions.

III. RESULTS

A. 2D Positioning Error

Fig. 5 shows the overall mean and maximum errors from all runs. Comparing the mean and the maximum 2D error there was a significant reduction in the mean when the virtual fixtures were used; while the maximum error is quite

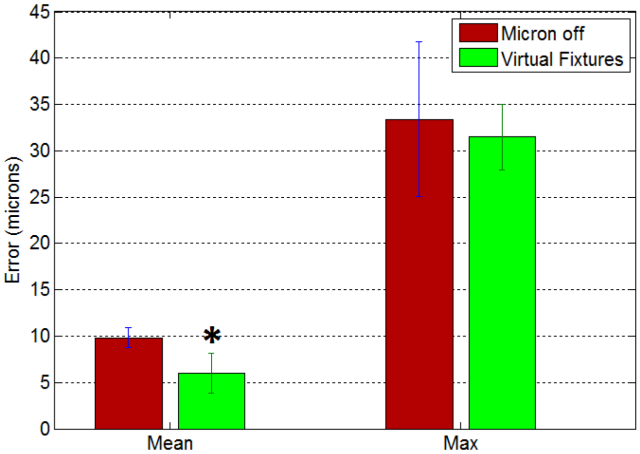

Fig 5. 2D Positioning error, aided (Micron on) *vs*. unaided (Micron off). An asterisk denotes statistically significant results ($p < 0.05$).

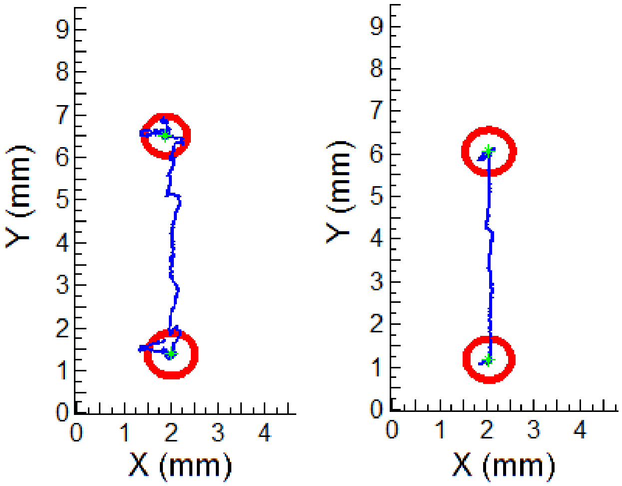

Fig. 6. Fenestration performance in a penetrations task: (left) Unaided traced path (with Micron off); (right) Aided traced path (with Micron on) with virtual fixtures.

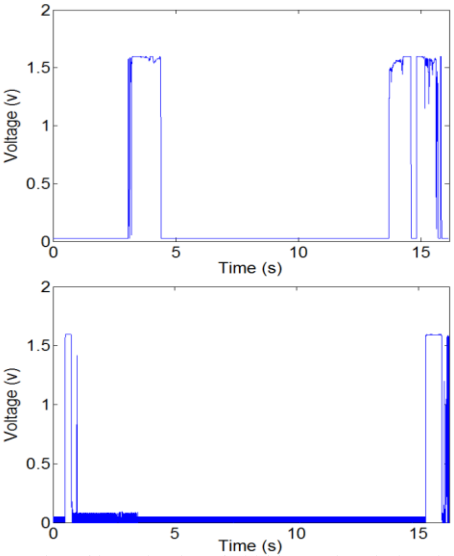

Fig 7. Examples of intrusion into forbidden region during the procedure, as indicated by output near 1.5 V. (top) Unaided. (bottom) Aided.

similar in both scenarios. Statistical significance was assessed with a two-tailed *t*-test ($p < 0.05$) and is indicated by an asterisk in Fig. 5. For maximum error, results were similar in the unaided and the aided case. This was due to bracing against the speculum, since tremor considerably. Examples of the path traced by the tool in the two scenarios are shown in Fig 6.

B. Forbidden Area Intrusions Analysis

Fig. 7 depicts a representative sample of the recorded analog signals in both scenarios. Notice that the intrusions were of shorter duration in the aided case. For a quantitative comparison, Fig. 8 shows the overall mean and maximum time spent in forbidden regions. A significant reduction in the mean intrusion time was obtained when virtual fixtures were used using a two-tailed-test ($p < 0.05$).

IV. DISCUSSION

In this paper, our work adapting the active handheld micromanipulator Micron for use in ear microsurgery has been expanded and tested in a somewhat more realistic environment. Previous work showed that tremor suppression can result in footplate penetration with smaller cross-sectional area [7]. This paper has demonstrated that tremor-reducing filtration with vision-guided virtual fixtures provides a significant reduction in the 2D mean error and the mean time that the tool is in a forbidden area. Fig. 6, together with the 2D error analysis, shows the benefit of using Micron with virtual fixtures. Further work is needed to determine if a significant reduction in the maximum intrusion time can be achieved. Future work will include more realistic experiments using artificial foam models manufactured with similar density to the stapes footplate. Experiments in cadaver human or sheep temporal bone are planned for further validation [11].

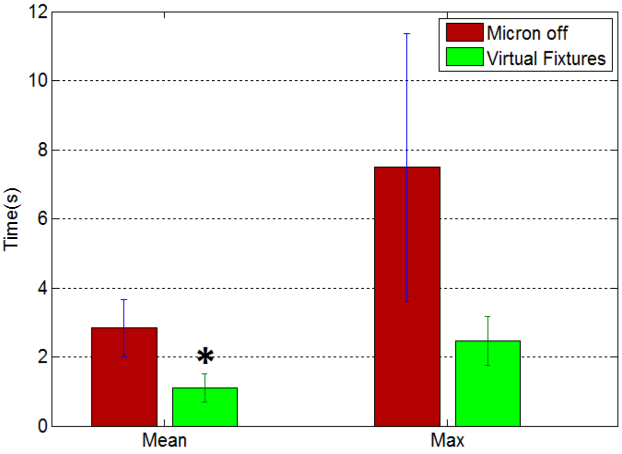

Fig. 8. Forbidden areas intrusion time, aided *vs.* unaided, both cases with image guidance. An asterisk denotes statistically significant results ($p < 0.05$).

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