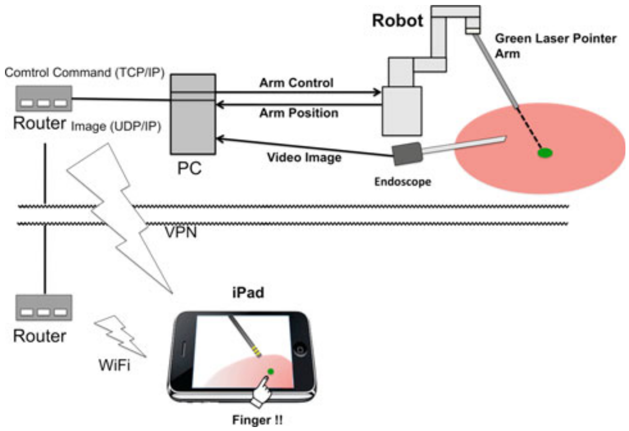

**Fig. 1** System overview of intuitive touch panel control system with tablet PC

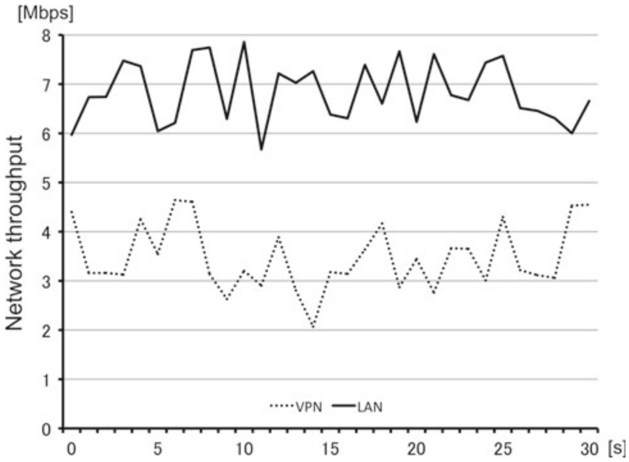

**Fig. 2** The network thoroughput speeds in VPN and LAN

be an affecting factor because we should move surgical devices when doing peel-off procedure. Hand-eye coordination can be easily achieved on the same plain.

### Conclusion

The robot system was successfully controlled by tablet PC through the local area network and the Internet. The throughputs of the network were lower than we had expected. “Surgery by monitor display” will be available from anywhere in the near future.

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## The last line of defense: integrated facial nerve monitoring for functional control of robotic assisted drilling in the mastoid

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**Keywords** Robot · Surgery · Mastoid · Image-guided

### Purpose

Image guidance and robotic assisted tool placement have been proposed to reduce the invasiveness of the current cochlear implantation procedure, which requires the removal of a significant portion of the mastoid in order to gain access to the middle and inner ear [1–3]. The main concern with such an approach however, is that the trajectory is drilled blindly in terms of visual confirmation, and the surgeon must place complete trust in the navigation system. One of the anatomical risk structures in the path of the direct access tunnel is the facial nerve, which innervates the ipsilateral muscles of the face. Damage to this structure constitutes a grave comorbidity, thus must be avoided. Protection of the facial nerve (and others) is routinely facilitated through the use of nerve monitoring equipment. Stimulation current passing from a probe through the nerve generates an action potential which is subsequently recorded by an electromyogram (EMG) electrode placed within one of the main muscles of the face, with the intensity of the EMG response being roughly proportional to the stimulation intensity. Recently, nerve monitoring technology has been integrated with surgical drills to provide a real time EMG signal to alert the surgeon of facial nerve proximity.

There are many factors influencing the sensitivity of the facial nerve in response to a stimulation current, making an exact relationship between EMG response and distance to the nerve difficult to predict. Recently, measurements of distance thresholds during nerve skeletization using an integrated monitoring device were performed during routine schwannoma removal [4]. In essence the surgeons set a fixed stimulation current and action potential threshold, and drilling immediately after being alerted by the nerve monitoring system. The variability of the effective distance to the facial nerve was ±0.69 mm for this study. As we intend to control the position of the robotically guided tool with a much higher accuracy, the effectiveness of the nerve monitor becomes questionable. Therefore, the purpose of this study is to more precisely derive the distance-EMG response relationship for a given stimulation current. It is hypothesized that the first derivative of this relationship may be more predictive of the distance to the facial nerve than the actual magnitude of the EMG signal.

### Materials and methods

Nerve model phantom

A sheep head model was chosen for these experiments due to the similarity of the ear anatomy and availability of cadavers. Once the skin was removed from the head and remaining first cervical vertebra, a phantom facial nerve was created by implanting a 2 mm kirschner wire into the mastoid near the facial nerve of the sheep head. In addition to placing the stainless steel wire, four small 1.5 × 3 mm titanium screws (M-5220.03, Medartis, Switzerland) were implanted immediately around the periphery of the mastoid region for later spatial referencing. Once these preparations were completed, the head was then imaged in a cone beam computed tomography scanner (Promax, Planmeca Oy, Finland) with a final isometric voxel size of 0.15 mm. Planning of drill trajectories was performed using a custom software designed specifically for otological interventions [1]. Using this software, the locations of each of the four reference screws were digitized, and the facial nerve phantom segmented. Next, entrance and target points of each trajectory were manually chosen by picking a location on the mastoid surface, and the center of the kirschner wire.

The normal EMG response of the facial muscles is simulated through the use of an RLC circuit as depicted in Fig. 1. Stimulation current passes from a nerve monitor (NIM 3.0, Medtronic, USA) through the drill power console (Integrated Power Console, Medtronic, USA) to a wiper (StimBur, Medtronic, USA) in contact with the drill bit which then passes current to the patient’s tissue. The majority of the current travels through the mastoid, to the base of the neck where the return and ground electrodes are located. A small amount of current is shunted through a RLC circuit (Patient Simulator, Medronic, USA), which simulates the EMG response of the facial nerve response to stimulation current.

### Robotic drilling

In order to obtain the most precise correlation between the distance of drill bit to the facial nerve, and EMG signal, we integrated a Visao

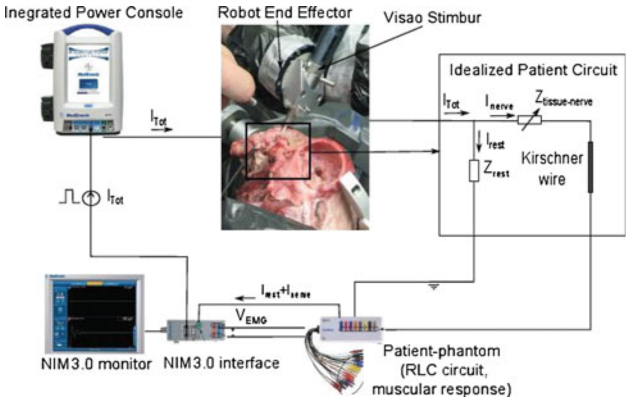

**Fig. 1** Schematic representation of the stimulation and EMG measurement circuit. Current flows from the NIM 3.0 monitor through the Integrated Power Console to the drill tool tip. The majority of the current flows through the tissue to the return electrode and a smaller portion through the nerve phantom and EMG simulation circuit

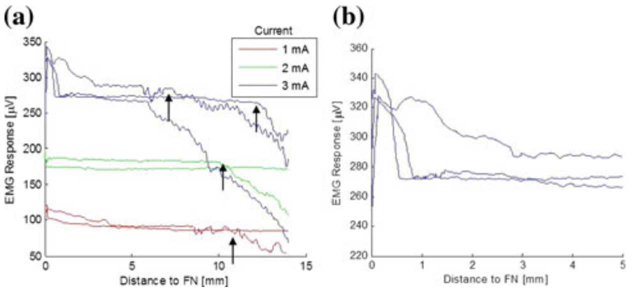

**Fig. 2** **a** EMG signal plotted versus Euclidian distance to the facial nerve for the three groups of stimulation intensities. The slope of the EMG signals consistently showed a drastic alteration as the tool passed from a large internal air cell to dense bone directly surrounding the facial nerve (FN) phantom (*arrows*). **b** Close-up of the 3 mA stimulation response. The higher stimulation current caused a dramatically higher rise of the EMG response just before reaching the nerve

**Table 1** Coefficients and norm of the residuals for a linear fit of the EMG response curve between 1 and 5 mm distance to the facial nerve

| | Trial | y = ax + b | | |
|---|---|---|---|---|
| | | a | b | norm R |
| 1 mA | 1 | −1.87155 | 98.38751 | 14.71688 |
| | 2 | −5.19019 | 115.0227 | 42.71444 |
| 2 mA | 3 | −0.94835 | 175.1496 | 20.6863 |
| | 4 | −0.72348 | 187.051 | 15.56204 |
| 3 mA | 5 | 0.13696 | 272.036 | 15.5477 |
| | 6 | −2.93527 | 280.5286 | 39.4166 |
| | 7 | −7.87998 | 318.8746 | 139.7761 |

With one exception, the EMG response curve shows an increase as the distance to the nerve decreases

otologic drill and NIM 3.0 nerve monitor (Medtronic, USA) into our custom built robot system. Stimulation and EMG response data was recorded from the NIM 3.0 FN monitor using a web cam and optical character recognition. This data, along with the precise location of the drill tip, was logged for offline evaluation.

Once the sheep head and robot were mounted in place on an OR table, the reference screw points were digitized with the robot system and the planned data was transformed into the navigation coordinate system. Seven trajectories were then automatically drilled to the facial nerve phantom using the robotic system. A Ø1.6 mm drill with a feed rate of 0.15 mm/sec and a drill speed of 6,000 rpm was used in each of the drilling cases.

## Results

7 separate trajectories were successfully drilled with the robot system while monitoring EMG response signals as shown in Fig. 2. Interestingly, the signal from the nerve phantom showed the largest increase as the drill traversed air pockets within the mastoid region. Once the tool contacted dense bone directly surrounding the nerve phantom (panel a, arrows), the slope of the EMG/distance correlation drastically decreased. Panel b of Fig. 2 shows a more detailed view of the 3 mA EMG response. This stimulation current induced the largest degree of change (10–20 %) to the EMG signal directly before contact was made. Basic fitting of the response curves failed to reveal a consistent relationship among the test groups, though the region between initial contact of uniform dense bone, and the onset of nerve contact was generally linear Table 1.

## Conclusions

The goal of this work was the initial integration of a commercial facial nerve monitoring system (NIM 3.0, Medtronic) with a high precision robotic manipulator developed by our group to be used for direct access cochlea implantations; a technique which aims to reduce the invasiveness of the procedure through image guidance and robotic tool positioning. The EMG response signal represents one signal which can be fused with other sensory data (force sensor) to improve the confidence in the navigated position. Similar to results published by Bernardeschi, we found a significant degree of variability in the EMG response signal. However, it remains to be seen how EMG signals will correspond to the distance from the nerve in a live scenario.

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## Marker-less articulated surgical tool detection

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**Keywords** Medical robotics · Tool tracking · Articulation · Da Vinci

## Purpose

We propose a system capable of detecting articulated surgical instruments without the use of assistive markers or manual initialization.