Towards middle ear robotic interventions: cholesteatoma removal

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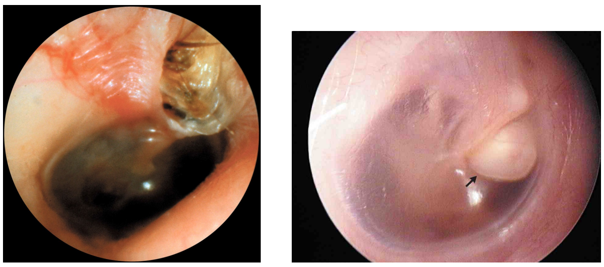
Otological surgical procedures tend over time to become minimally invasive due to the development of medicine, micro-techniques and robotics. This trend is expected to reduce the patient's recovery time and to improve the accuracy in diagnosis and treatment. One of most challenging difficulties that face such techniques are the precise control of the instrument and providing a wide field of view and an ergonomic system to the surgeon. The objective of our work is to develop an intuitive surgical robotic systems dedicated to middle ear surgery. This system will be particularly focused on cholesteatoma surgery which is one of the most frequent pathologies that urge for enhanced treatment. The targeted robotic system will be able to enter inside the middle ear cavity through an incision (about 2mm of diameter) in the mastoid bone behind the ear.

1 Introduction

The surgical assisted-robotics have been getting more demands over the last years as they help by providing ergonomic conditions for increasing accuracy and reducing surgeon fatigue. Moreover, the patients benefit from a reduced invasion, time and costs. The assistance will help the surgeon in performing more complex motion inside the patient's body, getting over the physical constraints and navigating in unknown environment. These robotic systems enter the human body from a small incision (or trocar point) which presents physical constraints on the surgical tool motion. These constraints created by the incision wall reduce the tool Degrees Of Freedom (DOF) to four (i.e., three rotations and one translation).

Such constraints are added to the previous challenges which the surgeon should overcome during the middle ear surgery. For instance, the surgeon during the cholesteatoma surgery performs a large incision in the mastoid bone behind the ear (mastoidectomy) in order to enlarge his/her field of view and to gain more dexter movement of his/her surgical tools. Such technique demands high expertise and dexterity of the surgeon. Therefore our work is motivated by the previous challenges for becoming minimally invasive and efficiently during the cholesteatoma surgery, while providing a great dexterity and ergonomically for the surgeon.



(a) (b)

Figure 1: *Typical cholesteatomas.*

Cholesteatoma (Fig. 1) consists of squamous epithelium that is trapped within the skull base and that can erode and destroy important structures within the temporal bone [4], especially middle ear structures (Fig. 2). As far as diagnosis is concerned, High-Resolution Computer Tomography (HR-CT) and Magnetic Resonance

Imaging (MRI) are widely used in pre-operative and post-operative cholesteatoma assessments. Endoscope, fluorescence and Optical Coherence Tomography (OCT) could also be used for intra-operative biopsy and imaging. As mentioned above, the only treatment in the current medical practice is surgery and its efficiency depends on the surgeon skills. In addition, post-operative complications may occur, such as facial nerve damage, total neurosensory hearing loss, residual tympanic membrane perforation and balance disturbance. Depending on the surgical procedure and on the literature [4], approximately 10% to 30% of cholesteatoma operations are unsuccessful, with residual or recurrent cholesteatoma which usually requires "second-look" operation.

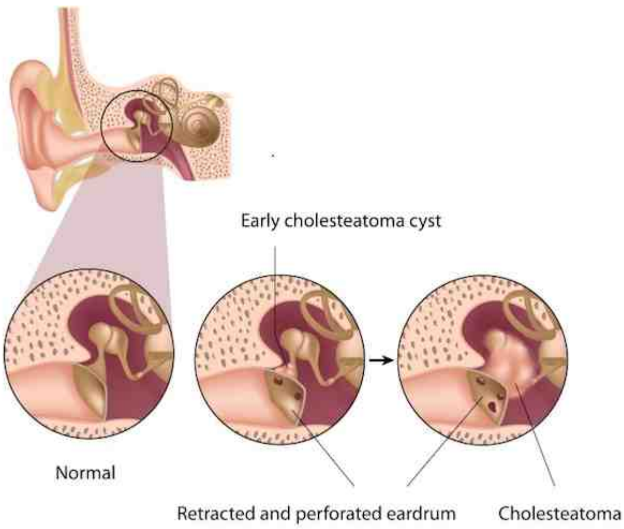


Figure 2: *Description of the different parts of auditory system and cholesteatoma progress over time.*

2 Control a surgical instrument inside the middle ear cavity

The cholesteatoma tissue removal from the middle ear cavity will be ensured using an actuated miniature surgical instrument which embeds both an interventional tip as well as a real-time investigation. The device will pass through a small incision into the mastoid bone behind the ear. To be able to control efficiency the displacements of the surgical instrument during the cholesteatoma tissue removal by taking into account the insertion point using a Remote Centre of Motion controller. Therefore, we developed a control law which commands the robot velocity in order to perform pre-defined surgical tasks with bilateral constraints. It achieves the objective with two task errors: (i) the first prior task is the alignment of the tool with incision point, and (ii) the second task error is the position of tool tip with respect to the predefined surgical task (Fig. 3).

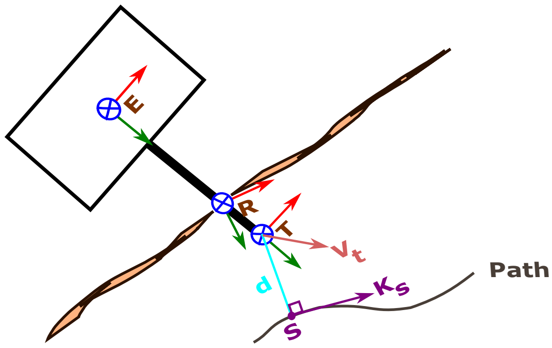
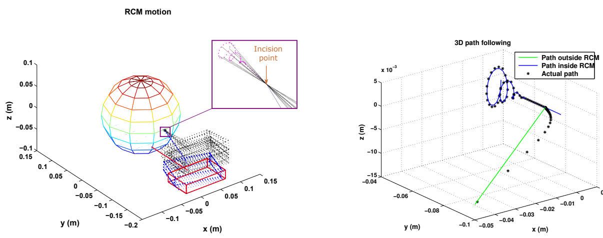


Figure 3: *Modelling of the whole system by taking into account the RCM configuration.*

3 Validation

The control law realizes the Remote Centre Motion (RCM) and it is divided mainly into two phases. The first phase is getting the robot close to the incision point and align the tool with the y-component of RCM frame. The second phase is guiding the robot to perform the pre-defined interventional task (for instance, a 3D path). Fig. 4 represents the resultant tool tip position with respect to the 3D predefined path (in blue) and the shortest way between the initial position of tool tip and the incision point (in green). Throughout the validation test, the standard deviation error of RCM constraints during the insertion phase is around 0.004mm and that of path following (e.g., a spiral incision path) is approximately 0.089mm [1].



(a) (b)

Figure 4: *(a) the end-effector motion during approach phase (doted blue) and insertion phase (doted black); (b) the position of tool tip with respect to the path.*

4 Conclusion

The developed control law presented in this article can be useful for several mini-invasive surgery applications, such as ENT (ear, nose and throat) and laparoscopic; since it is accurate to ensure predefined tasks (e.g., following an incision path and maintain the trocar kinematics). It will be extended to consider unilateral RCM constraints where the incision hole is bigger than the tool diameter and the instrument has more space to move before it hits the incision wall [2]. [3]

References

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