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Virtual reality simulation for training of endonasal robotic suturing using multiple difficulty levels

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Abstract: Although robotic systems support neurosurgeons in the realization of complex surgical tasks, a proper training curriculum is required for skills acquisition. We propose the use of VR simulation for training of endonasal dura mater suturing using multiple difficulty levels.

Keywords: virtual reality, robotic surgery, simulation, surgical training

1. Introduction

Suturing of dura mater in endonasal surgery is a complex manual task even for experienced neurosurgeons due to the narrow workspace and indirect visibility (Fig. 1). Visualization of the operative area is typically achieved using an endoscope with a tilted point of view, making the hand-eye coordination difficult during the manipulation of the surgical instruments. A master-slave robotic surgical system was developed in our group to assist in this task [1]. This decoupling of the master controller and the slave manipulator allows remapping of the motion commands to be consistent to the point of view of the endoscope, enabling intuitive manipulation of the robotic tools. Additionally, kinematic constraints are also implemented in the slave controller as part of the inverse kinematics to limit the movement of the robotic tools inside the operative area to enhance safety [2]. Still, due to the inherent intricacy of this surgical procedure, the neurosurgeons need hours of training to master this task. Because of the high cost of the robotic system, and the risk of damage especially during the early stage of the training, it is unpractical to perform hands-on training on the physical platform. For this reason, we have worked in the development of virtual reality (VR) simulators for training of robot-assisted surgery [3]. However, using a VR simulator that imitates the same operating conditions as in the real procedure (Fig. 2) makes it difficult for new users to understand the task and acquire the basics of the suturing technique. For which a training program

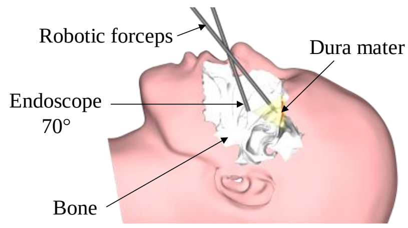

Figure 1: Sagittal slice of the head depicting endonasal surgery scenario (only relevant anatomy for this study).

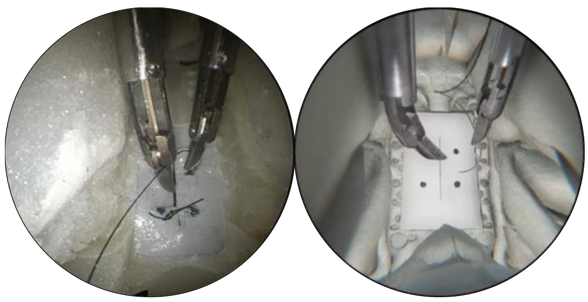

Figure 2: Endonasal robotic suturing on a synthetic dura mater model (left), compared with our VR simulator (right).

ranging from a simple to a complex task is necessary for the progressive acquisition of surgical skills in robot-assisted endonasal neurosurgery. Existing training programs for laparoscopic surgery [4] use a variety of abstract tasks and discrete difficulty levels (e.g. easy, medium, hard). Nevertheless, defining distinct tasks for each difficulty level as in [5] has the disadvantage that it is not possible to obtain a smooth transition

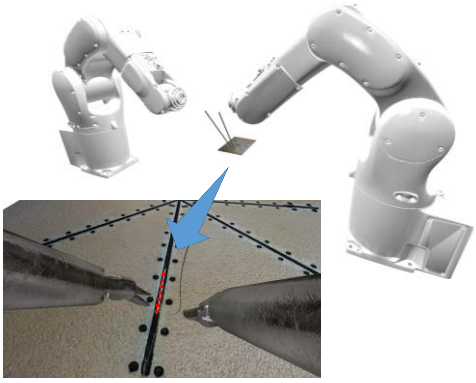

Figure 3: Simulated setup consisting of two robot arms, to practicing of suturing on a rubber sheet.

between training stages. In this work, we opt to define a common task and vary the operating conditions such as the pose of the objects, the point of view of the endoscope camera, and the size of the workspace. Under this approach, after the proper definition of the lowest and highest difficulty level, we hypothesize that an infinite number of intermediate levels can be obtained by interpolation, allowing smooth transition and personalization of the level of difficulty according to the surgeon's expertise.

2. Materials and methods

2.1 VR simulator

The VR simulator was developed taking as starting point our VR simulator for endonasal dura mater suturing [3]. The simulated scenario was simplified by eliminating the skull geometry, and the dura mater model was replaced with a standard rubber sheet for practicing suturing in a 10 mm length slit (Fig 3). To achieve real-time simulation, we approximated the behavior of soft bodies using rigid body dynamics. Under this

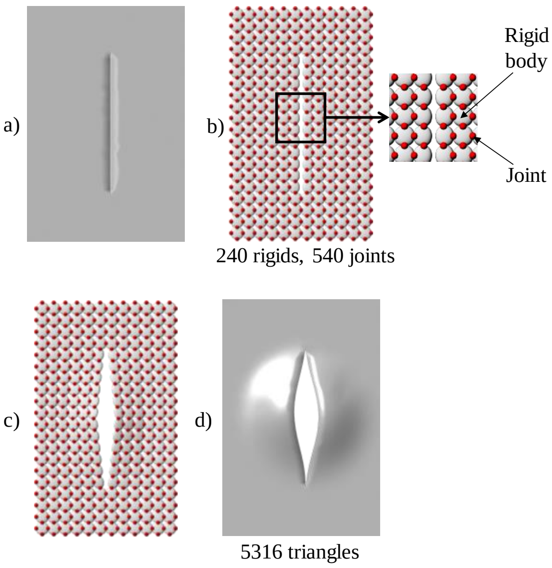

Figure 4: a) A membrane with slit high-resolution mesh; b) membrane simulation model; c) modified rigid bodies; d) visualization of deformed membrane.

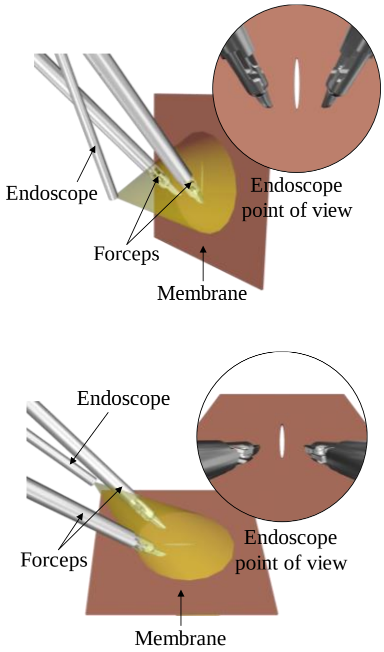

Figure 5a: Scene setup for hard (above) and easy level (below).

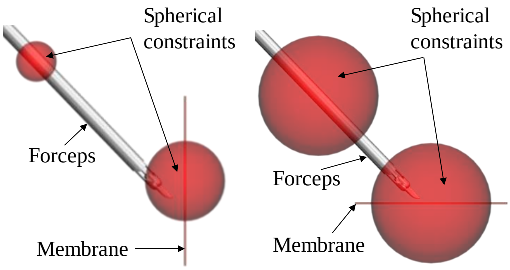

Figure 5b: Kinematic constraints for hard (left) and easy level (right).

approach, deformable structures are decomposed into rigid elements connected by soft constraints (i.e. actuated joints with viscoelastic properties), yielding to a dynamic multibody system analogous to a mass-spring network. By empirically adjusting the values of mass and inertia tensor at each rigid element, and the stiffness and damping at each joint, plausible viscoelastic behavior can be attained at interactive rates. This approach has the advantage that only few elements are required to be simulated, while the deformed high-resolution model is obtained by linear interpolation (Fig. 4). To solve the rigid body dynamics, we employed the PhysX Engine (NVIDIA, USA), and the full simulation software was implemented using C++ programming language. The simulated robotic surgical system consists of a pair of industrial robot arms (VS-050, Denso Wave Inc.), with a 4 DOF flexible forceps attached to the robot wrist [6]. To solve the inverse kinematics and for adding spherical constraints to constrain the movement of the tools' shaft within the workspace, we employed the framework proposed by [2]. A pair of haptic devices Phantom Premium (3D Systems, USA) were used as

Figure 6: VR simulation at the maximum level of difficulty being operated by using haptic interfaces.

user-interface to provide similar operation conditions as with the physical robotic system (Fig. 6). Additionally, we provide force feedback during the training to render haptic cues during collision of the tools, needle insertion, thread pulling, and when the user attempts to move outside of the workspace.

2.2 Difficulty levels

After our experience using the physical robotic surgical system on a head mockup [7], and our VR simulator resembling the same scenario (Fig. 2), we identified the following characteristics that make endonasal dura mater suturing particularly difficult. First, the relative orientation of the dura membrane with respect to the point of view. Since we are employing a 70 degrees endoscope, the plane of the membrane is almost facing the camera, forcing the suturing to be performed vertically. Next, the tools inserted from the nostrils appear vertically from above with respect to the point of view of the endoscope, being an uncomfortable posture for needle driving and knot tying. Moreover, the narrow workspace restricts the movement of the forceps inside the nasal cavity. We regarded the above-mentioned conditions as the hard difficulty level for this study. In counterpart, we defined the easy level such that the endoscope angle is 0 degrees, the orientation of the membrane is oblique with respect to the point of view and the forceps, within a less restrictive workspace (i.e. larger insertion point radii). For the preliminary test on this work we implemented the easy and hard difficulty level on separated software applications. While the simulated objects and the scenario are the same, the differences between the easy and the hard level are the relative pose of the membrane, endoscope and tools, the endoscope angle, and the size of the kinematic constraints (Fig. 5a-b).

3. Experiments and results

We accomplished real-time simulation of the robot-assisted suturing task at interactive rates (~60Hz). For testing our training system, a single user with no surgical experience performed a single stitch using our VR simulator at the easy and hard difficulty levels. Photorealistic rendered frames of the simulation using the software Unity 3D (Unity Technologies, USA) appear in the figure 7. The initial tests showed that it is possible to complete the task at both difficulty levels. The task completion

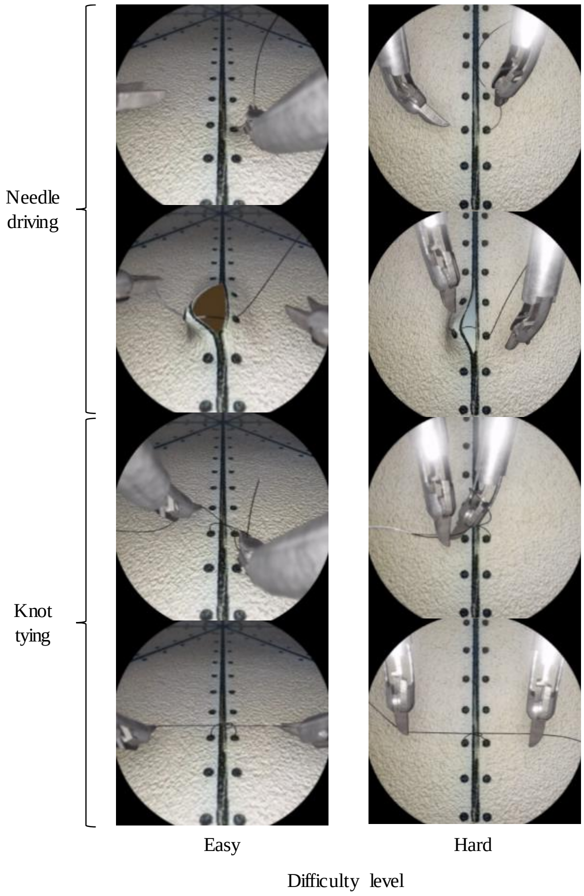

Figure 7: Screenshot of the VR simulator for practicing robot-assisted suturing on a rubber sheet.

time for a single trial was consistent with the difficulty level, requiring 7 min 21 s for the easy level and 14 min 35 s for the hard level.

4. Discussion

Using the proposed methodology using rigid body dynamics we achieved real-time simulation of deformable objects such as the rubber sheet, the surgical thread, and the flexible forceps. Although we implemented the easy and hard difficulty levels on separated software applications, the only changes were the pose of the objects, endoscope angle, and the size of the kinematic constraints, suggesting that the simulator can be implemented on a single application with variable level of difficulty controlled by a single parameter. Further studies will be carried out to validate the proposed simulator as a training program for the acquisition of suturing skills in robot-assisted endonasal surgery.

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