Towards Accurate Robot-Assisted Neuroendoscopy using an Ergonomic Handling Interface and a Lightweight Robot

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Abstract— **We considered a robot-assisted neuroendoscopy, and we developed a handling interface for linking a clinically-used endoscope to a lightweight robot (tool holder) with 7 DoFs. Such a robot holds potential for soft interaction with the surgeon, yet its intrinsic compliance must be suitably tamed not to lose tool targeting accuracy. Starting from practical specifications by neurosurgeons, we designed, fabricated and preliminarily assessed a compact and ergonomic handling interface. Such an interface permitted to easily insert/retract the tool (the measured force was 2 N), and to accurately hit a predefined target (the mean targeting error was below 0.5 mm, within the accuracy level of the optical tracker used for tool localization and pose). The feedback by neurosurgeons was very positive, thus encouraging further developments.**

I. Introduction

Despite the availability of advanced interventional techniques such as minimally-invasive approaches, many surgical tasks are still very challenging because of the complex and possibly time-varying anatomical constraints. This occurs, in particular, in brain surgery, where the biomechanical coupling with cerebral blood flow produces a dynamic environment, especially within the cerebral transventricular region. Many high-impact pathologies occur in this domain, such as tumors, epilepsy and hydrocephalus, which motivate the quest for ever-enhanced approaches. Together with minimally-invasive strategies (e.g. trans-nasal ENT approaches), computer/robot-assisted surgery holds potential for therapy improvements, in terms of enhanced safety, repeatability, procedure standardization, increased effectiveness of the surgical task, and reduced recovery times [1]. A few robotic systems for neurosurgery are commercially available, namely NeuroMate® (Renishaw plc) [2] and ROSA™ (MedTech s.a.s.) [3], which serve as accurate tool-holders thanks to their rigid structure. However, they are rather cumbersome and they are not natively integrated in the operating room. Moreover, an MRI-compatible robot for neurosurgery was also developed [4], whose widespread diffusion seems to be hampered by size constraints and high costs. More recently, system-level platforms are being proposed, aiming at implementing cognitive approaches built upon accurate preoperative reconstructions and addressing active working constraints [5]. In the same spirit, the present work addresses a computer/robot-assisted platform for neurosurgical applications, with the aim of developing robust approaches based on soft/safe surgeon-robot interaction. To this purpose, we considered a 7-DoF lightweight robot (LWR), namely the LightWeight IV+ arm (Kuka Roboter), since it holds potential for integration in the surgical scenario. Indeed, besides having a small footprint, a surgeon can take advantage of LWR redundancy in order to vary its elbow position (in response to interventional needs) without affecting the end-effector working pose. Moreover and more importantly, the LWR can be operated in a threefold manner: autonomously, teleoperated, and in a hands-on mode, in which a shared surgeon-robot control is implemented. The autonomous mode can be used to increase accuracy and repeatability, while the hands-on mode can be tailored to take advantage of the surgical gesture (especially when the surgeon is expert) while introducing virtual fixtures for a safer approach to the workspace (this is more relevant for less experienced surgeons). Teleoperation can further extend tool maneuverability and accuracy, yet it is less relevant for the present study, where we addressed a model neuroendoscopic procedure for assessing the usability of a compliant arm like the LWR as tool-holder.

In more detail, we considered an endoscopic third ventriculostomy (ETV). This is a surgical procedure for treating hydrocephalus, namely an abnormal accumulation of cerebrospinal fluid (CSF) in the cerebral ventricular system, e.g. due to a stenosis of the cerebral aqueduct. During ETV, a rigid endoscope is used to create an opening in the floor of the third ventricle, upon access through a Monro foramen, so as to allow CSF drainage towards the basal cisterns. Surgeon experience plays a critical role for the endoscope insertion pose; moreover, surgeons exploit tactile feedback when creating the access to the ventricular system. We therefore developed an interface for effectively handling a clinically-used neuroendoscope linked to the LWR, based on careful input by neurosurgeons. Moreover, we implemented a model ETV where the LWR firstly posed the endoscope based on preoperative planning, by subsequently allowing for hands-on insertion/retraction. Both a planar target and a cranial phantom were used, and the insertion force needed to handle the proposed interface was measured. We also measured the targeting accuracy by using the aforementioned planar target, having in mind that neurosurgical keyhole procedures typically require a positioning accuracy under 1 mm. We aimed at preliminarily assessing the effective usability of a compliant lightweight robot for accurate tool positioning. Medical doctors provided both the specifications and the essential feedback for the proposed bioengineering work.

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II. Material and Methods

A. Robotic Platform Overview

The robotic platform we integrated consists of an interventional module, a control module and a processing module. The interventional module is based on the LWR that acts as a tool holder. The main element of the control module is a desktop PC running a Linux RTAI real-time O/S, which acts as the central controller for the whole platform. Such a module also includes the operator interface. The processing module deals with both intraoperative and preoperative imaging data. It includes, in particular, an optical tracker (Hybrid Polaris Spectra, Northern Digital Inc.) for intraoperative tool localization, and a software application based on 3D Slicer (www.slicer.org), which is used for tool path planning as well. The platform is shown in Fig. 1, where the LWR and the optical tracker (OT) are highlighted. The control module also includes a graphical user interface to input LWR control parameters, and a wall display that supports preoperative planning as part of a virtual simulator [6]. The central controller communicates with LWR and OT through Ethernet and RS-232 connections, respectively. In particular, LWR remote operation is enabled by the Fast Research Interface (Kuka Roboter) that exploits UDP communication between the central controller and the LWR control unit. This architecture allows for a continuous dataflow among the robotic tools, sensors, and operators, which is of paramount importance for optimizing surgeon decision-making and intervention. The platform includes additional devices, namely an electromagnetic tracker (Aurora system, Northern Digital Inc.), an ultrasound system (iU22, Philips), as well as haptic interfaces (Phantom Omni, Sensable; Sigma.7, Force Dimension), which however were not exploited for the present work.

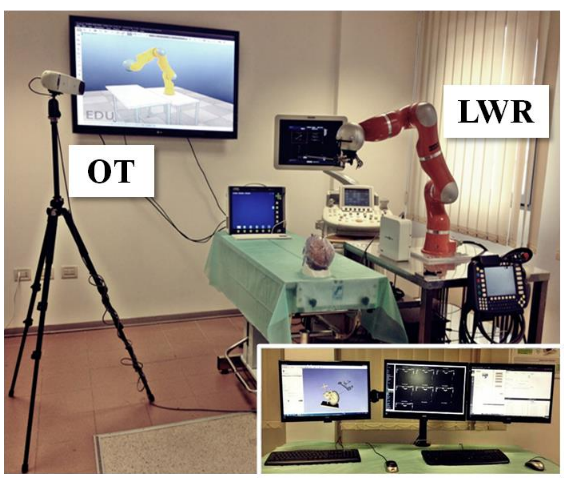

Figure 1. Computer/robot-assisted surgical platform; the operator interface for remote control in shown in the inset.

As anticipated, the LWR was chosen for its potential for soft/safe human-robot interaction, as enabled by joint compliance. However, joint impedance controllability intrinsically comes at the cost of reduced accuracy. Hence, a closed-loop compensation strategy was preliminarily implemented [7], in order to systematically correct positioning errors due to uncertainties on the LWR model and on the relative pose between the involved reference frames. This strategy was based on OT measurements and exploited an inverse kinematics suitable to deal with LWR redundancy. Such a control permitted to achieve a positioning accuracy around 0.5 mm on the LWR distal reference frame (wrist). This value is practically equal to the insurmountable accuracy limit of the OT (as measured through extensive tests), and therefore somehow optimal in view of subsequent platform applications [8]. For the considered ETV procedure, we used the LWR for positioning a neuroendoscope near and perpendicularly to the predefined model entry point, as well as to constrain its motion along the planned insertion path. In particular, the LWR carried out the former task in an autonomous way, while the latter one was accomplished in hands-on mode, by modulating LWR joint impedance so as to allow for shared surgeon-robot control.

B. Handling Interface Design

We designed a handling interface in order to link a commercially available neuroendoscope (27030 BA, Karl-Storz), see Fig. 2A, to the LWR. The considered endoscope is actually used in the clinical practice; it is equipped with a light source (fiber-optic cable) and a one-chip color camera, whose recording is output in real-time to a 15'' LCD display (TELE PACK X, Karl-Storz) also shown in Fig. 1. Such an intraoperative visual feedback is fundamental for surgeon monitoring, decision-making and intervention. The endoscope interfaces to the camera control and to the light powering device affect the surgeon grips, which is mainly achieved by three fingers, with the index typically holding onto the light powering connector as in Fig. 2B, and the rest of the hand warping the camera interface (a few configurations are typically used). Apart from these gripping constraints, the handling interface must be transparent (besides ergonomic) for the surgeon, in order not to negatively affect its manual/cognitive skills during operation. This also applies to any auxiliary components, like the set of optical markers which must be foreseen for the endoscope to be tracked by the OT.

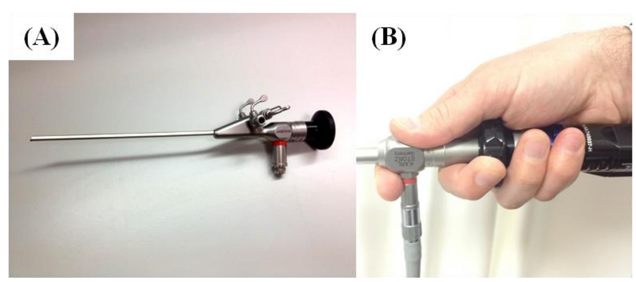

Figure 2. Neuroendoscope (A), and exemplificative grip (B).

Moreover, the interface must not interfere with the operating workspace at the base of the endoscope, where there are ports for flushing (through syrinxes/tubes) and tools insertion. Furthermore, the link to the LWR should be simple and compact, by also featuring a mechanism for fast tool change/securing, thus fostering modularity and extending platform effective usability. In light of the aforementioned specifications, we proposed the two-clutch concept in Fig. 3, which leads to a compact handle by taking advantage of the endoscope shape. In particular, endoscope locking is achieved upon fastening the two clutches (through n.5 screws): two main clamping surfaces match the proximal part of the endoscope body, and together with two small hook holders and a cylindrical holder they fully constrain tool motion against translational and rotational actions.

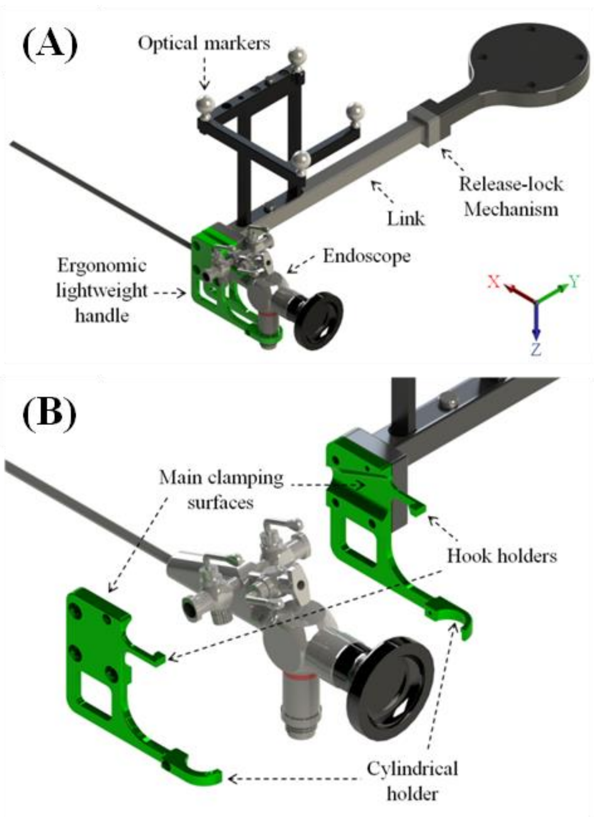

Figure 3. Endoscope handling interface. (A) Concept, also showing the link to the holding robotic arm and the optical markers for intraoperative localization. (B) Detailed view showing the two clutches of the handle, and the tool clamping elements.

Clearly, this concept also allows for a lightweight solution. Indeed, based on the actual size of the clutches shown in Fig. 4A, and by choosing the AISI 316 stainless steel as material, we obtain a 42 g handle. We verified the strength of each clutch by considering a ±20 N handling force; such a value is conservative in light of typical forces applied during the endoscopic procedures [9]. Moreover, by considering a 60 mm x 40 mm x 20 mm bounding box for the handle clamping the proximal part of the endoscope, we consistently verified each clutch by considering the following torques (the coordinate system is shown in Fig. 2A): Tx = ±0.4 Nm, Ty = Tz = ±0.6 Nm. These verifications were carried out by using the finite element analysis (FEA) capabilities of the SolidWorks (Dassault Systemes) software, which was also used for CAD modeling. The minimum safety factors turned out to be 7 and 6, for the forces and the torques respectively, thus fully supporting the strength of the proposed handle design.

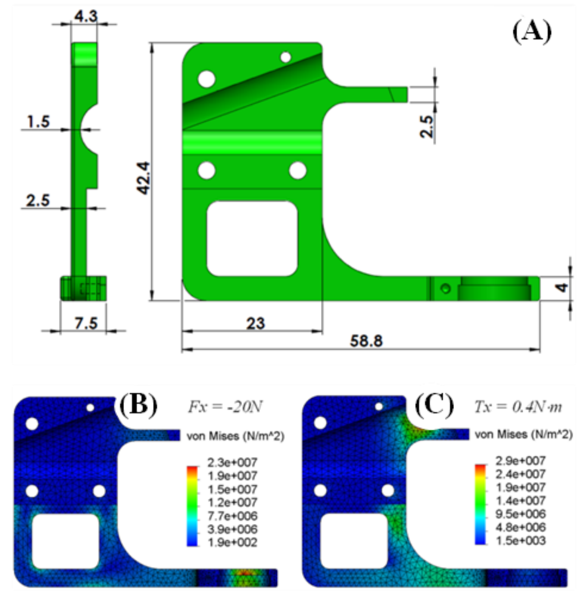

Figure 4. (A) Clutch geometry (lengths in mm). Exemplificative FEA results: von Mises stresses for Fx = -20 N (B) and Tx = 0.4 Nm (C). Corresponding safety factors are 7 and 6, respectively.

C. *Targeting Accuracy Assessment and Force Measurement*

Targeting accuracy was measured in a model procedure, once mounted an ink-releasing nib (diameter 0.1 mm) in the working channel outlet at the endoscope tip. A target point was defined on a suitably referenced paper sheet that was put on a planar support (inclined by 35 deg with respect to the horizontal direction). The support was equipped with optical markers so as to enable LWR calibration and close-loop compensation. Based on the support geometry, the LWR was asked to automatically pose the endoscope perpendicularly over the target, at a predefined distance d. Then, a hands-on procedure was commanded, by releasing the LWR stiffness except along the insertion direction, and the operator was asked to manually hit the target 8 times. Afterwards, high resolution images of the spotted sheet were processed by using Matlab (The Mathworks), so as to obtain the distance between the target and the centroid of the 8 spots. Three distances were considered, namely d = 2, 5, 10 cm, and for each of them we repeated the hitting task 5 times. During each test we recorded the torque on the last LWR joint (whose axis coincides with the one of the circular flange in Fig. 3A), and the forces on the handle, as estimated by the LWR controller based on the joint torques. We considered such a shared-control procedure since it allows the surgeon to keep the tactile feeling it requires for optimal intervention. For completeness, we repeated the force measurements test on cranial mockup obtained by endowing a commercial phantom (3B Scientific GmbH) with a 3D-printed model (Projet, HD3000) of the ventricular system reconstructed from 3T MRI images. Optical markers were added, to enable registration. The endoscope was posed at the distance d (values as above) over the selected entry point (Kocher point), around which a 15 mm diameter keyhole was performed. The endoscope was then inserted until touching the clivus zone (near the floor of the reconstructed third ventricle).

III. RESULTS

The handling interface was fabricated by conventional milling; an exemplificative grip by an expert neurosurgeon is shown in Fig. 5A. Endoscope handling was extensively assessed by 3 neurosurgeons (Meyer Pediatric Hospital, Florence, Italy), by using the LWR hands-on control mode. They fully confirmed handle transparency with respect to the surgical gesture, and they unanimously judged the developed interface as compact, ergonomic and effective usable for the robot-assisted ETV procedure. The experimental setups used for the force measurements are reported in Fig 5B; the one also used for the targeting accuracy tests is shown in the top inset. It can be noticed from the latter figure that for such a first prototype we did not fabricate the release/lock mechanism, for simplicity. However, we also prototyped a light wires-clamping apparatus (in Delrin) running under the link (in Aluminum), which enhances the LWR gravity compensation of the endoscope (while preventing the auxiliary cables from contacting the surgeon's hand).

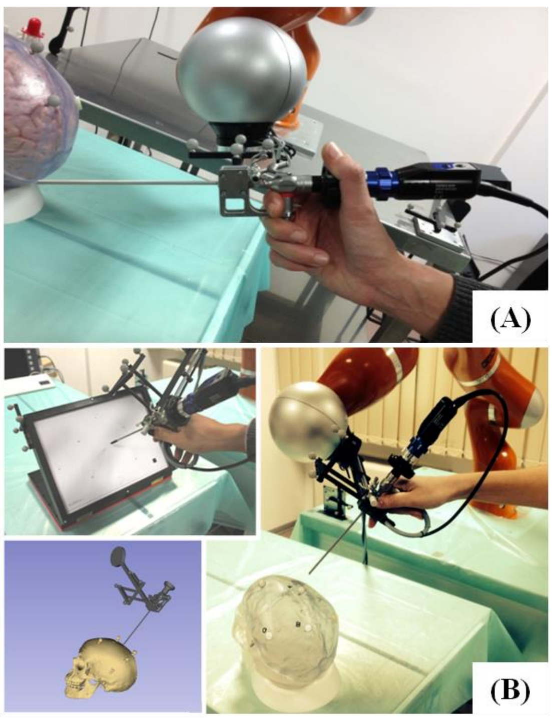

Figure 5. (A) Surgeon grip on the neuroendoscope handling interface. (B) Robot-assisted endoscopy on a cranial phantom; the planned insertion path is shown in the bottom inset. The setup used to quantify the targeting accuracy is shown in the top inset.

The resulting insertion/retraction force is shown in Fig. 6 for both the planar and the cranial targets, for all the considered endoscope initial distances. In all cases the force turned out to be around 2 N (slight overshoots denote the starting phase of tool insertion and retraction). Finally, the obtained targeting errors are reported in Tab. I (mean±std over the 8x5 hits); all of them are within the accuracy limit of the OT (0.5 mm). These accurate results, together with the aforementioned handle acceptance and the fact that the force needed to operate the LWR-assisted endoscope was low and practically independent of the initial tool-target distance (as expected), fully support the proposed handling interface, paving the way for more extensive and clinically-representative tests of the developed platform.

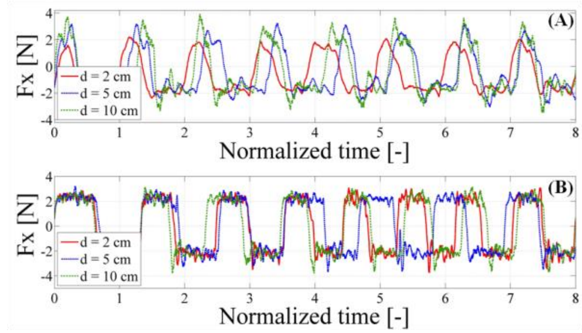

Figure 6. Exemplificative recordings of the handling force along the insertion direction, for the planar (A) and the cranial target (B). Time is normalized so as to highlights the 8 hits. In (B) the insertion/retraction duration in a cycle was relatively longer, since targeting was pushed until the clivus region, deep in the phantom.

TABLE I. TARGETING ACCURACY RESULTS

Initial distance d from the target [cm]	*Targeting error (mean±std) [mm]*
2	0.33±0.15
5	0.37±0.15
10	0.43±0.16

IV. CONCLUSION

We addressed a neuroendoscopic procedure in order to preliminary assess the suitability of using a lightweight robot as tool-holder, in a platform pursuing soft robot-surgeon interaction. Surgeon feedback on the developed handling interface was very positive, as well as the results of preliminary targeting tests. Both aspects fully support further platform development and assessment, by also considering further ETV tools [10], and thus prospectively contributing to improve current surgical approaches.

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