A Novel Surgical Robotic Platform Minimizing Access Trauma

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INTRODUCTION

Robotic surgery is nowadays common in clinical practice, thanks to the spread of the Intuitive Surgical's Da Vinci platform [1]. The next generation of surgical robots should still guarantee the same dexterity and performances, while reducing access trauma. A promising approach in this direction is represented by robotic platforms specifically developed for laparoendoscopic single site (LESS) surgery [2-4]. Actuation for the several degrees of freedom (DoFs) may be external, by means of cables [2], internal, using on-board motors [3], or hybrid [4]. In any case, the mechanical continuity of the kinematic chain constraints the workspace to the insertion point proximities. Having the single components of the platform, i.e. at least 2 manipulators and one camera, magnetically linked across the abdominal wall as in [5] would greatly enhance both freedom of operation and triangulation. On the other hand, relying just on on-board motor actuation, as in [6], results in limited dexterity and low speed. Larger, thus more powerful, motors can be used at the price of enlarging the access port. The aim of the present paper is to describe a novel concept for LESS robotic surgery, targeting Da Vinci system performances, but to be introduced and deployed by a single 12 mm access port. Thanks to a trans-abdominal magnetic link (TML), obtained by coupling external to internal permanent magnets (EPM and IPM), several DoFs of the internal tools can be actuated outside the patient's body. This reduces the number of DoFs to be actuated by on-board motors, thus minimizing the size of the internal robots. Additionally, thanks to the separation of the kinematic chain, the components of the robotic platform are not constrained to the access point, thus resulting in a wider workspace and in the possibility to reposition the tools during the surgical procedure. This disruptive approach has the potential to completely restore the workspace typical for open surgery, while limiting the access trauma to a single minimal incision.

MATERIALS AND METHODS

The proposed robotic platform is intended for bimanual abdominal surgery, therefore it is composed by at least 2 internal robotic arms and a camera. Once the internal modules have been introduced into the abdomen through a single 12 mm entry point and magnetically docked to the EPM, all the DoFs of the platform, both the external and the internal ones, are teleoperated by the user. Each EPM is independently held by an external robotic arm. As represented in Fig. 1, at least 5 DoFs can be transmitted across the TML, while additional distal DoFs are actuated by on board motors. Each internal module is provided with energy and data transmission by a soft tether, which can also be used for a safe retrieval in case of failure. While some parts of the platform are either commercially available (e.g. the external robotic arm) or already reported in literature (i.e. the camera robot [7] and the distal part of the internal robotic arms [8]), the main open challenge is the TML. This must reliably transmit the externally actuated DoFs to the internal robotic devices, while guaranteeing stable anchoring.

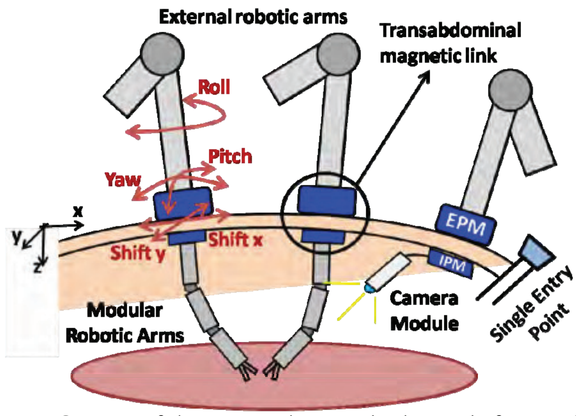

Fig. 1 Concept of the proposed surgical robotic platform. The DoFs transmitted by the TML are represented by the red arrows.

Three different actuation concepts for the TML (i.e. passive link (PL), active magnet rotation (AMR) and active magnet translation (AMT)) were identified and analyzed to find out the most effective actuation strategy. In PL (Fig. 2A), the actuation is provided just exploiting the magnetic coupling between EPM and IPM and taking advantage of the abdomen's elasticity. While roll and shift on x and y are obtained as in PL, the rotation or the translation of a single couple of magnets facing each other across the abdominal wall enables pitch and yaw of the internal joint in the AMR and AMT concepts, respectively (Fig. 2B-C). The AMR exploits a cable transmission and a winding mechanism to transmit forces from the IPM to the modular arm, whereas the AMT actuation takes advantage of rigid links. In order to compare these approaches, standard conditions were defined for magnet arrangement and features. In particular, a cross-shaped arrangement of 5 magnets was adopted for both EPM and IPM. Such a configuration can be deployed into the abdomen through a standard trocar by taking advantage of an umbrella-like opening mechanism.

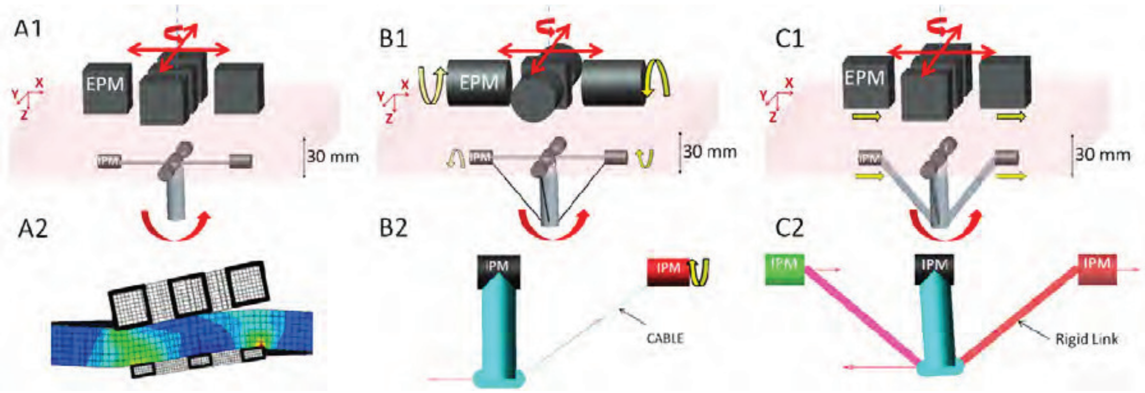

Fig. 2 A1, B1, C1: Schematic representations of PL, AMR and AMT approaches. **A2, B2, C2:** In A2 an ABAQUS FEA simulation of EPM-tissue-IPM interaction during a pitch displacement for the PL approach. In B2 and C2 ADAMS analysis of force/torque transmitted at the joint for the AMR and the AMT approaches, respectively.

Given the symmetric structure of the TML, each concept was modeled and studied along a single plane, perpendicular to the abdomen. TML maximum anchoring force (i.e. normal force during pitch/yaw actuation), maximum pitch/yaw force and range of motion were adopted as benchmarks for this study.
Based on a 30 mm average abdominal tissue thickness upon insufflation [9], maximum forces and torques induced from the EPM to the IPM were predicted. Mathematical estimation of the magnetic field was based on the charge model [10], which was implemented in MatLab (MathWorks). The magnetic interactions were then used to simulate the internal magnetically actuated joint and to find the pitch/yaw force and motion range. The AMR and AMT concepts were modeled using ADAMS (MSC Software Corporation), while for the PL design the abdomen mechanical resistance during pitch/yaw was evaluated with ABAQUS FEA (Simulia). Views of these simulations are represented in Fig. 2-A2, B2, C2. Finally, considering as worst case scenario a 100 mm long manipulator on the distal end of the TML, laying straight on the z axis, the maximum tangential force available at the end effector (EE) was estimated.

RESULTS & DISCUSSION

Numerical results coming from simulations are reported in Tab. 1. The PL approach shows the best performance in terms of anchoring force, while all the other benchmarks suggest the AMR approach as the most promising.

Table 1 Forces and pitch/yaw range for the three actuation concepts.

	Max anchoring force		Max pitch/yaw force		Max tangential force EE		Pitch/ yaw range
	N	Kg	N	Kg	N	Kg	
PL	15	1.53	4	0.40	1.3	0.13	±10°
AMR	14	1.43	8	0.82	2.6	0.27	±80°
AMT	12	1.22	3.4	0.35	1.1	0.11	±20°

In particular, the winding mechanism of AMR enables a much wider range than AMT, since wires are less bulky than rigid links.

Considering both the contact area and the results reported in [11], the tissue in between EPM and IPM gets damaged in case anchoring force exceeds 80 N. The estimated maximum anchoring and tangential forces at the EE for the AMR approach are 14 N and 2.6 N, respectively. Given that forces exerted on the tip of a surgical instruments do not usually exceed 5 N [12], an improvement in tangential loading capabilities is still called for. Next steps will be fabrication of the AMR approach and its integration into a robotic platform.

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