Mechanical Reinforcement Towards Fully Soft Magnetic Endoscopic Endonasal Surgical Manipulators

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May 31, 2022

Mechanical Reinforcement towards Fully Soft Magnetic Endoscopic Endonasal Surgical Manipulators

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INTRODUCTION

Endoscopic Endonasal Surgery (EES) targets the sinuses or base of the skull for treatment of lesions, tumors or polyps. The endonasal approach for these procedures is much safer than a craniotomy approach, involving removing part of the skull to access the operating site. Even though current EES is highly beneficial, technological limitations are still present [1]. EES is performed by inserting a rigid endoscope and accompanying tools through the nostrils. The coupled constraints of narrow, curved anatomy with straight and rigid tools present a significant challenge in EES, limiting visibility and maneuverability within the workspace. Enhancing the flexibility and controllable Degrees of Freedom (DoF) of the tools could make procedures safer and easier to perform. Most of the proposed robotic solutions for EES are mechanically driven with sizes close to standard and do not address the issue of miniaturisation or delicate tissue interaction [2], [3]. The field of soft robotics may offer solutions to the issues faced in EES, allowing small compliant manipulators with increased DoF for superior maneuverability and safer tissue interactions. Of these robotic designs, the relatively new field of Soft Magnetic Manipulators (SMMs) presents some notable advantages when designing for small scales. SMMs can be entirely soft and can be magnetically pre-programmed to produce desired deformations under exposure to specific and controlled external magnetic fields [4]. External, remote actuation of this type thus enables extreme miniaturization without loss of controllable DoFs, which is often impossible to achieve with other approaches due to the accommodation of onboard actuation. Due to these advantages magnetically actuated devices can be very beneficial in medical environment – specifically for improving navigation through tortuous anatomical pathways and difficult to access surgical sites, such as in EESs. In this paper we investigate the application of soft continuum magnetic manipulators to EES procedures. In combination, the presented approach aims to enable delicate interaction with tissue, and higher maneuverability with respect to current EES tools; overcoming issues associated with torsion.

MATERIALS AND METHODS

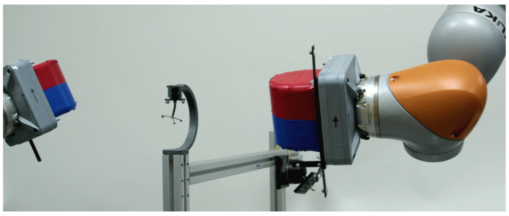

Fig. 1 Experimental set up: a manipulator with optical markers, robotic arms with External Permanent Magnets (EPMs) and frame with optical markers.

A magnetic agent with a magnetic moment m is subject to magnetic force (F) and torque (τ), under an applied field B, respectively as

$$\vec{F} = (\vec{m} \cdot \nabla)\vec{B} \tag{1}$$

$$\vec{\tau} = \vec{m} \times \vec{B}. \tag{2}$$

The magnetisation direction of a controlled body is a crucial element when it comes to magnetic actuation of soft structures. According to (2), when the magnetisation direction of the magnetic body aligns with the applied external magnetic field direction, it is subject to no resultant torque. If not aligned, magnetic torque will tend to rotate the body; it can be expressed as the cross product of magnetisation direction and applied external magnetic field (2). Using this phenomenon, the magnetic manipulator can be pre-programmed in a manner to achieve desired deflection, when exposed to specific external magnetic fields.

In cases where the angle between the magnetisation vector and applied magnetic field is higher than 90°, SMMs will commonly twist around the z axis of the manipulator, rather than producing expected deflection. The concept of constraining torsion in magnetic soft robots was explored by [4], through the addition of helical fibres; succeeding with twist reduction of 67 %. To address the issue of twisting, we consider a manipulator design with a monolithic elastic double helix reinforcement structure. Pursuing a geometrical solution to the torsional effect maintains the benefits of fully soft

TYPE	OD (mm)	ID (mm)	R	h (mm)	w (mm)
CYL	*3.5*	*N/A*	N/A	N/A	N/A
SMM 1	*3.5*	*1*	30	0.5	1.25
SMM 2	*3.5*	*1*	12.5	*1.5*	1.25

TABLE I Design parameters of SMMs including geometrical variation of helical reinforcement (Fig.1).

structure without a need for inclusion of hard structures such as springs or fibres. Figure (2) shows the design parameters in Y-Z and X-Z planes, related to the double helix SMM design. This results in relatively low stiffness along X and high stiffness along Y directions. Such stiffness variability allows for minimal bending in the Y direction and torsion around Z direction, while keeping high deflection in the X direction.
A cylinder and two designs of mechanical reinforcement with varied geometrical parameters were considered as defined in Table I.
Basing on clinical needs for miniaturisation, the outer diameter of the manipulators is set to 3.5 mm. The core cylinder diameter and width of the helices was held constant across designs (Table I). All samples were fabricated by casting, with 3D printed moulds (Grey V4 resin, Form III, Formlabs, USA). Equal parts of Dragon Skin™ 30 (Smooth-On, Inc., U.S.A.) A and B were mixed with 100 wt% of hard magnetic micro-particles (Nd-FeB with an average 5 μm diameter and intrinsic coercivity of Hci = 9.65 kOe, MQFP-B+, Magnequench GmnH, Germany). The magnetic slurry was then treated in a high vacuum-mixer (ARV- 310, THINKYMIXER, Japan) for 90 seconds at a speed of 1400 rpm and pressure of 20.0 kPa. The degassed slurry was injected in to the closed molds and cured at 45° for 30 minutes. To track samples during characterization with the dual arm system, a frame with optical markers was attached to the tip (Fig.1). Each design was fabricated twice to be magnetised in along their X and Y axes to allow comparison of stiffness variability between the axes. (Fig. 2).

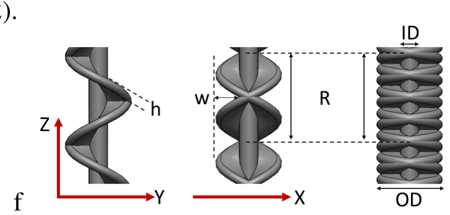

Fig. 2 Examples of monolithic reinforcement design, where h is the helix thickness; w is helix width; ID is the core diameter; R is number of revolutions per unit length and OD is an overall diameter.

Three candidate designs (Table I) magnetised in X and Y directions were evaluated by recording data on manipulator deformation under varied conditions of external magnetic fields applied by dual arm robotic system with permanent magnets (Fig.1). The tip poses of manipulators are recorded via an Optitrack system with optical markers attached to the manipulator during testing. The bending information around X, Y and Z was obtained from rotation of the rigid body.

RESULTS

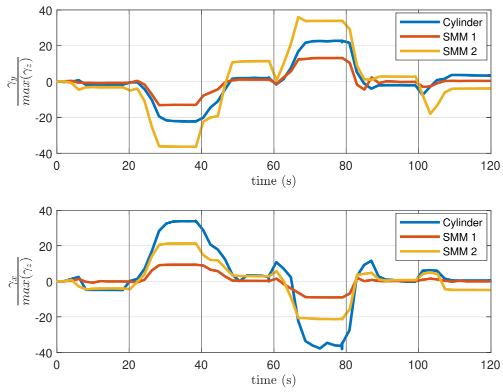

Fig. 3 Results of testing 3 candidate designs under different magnetic field conditions as a ratio of deflection to torsion. Top: Samples magnetized in X direction; Bottom: Samples magnetized in Y direction.

An optimal geometry for this type of manipulator should show minimal twisting behaviour and maximum deflection in the easy axis, therefore we consider a ratio of bending in the magnetized direction to the maximum recorded torsion for all six samples. In the case of magnetization along X, the optimal design is expected to have the highest ratio and the lowest in case of magnetization along Y. In the Fig. 3(top), SMM2 shows a greater ratio than a cylinder of the same diameter. In addition, the ratio value for SMM1 is lower than the value for both, cylinder and SMM2. In the Fig. 3(bottom), SMM1 shows the lowest ratio of all three samples. However, analysing both plots, it can be seen that only the design SMM2 shows desired behaviour in both magnetization cases.

DISCUSSION

Results collected for three candidate designs showed that the SMM2 design reduces torsion while keeping high deflection in X direction and relatively low deflection in Y direction. Therefore from samples tested in this paper, SMM2 is an optimal design to be used as a soft magnetic manipulator for EES. Future work will include investigation on a greater range of designs, varying more parameters of reinforcing geometry.

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