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Magnetic Endoluminal Devices Can Assist In Their Own Insertion

Nicholas R. Posselli, Emma K. Pinegar, and Jake J. Abbott

Department of Mechanical Engineering and Robotics Center, University of Utah
{nicholas.posselli, emma.pinegar, jake.abbott}@utah.edu

INTRODUCTION

In the design of long, flexible medical devices that are inserted into a lumen by pushing them from their proximal end (e.g., catheters, scopes, cochlear-implant electrode arrays), there is a fundamental trade-off between making the device flexible/soft to safely conform to the environment, and making the device stiff to enable the device to be inserted without buckling [1]. A number of continuum medical devices have incorporated magnetic actuation [2]–[5], typically at the distal end to magnetically steer the device in a desired direction. This type of magnetic actuation can reduce insertion forces and/or delay buckling by reducing the total friction between the continuum device and the environment. However, because the magnetic actuation is limited to the distal end, its effectiveness is reduced with increased insertion depth. Our group recently proposed a magnetic-actuation concept for soft endoluminal robots in which the soft robot has two or more axially magnetized permanent magnets distributed along its length, with the magnetization direction alternating between neighboring magnets, and a rotating external magnet is used to induce a traveling wave in the soft device, causing it to crawl in a deterministic and reversible direction [6]. In this paper, we extend the concept in [6] to soft continuum devices that are inserted by pushing them from their proximal end (Fig. 1). Our basic hypothesis is that if the magnetic-actuation concept is sufficient to cause crawling in untethered devices, it will also reduce the insertion forces required to insert continuum devices. We will show that this is, in fact, the case. We will also show that, in limiting cases, it is even possible to reduce the insertion forces to zero such that the continuum device inserts itself without any proximal-end push.

MATERIALS AND METHODS

We fabricated a simple continuum device comprising ring magnets with 1 mm inner diameter (dia.), 2 mm outer dia., and 1 mm thickness attached every 26 mm along the length of a Tygon tube with 0.75 mm outer dia. and 0.254 mm inner dia., using cyanoacrylate, such that the magnetization directions alternate between neighboring magnets (Fig. 2(b)).

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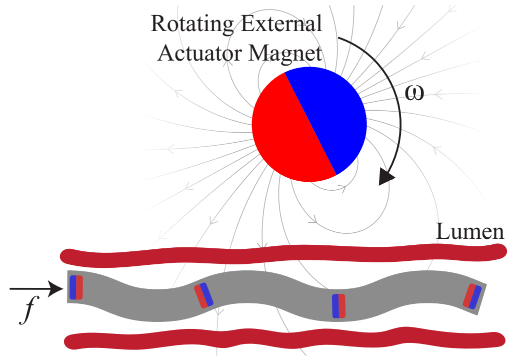

Fig. 1 Schematic of a flexible/soft continuum device, which has permanent magnets with alternating axial magnetization embedded along its length, being inserted into a lumen by applying an insertion force f at its proximal end while an external magnetic-field source, rotating with angular velocity ω, generates a nonuniform rotating field that induces a traveling wave to assist in the insertion of the device. The embedded magnets in closest proximity to the external magnet are the most greatly affected. The embedded magnets can be rings, to maintain a working channel in the continuum device.

We created an artificial lumen environment comprising a Tygon 3603 tube with 4 mm inner dia. wrapped into a planar spiral. We placed a 51 mm cubic NdFeB permanent magnet above the spiral such that its axis of rotation is approximately collinear with the spiral's axis, and its magnetization direction is orthogonal to this axis (Fig. 2(a)). This setup approximates magnetic actuation of a cochlear-implant electrode array [2], but it also lets us explore the physics of this magnetic-actuation concept in a truly open-loop fashion in which the behavior of the external magnet is invariant to the state of the continuum device. We conducted an experiment in which we placed the external magnet at five heights above the planar spiral between 70 mm and 190 mm, as well as with the external magnet completely removed, while rotating the external magnet at a somewhat-arbitrary angular velocity of 7.2 rad/s while manually inserting the continuum device as deep as possible until buckling prevented further insertion (ten trials in each configuration).
We conducted a second experiment in which we stretched the artificial lumen out in a straight horizontal line (Fig. 2(e)), and oriented the external magnet to match the configuration shown in Fig. 1, with its axis of rotation orthogonal to the lumen's axis. The

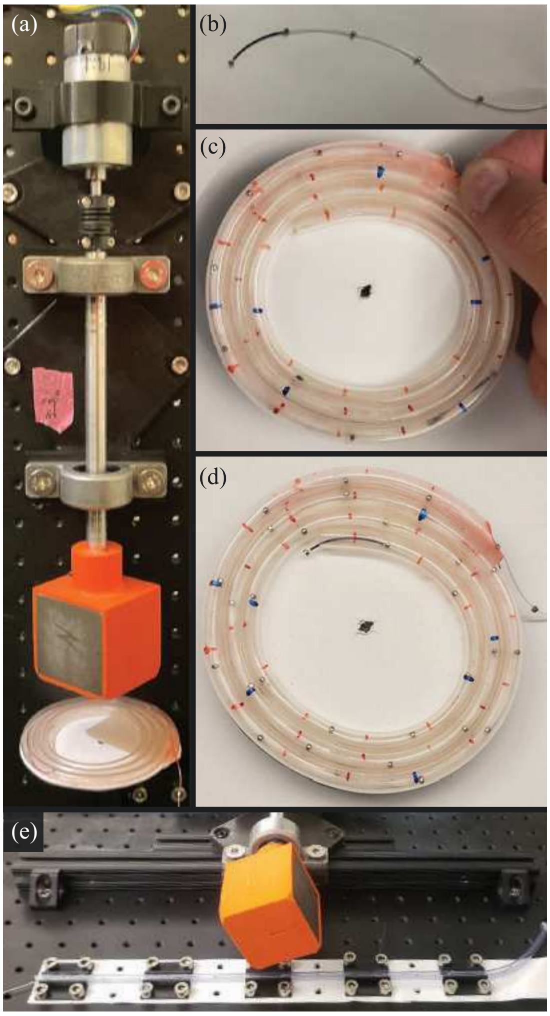

Fig. 2 (a) Experimental setup comprising a cubic permanent magnet rotated by a motor, at a reconfigurable height above an artificial lumen wrapped into a planar spiral. (b) Magnetic continuum device, with distal segment painted for visualization. (c) Example of buckling preventing deeper insertion at less than one complete turn of the spiral. (d) Example with continuum device having reached the final depth of the lumen at more than three full turns of the spiral. (e) Experimental setup comprising a cubic permanent magnet rotated by a motor, with manual horizontal translation at a fixed height, above an artificial lumen in a straight line.

experimenter moved the rotating external magnet to keep it approximately 60 mm behind the distal tip of the continuum device at a fixed height of 72 mm, again with an angular velocity of 7.2 rad/s, while manually inserting the continuum device as deep as possible (ten trials). We also performed ten insertion trials with the external magnet completely removed.

RESULTS

The results of the first experiment are shown in Fig. 3: the magnetic actuation resulted in much deeper insertion (up to the full 770 mm) than we could obtain without any magnetic actuation (up to 265 mm). Analysis of variance

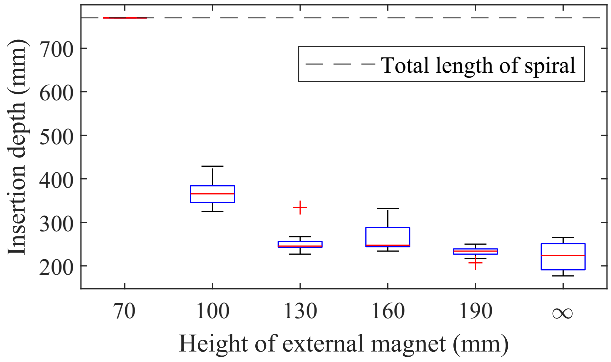

Fig. 3 Box-whisker plots showing results of ten insertion trials in planar-spiral at six magnet configurations.

indicates that external magnet height has a statistically significant effect ($p < 0.001$).

In the second experiment, the insertion depth was 337 mm (the full length of the straight artificial lumen) in all ten trials with magnetic assistance, and fell within the range 69–143 mm without magnetic assistance. During both experiments, we observed that for external magnet heights 72 mm and below, once the continuum device was inserted to some specific critical depth into the artificial lumen, it began to insert itself without any manual insertion force applied at the proximal end.

DISCUSSION

We have demonstrated a simple magnetic design and open-loop-actuation concept that both creates a pulling effect and inhibits the friction build-up that would eventually lead to buckling, which enables deeper insertion of a device than could be achieved otherwise. Further, given ideal conditions, it enables a continuum endoluminal device to insert itself into a lumen. Of course, our *in vitro* experiments are still fairly different from biological lumens, but the physical principles are likely to translate. We have not yet attempted to optimize the separation distance between the continuum device's magnets or the rotation frequency of the applied field. It is our conjecture that the actuation principles demonstrated here for spiral and straight paths could be applied to insertions along more general paths. However, there are still many unanswered questions about how that should best be done.

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