MECHANICAL FORCE MODULATION WITH PERMANENT MAGNETS AT SMALL SCALE

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Summary Magnetic actuation of medical devices has led to many complex concepts. The goal of this paper is to present different ways of modulating magnetic attractions of two catheters sandwiching a tissue. The active member contains a force modulator and the passive member comprises a single permanent magnet (PM). Solutions with steerable PMs are compared with electromagnets and discussed. Steering of PMs offer the largest range of modulation and are technically advantageous at small scale.

INTRODUCTION

Progress in the medical instrumentation field is mainly pushed by the need to make clinical procedures less invasive and traumatic for the patient. Growing research and advances in technology, miniaturization, robotics, autonomous systems and microelectronics are boosting the development of minimally invasive techniques. Magnetic actuation of medical devices has led to many new concepts growing in complexity, such as capsule endoscopy using external magnetic fields [1]; microrobots of sub-millimeter size steered inside the body fluids with external magnetic fields [2]; laparoscopic instruments inserted into the abdomen which are anchored through coupling with an externally held magnet [3] or ablation catheters remotely magnetically guided to treat cardiac arrhythmias [4]. Magnetic guidance and anchoring of medical devices require precise control of the magnetic force inside the body [5]. Generally, the control of the force is made outside with a second component having very large electromagnets or movable permanent magnets [1, 2, 4]. In some cases, the second component modulating the magnetic force is in contact with the tissue [3]. To the best of our knowledge, no existing devices offer magnetic guidance using force modulation where both components are inserted inside the body. Our research is on magnetic master-slave systems, particularly a catheter system to treat cardiac arrhythmias. The catheters are equipped with permanent magnets (PM) and are sandwiching the cardiac tissue. The catheter inside the heart can be displaced with the help of a second catheter in close vicinity to the heart. The control of the magnetic force and sliding of the catheter tip are key points to the success of our application. The aim of this paper is to present different ways of modulating magnetic attractions between two catheters sandwiching a tissue. In our case, the active catheter contains the force modulator and the passive catheter comprises a single permanent magnet. Solutions with permanent magnets are discussed. Electromagnets are an attractive solution because of the ability to control the strength, polarity and shape of the magnetic field. However, electromagnets are extremely challenging at small scale. Obtaining substantial magnetic field strength is impossible due to excessive dissipation (heat) and dangerous high voltages (needed for obtaining appropriate currents). Mechanical concepts with permanent magnets are compared with an electromagnet.

MATERIALS AND METHODS

Force modulation concepts are described and compared under the same realistic design specifications. The available volume for the force modulator in the active catheter tip is a cylinder of 5 mm in diameter and 10 mm in length (5x10 mm), which should comprise the magnetic material and modulation components. The passive catheter tip comprises a single cylindrical permanent magnet of 3x10 mm. The distance separating the two catheter tips varies in the millimetric range. For the analysis, the separation distance is set to 5 mm between the outer surfaces of the catheters. Permanent magnets are made of Neodymium-Iron-Boron alloys (NdFeB). The magnets are diametrically magnetized with a magnetization of 1'115 kA/m or with a magnetic energy density of 52 MGOe (414 kJ/m^3). Iron is used for the electromagnet core, $\mu_r = 4000$. COMSOL Multiphysics, a Finite Element Method (FEM) software, is used to calculate the magnetic forces for each proposed concept. All the concepts are simulated in 3-dimensions using the AC/DC module.

Mechanical Design

Figure 1(A) shows the different principles for modulating the attraction force between the catheters. The basic principle for the first two designs, Fig. 1(A) (a) and (b), is to rotate two identical permanent magnets (2x10 mm) in opposite directions to modulate the attraction force between the catheters. To offset the attraction force for this particular design, a static permanent magnet (0.8x2x10 mm) is placed along the modulation axis, Fig. 1(A) (b). For comparison, an electromagnet is also included, Fig. 1(A) (c). The electromagnet is built from a cylindrical ferromagnetic core (4x10 mm) material and a coil (1x1 mm^2 coil cross-section, wire of 0.1 mm in diameter) controlled by a current of 1 A (the maximum allowed current for a wire of this dimension) to produce a magnetic field perpendicular to the axis of the cylinder.

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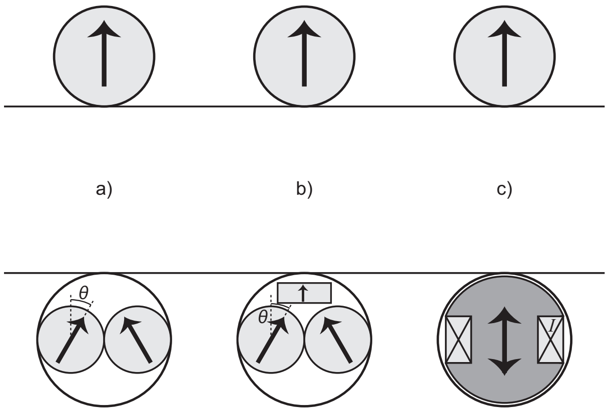
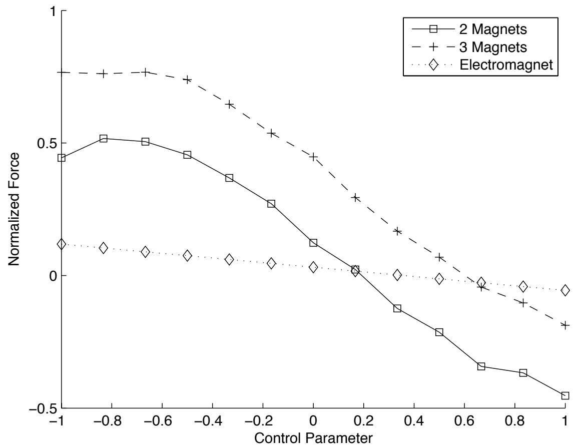
RESULTS

Finite element analysis has been performed for each modulation principle, Fig 1(B). The plotted attraction forces are normalized to a reference fixed permanent magnet occupying the available volume for the force modulator in the active catheter tip. This magnetic reference provides an upper limit for the maximum available attraction force between the two catheters. The angular orientation from 0° to 180° represents the control parameter for designs (a) and (b). For the electromagnet, the applied current from 1 to -1 A represents the control parameter, design (c).



(A) Force modulation principles



(B) Finite element magnetic force calculation

Figure 1. **(A)** a) 2 Magnets: two steerable diametrically magnetized permanent magnets. b) 3 Magnets: two steerable diametrically magnetized magnets plus one static vertically magnetized magnet. c) Electromagnet. **(B)** The x-axis represents a control parameter, namely an angle θ for the permanent magnets concept or a current I for the electromagnet. The y-axis represents a normalized magnetic force between the two catheter tips. The comparison of each concept is done relatively to a given fixed permanent magnet occupying the available volume defined for the force modulator, therefore representing the maximum attraction force possible.

Table 1 summarizes the results of the magnetic analysis and provides the maximum actuation torque required to rotate the permanent magnets. The main pros/cons for each concept are also included.

Table 1. Comparison of different force modulators

	2 Magnets	**3 Magnets**	**Electromagnet**
Normalized force range	[-0.46, 0.44]	[-0.16, 0.75]	[-0.11, 0.22]
Maximum actuation torque	1.1 Nmm	3.3 Nmm	NA
Advantage	Symmetric field	Symmetric field	Highly controllable
Disadvantage	Actuation torque	Actuation torque	Excessive heat

CONCLUSION

Different mechanical modulation principles have been proposed and magnetically compared. Solutions with steerable permanent magnets offer the largest range for modulation and represent the most suitable technical way of safely modulating magnetic forces at small scale. A prototype of the steering mechanism is currently being realized and will be used for experimental data collection. This work is funded by the Swiss Committee for Technology and Innovation (CTI).

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