Characterization of Helical Propulsion
Inside In Vitro and Ex Vivo Models of a Rabbit Aorta

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Abstract—In this work, the propulsion of a helical robot is experimentally characterized inside whole blood (in vitro model) and against the flowing streams of phosphate buffered saline (PBS) inside rabbit aorta (ex vivo model). The helical robot is magnetically actuated inside these models under the influence of rotating magnetic fields. The frequency response of the helical robot is characterized. Averaged speed is measured at actuation frequency of 8 Hz as 11.3 ± 0.52 (n = 5) and 7.45 ± 1.2 mm/s (n = 3) inside rabbit aorta and whole blood, respectively. The speed of the robot inside rabbit aorta is characterized against flowing streams of PBS at flow rate of 90 ml/hr.

I. INTRODUCTION

Characterization of micro and nanorobots inside in vitro and ex vivo models is essential for their translation into biomedical applications. These devices are powered and controlled remotely using externally-applied magnetic fields for motion control in two- and three-dimensional space. Drug delivery [1], micro-assembly [2], transportation and manipulation of biological cells [3], and diagnostics and bio-detection [4] have been demonstrated using microrobots. Felfoul et al. have utilized magnetotactic bacteria to enhance the therapeutic index during targeted therapy in vivo. They have employed the migration behaviour of Magnetococcus marinus strain MC-1 for their control towards a desired location [5]. Vonthron et al. have also demonstrated motion control of microrobots using a clinical magnetic resonance imaging system. They have implemented steering and localization of microrobots to achieve controlled navigation inside narrow blood vessels [6]. Also, A swarm of functionalized artificial bacterial flagella has been controlled in vivo using rotating magnetic fields based on the feedback of an optical fluorescence imaging system by Servant et al. [7]. Propulsion of drug-loaded magnesium microrobots have been demonstrated inside the gastric media of a mouse model by Fernández de vila et al. [8]. Although the mentioned results are promising, the conditions that will be encountered inside the human body are more challenging. For instance, the average blood flow rate in adults through the carotid artery is approximately 350 ml/min and 750 ml/min through the whole brain [9]. Motion control of microrobots against such flow rates has not been achieved yet. In addition, the thrombogenic response of the material of the microrobot will likely influence its locomotion in blood vessels. For instance, a microrobot with relatively high thrombogenic (such as titanium and tantalum) is expected to be surrounded with platelets while swimming in blood, and hence the swimming speed is expected to decrease as the drag force will increase for the same propulsive force.

In this work, the propulsion of a helical robot is experimentally characterized inside in vitro and ex vivo models. The helical robot is actuated by a permanent magnet-based robotic system using two synchronized rotating dipole fields [10], and we achieve the following:

- in vitro characterization of the frequency response of a helical robot inside a blood-filled catheter segment, using an array of Hall-effect sensors for localization.
- ex vivo characterization of the frequency response of a helical robot inside an isolated rabbit aorta, against the
flowing streams of phosphate buffered saline (PBS) at a flow rate of 90 ml/hr. The remainder of this paper is organized as follows: Section II provides descriptions pertaining to the magnetic-based robotic system, the in vitro, and ex vivo models implemented for experimental characterization. In addition, the influence of these models on the helical propulsion are discussed in the same Section. The experimental results are provided in Section III. Finally, Section V concludes and provides directions for future work.

II. HELICAL PROPULSION AND SYSTEM DESCRIPTION

The helical robot is allowed to swim under the influence of two synchronized rotating dipole fields inside a blood-filled catheter segment and a segment of a dissected rabbit aorta. These fields are generated using a permanent magnet-based robotic system.

A. System Description

The helical robot is characterized using a permanent magnet-based robotic system. This system comprises two rotating permanent magnets (R750F, Amazing Magnets LLC, California, USA) to generate rotating magnetic fields. Each permanent magnet generates magnetic field of 0.552 T on its surface. These fields exert a magnetic torque on the dipole moment of the helical robot that is allowed to swim between the permanent magnets, and contained inside a catheter segment or a rabbit aorta. The robot consists of a magnetic head and a tail. The head is a cylindrical permanent magnet (S-01-01-N, Supermagnete, Göttingen, Germany) and the tail is a helix-shaped copper wire (length, diameter, and pitch of 4 mm, 0.2 mm, and 0.85 mm, respectively). The head is attached rigidly to the tail such that its magnetization axis is orthogonal to the helix axis. Rotation of the permanent magnets enables helical propulsion of the robot against the mentioned mediums. In the case of in vitro model, a polyvinyl chloride catheter segment is filled with the mediums, whereas in the ex vivo model a segment from the aorta is isolated from a rabbit and connected to catheters to provide flow.

B. Helical propulsion

The helical robot is propelled inside the catheter segment or the aorta using two rotating permanent magnets. The axes of rotation of the permanent magnets are parallel to the helical robot to achieve one-dimensional locomotion inside the segment. We calculate the Reynolds number as

\[ Re = \frac{\rho U L}{\mu} \approx 0.004, \]

where \( \rho \) is the density of the medium, \( U \) is the speed of the helical robot, \( L \) is its length, and \( \mu \) is the dynamic viscosity of the medium. The calculated Reynolds number is in the order of \( 10^{-5} \). In such low Reynolds numbers viscous forces are dominant. Based on the hydrodynamic model presented in [11], the governing equations are given by

\[
\begin{align*}
(F_m + F_g + F_d + F_c) \\
(T_m + T_g + T_d + T_c)
\end{align*}
= 0,
\]

where \( F_m \) and \( T_m \) are the magnetic force and torque exerted on the dipole moment of the helical robot, respectively. Further, \( F_g \) and \( T_g \) are the force and torque exerted on the robot due to gravity, respectively. Furthermore, \( F_d \) and \( T_d \) are the drag force and torque, respectively, and \( F_c \) and \( T_c \) are the force and torque due to the contact of the robot with the channel wall, respectively. The influence of the contact forces on the helical propulsion can be neglected in the absence of contact with the channel walls or when the gravity is compensated using a vertical propulsive force component. This compensation is not possible in narrow channels as the robot becomes in continuous contact with the inner surface of the channel and constrained. In (1), the magnetic and gravitational forces and torques are given by

\[
\begin{align*}
F_m \quad &\quad T_m = \left( m \cdot \nabla \right) B \quad m \times B \\
F_g \quad &\quad T_g = \left( \rho R^T g \right) \quad r \times F_g
\end{align*}
\]

where \( B \) and \( m \) are the magnetic field of the rotating dipole fields and the magnetic dipole moment of the helical robot, respectively. Further, \( \rho = \rho_t - \rho_f \), where \( \rho_f \) is the density of the helical robot. Furthermore, \( r = r_{\text{cov}} - r_{\text{com}} \), where \( r_{\text{cov}} \) and \( r_{\text{com}} \) are the center of volume and center of mass of the robot, respectively. In (2), \( R \) and \( g \) are the rotation matrix between the robot and a frame of reference, and a vector of gravitational attraction, respectively. The drag and contact forces and torques are given by

\[
\begin{align*}
F_d \quad &\quad T_d = Z \left( U + U_{ch} \right) \quad \Omega \\
F_c \quad &\quad T_c = \left( k\beta + c\gamma \right) n_c \quad r_c \times F_c
\end{align*}
\]

where \( Z \) is a matrix that depends on the geometry of the helical robot and the properties of the fluid, \( U_{ch} \) and \( \Omega \) are the velocity field of the flow inside the channel and the angular velocity of the helical robot, respectively. Further, \( k \) and \( c \) are the stiffness and damping of the channel wall, respectively, and the coefficients \( \beta \) and \( \gamma \) are given by

\[
\begin{align*}
\beta = \begin{cases} 
\delta, & \text{if } \delta \leq 0 \\
0, & \text{if } \delta > 0
\end{cases} \quad \gamma = \begin{cases} 
\frac{df}{dt}, & \text{if } \frac{df}{dt} > 0 \\
0, & \text{if } \frac{df}{dt} \leq 0
\end{cases},
\end{align*}
\]

where \( \delta \) is the penetration depth along the lateral direction. Further, \( n_c \) and \( r_c \) is the surface normal of the channel wall at the point of contact and the position vector of the contact point, respectively.

III. In Vitro AND Ex-Vivo CHARACTERIZATION

The speed of a helical robot is characterized inside whole blood and a segment of a dissected rabbit aorta, under the influence of rotating magnetic fields with frequency range of 3 Hz to 8 Hz. All experiments are conducted at room temperature (25°C).

A. Characterization inside whole blood

Venous blood is drawn from a healthy donor (male 22 years old) into a vacutainer containing an anticoagulant (lithium heparin) to prevent blood clotting and keep the blood in its fluid form, and Local Institutional Ethical Board
Aorta is an elastic artery with an expandable media for circulating blood. It consists of three main layers from inside to outside, i.e., tunica intima, tunica media, and tunica adventitia [14]. The inner layer Tunica media is the muscular layer of arteries and veins, it provides elasticity and controls the diameter of a blood vessel. In arteries, the tunica adventitia is supported by an external lamina that increases the elasticity needed for greater expansion in case of relatively higher flow rate. Such elastic properties affect the propulsion of the robot and its swimming speed inside the aorta. We characterize the speed of the helical robot in a segment of a rabbit aorta (Fig. 3(a)). A rabbit weighting 1.5 kg is dissected and its aorta is isolated. The ends of the aorta segment are connected to a catheter segment of 3 mm inner-diameter for PBS circulation. The aorta is connected to a syringe pump (Genie Plus, GT-4201D-12, Kent Scientific, Connecticut, USA) and a flow of 90 ml/hr is induced against the direction of propulsion, which maintains the viability of the aorta during the experiments. The diameter of the aorta is measured as 4 ± 0.3 mm, this variation in the diameter could be attributed to the elasticity of the aorta. Maximum speed of the robot in the aorta segment is achieved at actuation frequency of 8 Hz, and measured as 11.3 ± 0.52 mm/s versus 14.8 ± 0.37 mm/s in the catheter segment. Averaged speed and standard deviations are calculated from 5 trials (n = 5). A representative trial at actuation frequency of 7 Hz is shown in Fig. 3(b). The speed reduction inside the aorta segment in comparison to PBS could be attributed to the elastic properties of the aorta, and the interaction between the robot and the inner layer of the aorta compared to the interaction with the rigid channel wall of the catheter segment. In addition, the reduction in the swimming speed of the helical robot inside the catheter segment in Fig. 3(a) in comparison to Fig. 2(b), is attributed to the presence of a flow rate of 90 ml/hr against the direction of propulsion for comparison with swimming speed inside rabbit under the same settings.

IV. CONCLUSIONS AND FUTURE WORK

The speed of a helical robot is experimentally characterized inside blood-filled catheter segment and a segment of an isolated rabbit aorta, under the influence of rotating magnetic fields with varying frequency in the range of 3 Hz to 8 Hz. The robot swims against a flow of PBS at 90 ml/hr with a maximum speed of 11.3 ± 0.52 mm/s inside the aorta compared to 14.8 ± 0.37 mm/s in catheter...
segment at frequency of 8 Hz. The outer-diameter of the aorta is measured as 4 ± 0.3 mm varying according to the expansion by the applied flow rate. We attribute the reduction of swimming speed to the elastic properties of the aorta in comparison to a rigid catheter segment. In addition, maximum speed of the robot in whole blood is calculated as 7.45 ± 1.2 mm/s compared to 16.3 ± 0.48 mm/s in PBS. Experimental results show that the propulsion of the robot is influenced by the properties of the surrounding channels. The swimming speed of the helical robot inside the catheter segment is relatively higher than the speed in the rabbit aorta segment. The robot is in continuous contact with the surface of the aorta. Therefore, it is subject to high contact forces for the same propulsive force. This speed reduction can be mitigated by decreasing the contact between the robot and the channel wall. In our experiments, the force due to gravity is not compensated. Gravity compensation using a force due to the expansion by the applied flow rate. We attribute the reduction of swimming speed to the elastic properties of the aorta in comparison to a rigid catheter segment. In addition, maximum speed of the robot in whole blood is calculated as 7.45 ± 1.2 mm/s compared to 16.3 ± 0.48 mm/s in PBS. Experimental results show that the propulsion of the robot is influenced by the properties of the surrounding channels. The swimming speed of the helical robot inside the catheter segment is relatively higher than the speed in the rabbit aorta segment. The robot is in continuous contact with the surface of the aorta. Therefore, it is subject to high contact forces for the same propulsive force. This speed reduction can be mitigated by decreasing the contact between the robot and the channel wall. The helical robot swims inside a dissected segment of a rabbit aorta with a diameter of 4 ± 0.3 mm. (a) The speed of the robot is characterized under the influence of rotating magnetic fields with frequency range of 3 Hz to 8 Hz. (b) A representative trial shows the actuation of the helical robot inside the aorta. The averaged speed of helical robot at actuation frequency of 7 Hz is measured as 9.59 ± 0.91 mm/s.

As part of future studies, we will characterize the mechanical properties of the blood vessels and develop a model to simulate the behaviour of the helical robot and understand its response to conditions encountered in vivo. In addition, propulsion of the helical robot will be tested against higher flow rates than 90 ml/hr and we will investigate methods to enhance the propulsive force of the robot. It is also essential to fabricate the robot from a biodegradable material and use a coating with relatively low thrombogenic response to decrease the formation of platelets on the surface of the robot to be suitable for in vivo applications.

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