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Comparison of theoretical and measured forces on magnetically propelled microrobots in a vascular phantom

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Abstract

Microrobots can travel in blood flow to targets that are currently difficult to reach. Stationary control is a prerequisite and requires the prediction of major influencing forces. During experiments, a magnetic cylindrical microrobot was moved in a tube filled with water or a glucose mixture (blood analog), controlled by an external electromagnetic field. The experimental results showed that the magnetic field gradient needed to be increased at the highest rate for smaller microrobots in the glucose mixture. At low fluid flow velocities, a magnetic gradient field of approximately 130–200 mT/m was required to overcome the static friction force, which was significantly higher than the drag force.

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Keywords: electromagnetic; microrobot; control; magnetic; medical robot; cardiovascular system; drag force; friction force

1. Introduction

Medical microrobots have many possible advantages in various treatments. Consequently, numerous different microrobots have been investigated for the diverse environments inside the human body [1–3]. The main advantage of cardiovascular microrobots is the high accessibility that they enable, especially in areas that are difficult to reach by traditional surgical methods or that require highly invasive methods. Therefore, in relation to the treatment of cardiovascular diseases and drug delivery to regions that are challenging to access, the enhanced agility of microrobots compared to traditional catheters offers a promising field for improvement. For example, the treatment of cerebral aneurysms can require access to blood vessels smaller than 2 mm. The treatment of aneurysms in small blood vessels is very challenging and often impossible with current methods. In addition, the size of the blood vessels limits the area in which a catheter can be applied. Alternatively, a highly invasive

Nomenclature

F_m	magnetic force	[N]
F_{m1}	magnetic force to move robot against flow	[N]
F_{m2}	magnetic force to move robot with flow	[N]
F_f	friction force	[N]
F_d	drag force	[N]
ρ_f	fluid density	[kg/m^3]
u_d	relative velocity (microrobot/blood)	[m/s]
A	frontal area of the microrobot	[m^2]
C_d	drag coefficient	[-]
V	magnetic volume	[m^3]
$\mathbf{M}$	magnetization	[A/m]
$\nabla\mathbf{B}$	magnetic field gradient	[T/m]

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craniotomy may be chosen. The reduction of highly invasive procedures is a motivation in investigating cardiovascular microrobots.

However, challenges exist that must be solved before a clinical application can be anticipated. One of the most significant design challenges for a cardiovascular microrobot is navigation in the complex cardiovascular system, which includes areas with intense pulsatile flow [4]. However, full controllability must be ensured at all times to enable the secure navigation and retraction of the microrobot, which are prerequisites for successful treatment.

Currently, specific procedures utilize catheters with a magnetic tip for enhanced navigation capabilities, including automatic advancement and retraction [5]. Some researchers have focused on relatively large robots (~10 mm in length and ~5 mm in diameter) with a higher degree of complexity, which accommodates special treatment tools, such as those for cardiovascular disease [6], [7]. These larger microrobots are easier to control and navigate on account of the increased magnetic force that can be transmitted. However, the microrobot diameter of approximately 5 mm limits the accessible region of the cardiovascular system. Other researchers have focused on microrobot design—for example, the transport capability [8]—and have shown the feasibility of controlling the designed microrobots.

As was done in previous research [9], the present study employees follow a more simplistic approach to microrobots to achieve a higher degree of miniaturization as well as controllability in the blood flow. Early navigation concepts were tested using a cuboid microrobot that was 1 mm × 1 mm × 4 mm. The aim was to reduce the size of the microrobot while still enabling navigation in the intricate cardiovascular network [10].

The propulsion of microrobots by magnetic fields of either the rotating or gradient type is a frequently used solution. Microrobots with different characteristics have been investigated, such as in [11–13]. Most research conducted on navigation in blood vessels has had at least one of the following characteristics: one- or two-dimensional control with a moving microrobot (e.g., [14], [15]), the use of an MRI as the magnetic field source [16–18], or no fluid flow. Although an MRI is a viable solution, there are constraints on the time resolution and accuracy; moreover, customization of the MRI control is challenging.

This study therefore focuses on the use of simple electromagnetic coils and investigates a method for holding a microrobot at a fixed position during constant fluid flow. This approach can facilitate more complex control of the microrobot and navigation against the flow. Maintaining the stationary position requires a complete understanding of the active forces, as well as closed loop control. The major forces on an intravascular microrobot are the drag force incurred by the fluid flow and the friction force resulting from the interaction of the microrobot and vascular model or blood vessel wall. Finally, an imposed magnetic force is used to control the microrobot. An accurate estimation of the drag force is necessary to obtain a better understanding of the behavior of a microrobot inside the blood flow and to enable full controllability. For this purpose, the drag force was analyzed using the theories presented in previous work [10]. A basic theoretical summary is given in this paper. Subsequently, experimental results from measurements of the forces on the microrobot at different fluid flow velocities are compared to the theoretical results. Finally, a preview of future work is provided.

2. Method to measure and compare forces on an intravascular microrobot

A horizontal position was selected for the vascular model to minimize the closed loop control and tracking system requirements for determining the drag force on the microrobot. Owing to the higher density of neodymium—the microrobot material—compared to water, the microrobot was pulled to the bottom by gravitational force. Thus, the microrobot was in contact with the inner wall of the vascular phantom, which resulted in a significant friction force. This friction force had to be considered when determining the drag force on the microrobot.

When the microrobot was moved from a resting position aligned with and against the fluid flow direction (shown in Fig. 1), the drag force and friction force could be separately identified. The magnetic force that was required to move the microrobot was equivalent to the friction force between the microrobot and vascular model with no fluid flow. In the case of the moving fluid, the friction and drag force could be calculated using (1) for movement against the fluid flow direction and using (2) for movement in the fluid flow direction.

$$F_{m1} = F_f + F_d \,, \tag{1}$$

$$F_{m2} + F_f = F_d \,, \tag{2}$$

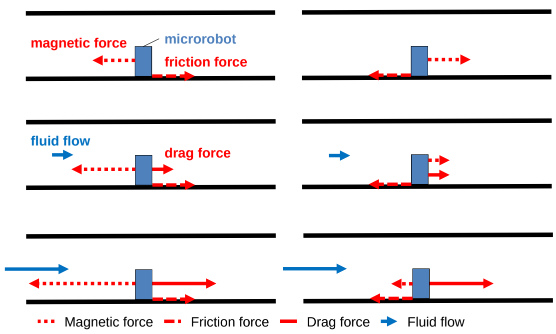

Fig. 1. Movement of the microrobot against (left) and with the flow diretion (rigth) due to an external magnetic field without flow (top), with slow fluid flow (middle) and with strong fluid flow (bottom)