3D PRINTED MAGNET ROBOTS FOR CELL DELIVERY WITH TUNED FLEXIBILITY

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ABSTRACT

Magnetically actuated microrobots have the potential to make medical operations less invasive, more precise and remotely controlled. Therefore, they are promising for many applications such as targeted therapy or minimally invasive surgeries. Current challenges in the field of magnetic microrobotics include efficient propulsion and biocompatibility. This article addresses both of these aspects and aims to optimize the flexibility of a soft magnetic swimmer by tuning its material properties, define different magnetic segments and investigate its biocompatibility and potential as cell delivery machine.

KEYWORDS: magnetic actuation, remote control, 3D printing, flexible, elastomer, microrobotics

INTRODUCTION

Miniaturized systems aim at facilitating medical operations on the small scale. External magnetic fields offer the opportunity to control these microdevices in a remote and highly precise fashion, while they perform autonomous motion and desired tasks. Flexibility of microrobots offers specific benefits such as propulsion in low Reynolds number by breaking time-reversal symmetry and their soft bodies allow gentle interaction with tissue to avoid mechanical damage and the ability to squeeze through tight spaces by changing their shape[1]. The state-of-the-art of flexible flagellated microrobots include artificial and biohybrid approaches[2]–[7]. The significance of the flexibility and location of the magnetic segment along the tail was recently demonstrated with sperm-templated magnetic microrobots[8], [9]. A few favorable designs were demonstrated which capitalize on distributed magnetization and intrinsic flexibility. In this article we demonstrate the 3D printing of elastomeric flexible flagellated millimeter-sized robots with defined location of sputtered nickel segments. Subsequently, the filaments are propelled in an oscillating magnetic field. Particularly, the objective is to study the influence of the stiffness and location of the magnetic segment on the motion of the magnetic flexible robots. Secondly, the biocompatibility and potential as cell delivery machine are investigated.

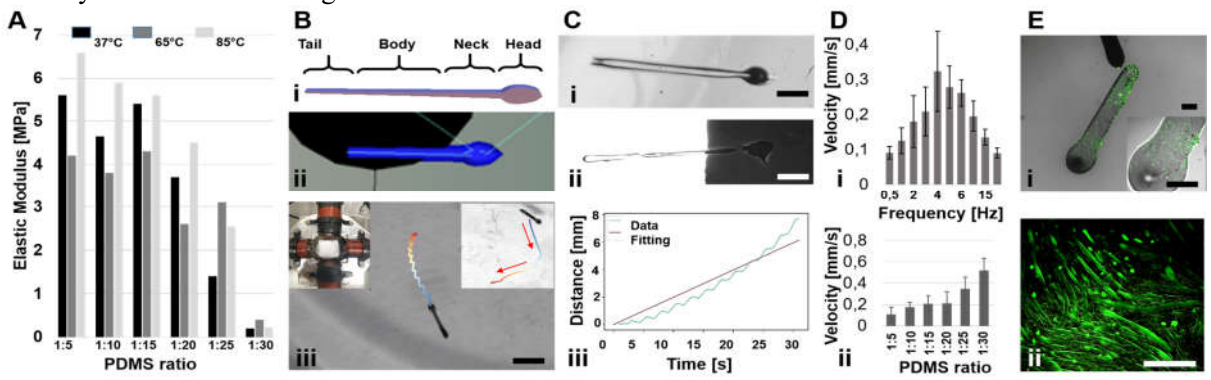

Figure 1: Flexible magnetic 3D printed robots: A) stiffness (elastic modulus) of 3D printed filaments depending on PDMS mixing ratio. Bi) 4 segments are possible magnetic elements: head, neck, body and tail in analogy to sperm structure. Bii) design fed into 3D printer, Biii) tracking of magnetic robot during magnetic actuation. Left inset shows the electromagnetic coil setup, right inset: turn by magnetic steering. Ci) 3D printed and cured PDMS filament. Cii) head and beck sputtered with Nickel. Ciii) the tracking distance over time shows the oscillating motion and delivers average velocity of the robot. Di) average robot velocity depending on the magnetic oscillation frequency. Dii) robot velocity depending on PDMS ratio. Ei) PDMS filament with mouse muscle cells grown on top. Green cells indicate stained live cells. Eii) fluorescent stain of differentiated (elongated) muscle cells on top of PDMS filament after 11 days cultivation.

EXPERIMENTAL

1. Elastomeric flexible flagellated magnetic. Different ratios of DOWSIL 1700 PDMS catalyst : base are mixed (1:5, 1:10, 1:15,1:20,1:25,1:30) and added to a printer syringe. Filament-like structures of 4mm length and 300µm

diameter are printed using the Inkredible+ extrusion printer (Fig.1Bii and 1Ci). The PDMS structures are cured at 37°C, 65° or 85°C and then sputtered with 100nm Nickel in one or several of the 4 segments: head, neck, body or tail (Fig.1Bi and 1Cii). Subsequently, the structures were immersed in water in a petri dish and placed into the electromagnetic coil setup (Fig.1Biii). Oscillating magnetic fields are applied with increasing frequency of 0.5-10 Hz while the motion of the robots is recorded. A python tracking code[10] was used to analyze the speed and trajectory of the robots (Fig.1Ciii).

2. Cell compatibility study. Mouse skeletal muscle cells C2C12 were cultured as described[10], [11] in presence of the PDMS filaments. For the first five days, the cells were kept in growth medium at 37°C with 5% CO_2. After confluence of the cells was almost reached, the medium was switched to differentiation medium to obtain myotubes. The C2C12 cells on PDMS filaments were cultured until day 11.

RESULTS AND DISCUSSION

Dynamic mechanical analysis shows decreased stiffness from 6MPa to below 1MPa when increasing the PDMS ratio from 1:5 to 1:30 (Fig.1A). Regarding curing temperatures, 65°C provides lowest elastic modulus compared to 37°C or 85°C. The robot velocity in response to increasing oscillation frequency shows the typical curve due to the step-out behavior above 5 Hz (Fig.Di). We find that with increasing flexibility, the magnetic robots respond with higher velocity in the oscillating field (Fig.1Dii). Having the "head" position of the PDMS filament magnetized showed the best response to the magnetic field, but not significantly above the neck, body or tail position. The more segments were magnetized, the stronger was the response to the magnetic field due to increase in magnetization and magnetic torque. Cell culture studies confirm that murine skeletal muscle cells can be grown (Fig.Ei) and differentiated on the 3D printed PDMS filaments (Fig.Eii).

CONCLUSION

The novelty and potential impact of the presented magnetic robots lies in their flexibility and superior cell growth and differentiation compatibility. The 3D printing method has immense potential for regenerative therapy, where stem cell delivery, *in vivo* tissue patches and cell-laden implants are a promising method to introduce and repair tissue inside the body. A cell delivery system providing little invasiveness during delivery, adaptability and guidance of tissue growth and regeneration is particularly beneficial. Further possible areas of applications are the delivery of medication to hard-to-reach areas inside the body, such as millimeter-sized cavities or vessels.

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