Shape memory alloy helical microrobots with transformable capability towards vascular occlusion treatment

Transformable microrobots for vascular disease

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Practical implementation of minimally invasive biomedical applications has been a long-sought goal for microrobots. In this field, most previous studies only demonstrate microrobots with locomotion ability or performing a single task, unable to be functionalized effectively. Here, we propose a biocompatible shape memory alloy helical microrobot with regulative structure transformation, making it possible to adjust its motion behavior and mechanical properties precisely. Especially, towards vascular occlusion problem, these microrobots reveal a fundamental solution strategy in the mechanical capability using shape memory effect. Such shape-transformable microrobots can not only manipulate thrust and torque by structure to enhance the unclogging efficiency as a microdriller, but also utilize the high work energy to apply the expandable helical tail as a self-propulsive stent. The strategy takes advantage of untethered manipulation to operate microsurgery
without unnecessary damage. This study opens a route to functionalize microrobots via accurate tuning in structures, motions and mechanical properties.

**MAIN TEXT**

1. **Introduction**

Biomedical microrobot has been widely accepted as a promising in vivo technology for minimally invasive procedures.[1-4] Despite the small scale of microrobot limits it to perform versatile tasks independently similar with a traditional robot, microorganism in nature provides diverse strategies to actively swim, sense and act without a complex nervous system.[5-7] Specifically, microorganism capable of active transformation proffers a methodology to enrich functionalities via reacting to signals in real time.[8-10] Inspired by that, several smart material and structure models have been applied to artificial microrobot,[11-13] including temperature-responsive polymers[14], hydrogels[15], shape memory alloy[16], light-responsive liquid crystal elastomers[17], graphene[18], programmable magnetic particles[19, 20] and configurable swarms[21]. However, the transformable ability of microrobot mostly serves as actuation or propulsion mechanism for valid motion, and additional modification is still required to realize specific function.

In the biomedical field, vascular occlusion which is mainly characterized by blood clot and plaques becomes a highly hazardous threatening to human health, including heart attack, stroke, renal artery disease or stenosis, etc. At present, the clinical treatment containing drug therapy, vascular bypass graft and percutaneous transluminal angioplasty, exists risk in unnecessary bleeding and damage.[22] At the meantime, in the classic film Fantastic Voyage, the plot that tiny robot submerges into human blood vessel to break the blood clot seems to be a tantalizing inspiration.[23] As profitable solution for invasive vascular procedures problem, the revolutionary medical technology of practical microrobots has received considerable critical attention[24, 25], mainly pharmaceutical and mechanical techniques towards blood clots[26-28] and novel stent towards narrow vascular.[29-31]

Here, we develop a shape memory alloy (SMA) microrobot composed of a NiTi-wire tail and a magnetic head, capable of performing multi-tasks in optimal manner towards vascular occlusion treatment. Under rotation magnetic field, the helical microrobot is actuated to propel and steer in viscous fluid. The helical tail made of SMA endows the microrobot with manageable structure transformation triggered by heating, leading to the desired translational locomotion shifting due to the highly correlation between the motion behavior and helical structure. Based on the transformable helical microrobot model, we propose targeted strategies for vascular occlusion diseases by in vitro experiments. For blood clot problem, the microrobot is investigated to enhance mechanical unclogging effect with shape transformation during the procedure. Besides, the self-propelled microrobot is implemented for
plaques problem via triggered expansion by transient heat stimulus once it is guided to the target area. This work presents a practical microrobot functionalized by its reliable transformable capability in a wide range, advancing microrobots of carrying out versatile and sophisticated tasks.

2. Results

2.1. Fabrication and transformable locomotion.

The microrobot consists of a polydimethylsiloxane (PDMS) head with magnetic particles and SMA tail in helical geometry. Here, the helical body is conducted by a NiTi wire (top left panel of Figure 1A). The NiTi wire was wound around the central tungsten axis and adjusted by changing the axial relative position of the two screws to desired pitch. Then, the fixed NiTi helical structure was annealed to obtain the memorized shape of SMA helical tail. And it was further turned into the deformed shape by external force. Meanwhile, the magnetic head was cut from a PDMS film embedded with aligned NdFeB particles (Top middle panel of Figure 1A). The hysteresis loop of obtained magnetic head substantiates the response capability to external magnetic field (Supporting Information, Figure S1). Subsequently, the magnetic head was stuck to the helical tail with glue. As the orientation of the head is redirected along the long direction of the helical tail, the magnetization of the

![Figure 1. Concept of magnetic helical microrobot with transformable capability. (A) Schematic diagram of the fabrication strategy and transformable](image)
motion principles of helical microrobot. The detail of assembling process is described in materials and methods. The assembled microrobot consists of NdFeB particles/PDMS head and NiTi helical tail. The shape-memory helical microrobot is propelled by an external rotation magnetic field. Controllable body shape transformation based on shape memory effect triggered by heating leads to the transformation of helical microrobot locomotion. The top left inset depicts that pitch is altered by adjusting the position of the screws. The top right inset depicts the SEM image of a microrobot. Scale bar is 300 μm. (B) Image sequences showing the moving performance before and after the shape transformation. Scale bar is 500 μm. (C) Velocity of microrobot over time in response to shape transformation.

parallel to the adjacent body wire and misaligned with the helix axis and magnetic field. Besides, the head instinctively performed to an ellipsoidal shape due to the surface tension of the glue during solidification. The inset of Figure 1A presents successful fabrication of SMA helical microrobot. Under a rotating magnetic field generated by Helmholtz coils (Supporting Information, Figure S2), the helical microrobot is propelled forward in a rotating manner. The magnetic head responding to the rotating magnetic field offers magnetic torque for propulsion, and the helical tail converses the rotational motion to translational propulsion.[32, 33] Then, the swimming helical microrobot in deformed shape is triggered to recover to memorized shape by heating. In low Reynold number environment, the manageable structure transformation of SMA helical microrobot leads to the transformation of translational locomotion (Figure 1B and Movie S1). In a polyvinyl acetate (PVA) solution with viscosity of 4.7 mPa·s similar to blood, the SMA helical microrobot is propelled inside a capillary. After heating, the helical tail transforms to shorter in 0.2 s, and the velocity decreases about 30 μm/s simultaneously (Figure 1C). Such speed variation reflects the valid altering in microrobot’s motion.

2.2 Shape memory characteristics of the helical tail.
Helical tail with shape memory effect governs the precise transformation capability of SMA helical microrobot. As illustrated in the fabrication process, the NiTi wire is constrained into a helical geometry and then annealed to memorize its shape. The SEM image of annealed SMA helix is shown in Figure 2A, together with the energy dispersive spectrometer (EDS) results of Ni and Ti elements distribution. The element weight ratio of Ni is 59.22 % and Ti is 40.78 % after annealing (Figure 2B), of which the Ti component is slightly reduced compared with the NiTi wire before annealing (Supporting Information, Figure S3A). Furthermore, the phase transition temperature of annealed NiTi wire was characterized by differential scanning calorimetry (DSC), revealing that during heating process annealed NiTi wire
completes phase transition in 45.56 °C and the austenite peak is obtained as \( Ap = 39.85 \) °C (Figure 2C). As a comparison, the phase transition temperature of unannealed NiTi wire is measured as \( Ap = 48.52 \) °C (Figure S3B). The decrease of transition temperature after annealing attributes to the evaporation of Ti element during heat treatment.

To explore the shape memory characteristics of annealed NiTi helix, a set of deformation tests followed by heating to recover shape were performed. Firstly, the helix with the pitch of 522.1 μm in memorized shape was compressed to different lengths (Deformed shape in Figure 2D). The deformed helix was then placed on a hot plate with temperature at 65 °C to trigger the phase transition (Recovered shape). A clear difference between deformed and recovered shapes indicates that shape memory effect induces shape transformation in a wide range (Figure 2D). Figure 2E gives the measured pitch variation in these circumstances. Here, the length change ratio (LCR) is the length variation between recovered and deformed shape, defined as

\[
LCR = (l' - l_1)/l_1
\]

where \( l_1 \) is the deformed pitch length, and \( l' \) is the recovered pitch length. All compressed SMA helices with LCR up to 60% can recover to their memorized shape. However, small amount of irrecoverable deformation remains. It can be deduced that for a compressed deformation the annealed NiTi helix exhibits good shape recovery performance as the irrecoverable deformation ratio is less than 10%. Similar situation is also observed in the SMA helix under stretched deformation (Figure 2F and G). According to these results, the controllable shape transformation of the SMA helical tail with helix angle ranging from 49.2° to 71.7° is robust based on shape memory effect. It's worth noting that the temperature of transformation for NiTi wire is about 45.56 °C in this work, and the triggering method is particularly important for target biomedical application. For the problem, we consider the localized hyperthermia technology which has proven to be a well-established cancer treatment by destroying the cancer cells. Until now many techniques have realized heat-delivery locally involving focused ultrasound, near infrared, magnetic hyperthermia, infusion of warmed liquids. We believe local heating of local tissue to 45.56 °C could be achieved with the aid of these technologies.
Figure 2. Characterization of the shape-memory helical body of microrobot. (A) SEM image and EDS result of annealed NiTi wire. Scale bar is 50 μm. (B) Weight ratio of Ni and Ti element. (C) DSC result of annealed NiTi wire. (D) Shape memory performance of NiTi helical body when recovered from compressed states. Scale bar is 500 μm. (E) Recovery strain and pitch as a function of different compressed pitches. (F) Shape memory performance of NiTi helical body when recovered from different stretched state. Scale bar is 500 μm. (G) Recovery strain and pitch as a function of different stretched pitches.

2.3 Regulative propulsion behavior under rotational magnetic field.

The propulsion behavior of SMA helical microrobot is controlled by external rotating magnetic field properties. Figure 3A shows the velocity with response to the rotation frequency of magnetic field when applying magnetic field intensity is 1 mT, 2 mT, and 3 mT. The velocity is proportional to the rotation frequency on condition of lowering a certain rotation frequency named as step out frequency. This is similar to the pattern found in the work of other helical microrobot. [34] And the velocity decreases drastically once beyond step out frequency in which microrobot loses its synch with the magnetic field due to insufficient torque (Inset of Figure 3A). Based on the theory of rotating permanent magnets,[32] the calculated angular velocity is in good agreement with experimental results. In addition, higher magnetic field intensity directly increases the step out frequency due to the stronger torque supply, yet conducts no effect on the velocity before the step out condition.
**Figure 3. Locomotion behavior of SMA helical microrobot.** (A) Velocity with response to different rotation frequency. The inset shows that the experimental and theoretical results of angular velocity related to external field frequency both in synchronous and step-out region. (B) Dependence of step-out frequency and maximum velocity on the viscosity of liquid viscosity. (C) Schematic illustrating the wobbling locomotion of helical microrobot. $\beta$ is the angle between the axis of wobbling gaits and the axis of propulsion locomotion. (D) Optical images showing three gaits of magnetic helical microrobot. $T$ is a period of rotation. (E) Variation of wobbling angle and velocity as a function of frequency. The region in different colors refers to different gaits. The density of magnetic field is 10 mT. (F) Schematic
presenting structure parameters of a shape-memory helical microrobot. (G) Effect of the helix angle on the velocity when driven by 6 Hz magnetic field with density of 6 mT.

Figure 3B presents the step-out frequency and maximum velocity of a SMA helical microrobot in liquid environment with different viscosity at 4.5, 10 and 50 mPa·s, which are brought from Supporting Information, Figure S4. It is clearly shown that both step-out frequency and maximum velocity decrease with the rising viscosity. Specifically, it is noticed that the step-out frequency and maximum velocity keep linear relationship with fluid viscosity, reflecting that both are inversely proportional to the fluid viscosity. This relationship is attributed to the variation in fluidic drag torque where viscosity works as a multiplying coefficient.[35] The decrease of step out frequency is because that more viscous liquid environment requires more magnetic torque to supply synchronous spiral motion. Besides, considering the proportional relation between the velocity and rotation frequency, larger step-out frequency refers to the higher velocity the microrobot can reach.

Additionally, an attractive phenomenon is observed that the SMA helical microrobot moves in frequency-dependent modes before step out condition. To clarify these different modes, a model containing wobbling angle is demonstrated in Figure 3C. Here, the wobbling angle $\beta$ is defined as the angle between the helical axis and the translational motion direction. There exist three modes of motion determined by rotating magnetic field frequency (Figure 3D and Movie S2). At mode I, the axis of the helical microrobot keeps spinning for 360° in every rotation period, around translational motion direction at a wobbling angle. At mode II, the axis of helix tail keeps constant and coincident with translational motion direction. As for the mode III, the helical microrobot starts to keep a wobbling angle with translational motion direction but helix tail axis still performs no spinning.

Detailed investigation on the relation between observed modes and rotating magnetic field frequency is shown in Figure 3E. The applied magnetic field intensity is 15 mT, which is sufficient for microrobot to keep sync with rotating magnetic field within the frequency range up to 60 Hz. It can be concluded that the helical microrobot stays in mode I as the frequency is lower than 15 Hz. And the wobbling angle decreases with increasing frequency. As the frequency increases to 15 Hz, the wobbling angle gets close to zero, leading to a stable movement as mode II. When the frequency is higher than 25 Hz, the helical microrobot moves in mode III, and the wobbling angle slightly increases with the rising frequency. Interestingly, while the helical microrobot performs different modes in different ranges of frequency, the velocity is proportional to the rotation magnetic field frequency. In a word, with increase of frequency, demand for torque is rising in response, that is, even before step-out circumstance (magnetic torque is sufficient for sync rotation motion) the external torque still impacts the locomotion modes by the difference between supply
and demand of torque. These different modes of helical microrobot motion presents a detailed alteration of navigation strategies, which is expected to applied in different tasks.

Translational motion of SMA helical microrobot is converted by the rotation of the attached rigid chiral tail. A simple relation between its main structure parameters including pitch ($\lambda$), diameter ($d$), and helix angle ($\theta$) (Figure 3F). Helix angle is written as

$$\tan \theta = \frac{\pi d}{\lambda}$$  \hspace{1cm} (2)

The velocity of SMA microrobot varies when the helix angle ranges from 49.6° to 74.5°. The frequency and intensity of rotation magnetic field are set as 6 Hz and 6 mT, respectively (Figure 3G). The tendency that the velocity increases first and then deceases is attributed to the relationship between geometry-dependent viscous resistance and magnetic torque. Due to the contribution of helix structure on propulsion locomotion, the variation of helical tail structure based on shape memory effect is expected to impact on the motion behavior enormously. The heating process is conducted by a hot water drop, which is enough to guarantee the full phase transition of SMA helical microrobot inside the capillary (Supporting Information, Figure S5). With different fabrication process, the SMA helical microrobots transform into a longer or shorter shape, and thus alter the moving velocity as well (Supporting Information, Figure S6 and Movie S3). In detail, the shifting of the helix angle was designed respectively to distribute in the increasing phase, decreasing phase, or across the peak of the curve in Figure 3G, thus realizing the arbitrary adjustment of propulsion velocity. Besides, the propulsion modes can also be tuned by helix structure transformation and misalignment angle shifting (Supporting Information, Figure S7 and Movie S4).

### 2.4 Microdriller enhanced mechanical unclogging ability via shape transition.

In low Reynolds number environment, a rigid rotating flagellum generates force and torque according to the resistive force theory which is developed to describe swimming driven by a rotating helical flagellum. The induced mechanical effect by swimming motion facilitates the local operation of microrobot in narrow and confined area without tethered manipulation. Here, we demonstrate a potential application as a helical microdriller and enhances its mechanical unclogging effect to penetrate clogged area in blood vessel. (Figure 4A). To determine the relationship between microrobot structure and mechanical effects, especially the force and torque derived by swimming motion, experiments and calculation have been developed and introduced.

As a promising expectation, these microdrillers can be injected by syringe into artery, driven to lesions under the guidance of external rotation magnetic field [36], and designed to perform unclogging task (Figure 4E). We initially tried to figure out the solution of the helical microrobot when faced with clogged area. We set three relative
slight blockings (gelatin) from small to large in the capillary tube and the helical microrobot was driven under constant magnetic field (7 Hz, 5 mT). As shown in Movie S5 and Figure S9, with the mechanical affections, helical microrobot is capable of swimming inside the vessel containing various obstacles as clustered blood cells. The microrobot exhibits three different ways related to the size of blockings due to the difference in the relative magnitude of friction and adhesion, which includes pushing away, passing by and drilling across. It can be concluded that the helical microrobot is able to fix the potential obstacle problem in a certain degree without optimized, which is also display by Liu et.al [37] However, it takes a minute to drill across the third blocking which is actually a small clogging area. Thus, to improve the efficiency of unclogging process by helical microrobot, we plan to optimize in different aspects.

Firstly, we consider to optimize the torque. The magnetic torque generated by magnetic field is supplied to maintain the rotation of the microrobot for translational movement, and the microrobot would lose synchronization with the rotating magnetic field when the torque is not sufficient to balance viscous force. As discussed above, the step-out frequency decreases sharply when the viscosity increases. In subsequent experiment, we used 9% gelatin to model the blood clot which is jelly-like texture. We could regard the clogged area as an extremely viscous environment, in which continuous motion is almost impossible. Thus, fewer step-out behavior and greater rotation ability is an imperative goal for unclogging. According to our fabrication process, the helix angle of SMA helical microrobot is altered during the shape transformation while the number of spirals remains constant. Therefore, the effect of helix angle on the step-out frequency and corresponding maximum velocity is studied with the magnetic field intensity of 5 mT (Figure 4B). The microrobot with bigger helix angle results in higher step-out frequency. Considering that the bonded head is always parallel to the body wire, bigger helix angle refers to larger misalignment angle. For our SMA helical microrobot, the magnetic head determines the supply of magnetic torque according to the equation written as \( \tau = m \times B \), where \( \tau \) is the torque, \( B \) is the external magnetic field intensity, and \( m \) is the magnetic moment of magnetic head. Therefore, the magnetic torque supply increases with rising helix angle as the projection of magnetic moment on rotation plane gets larger, leading to a higher step-out frequency. However, the microrobot with higher step-out frequency not always processes higher maximum velocity. The reason was explained in the inset of Figure 4B, in which the velocity of the shape memory helical microrobots with different five helix angles is presented when applying 3 Hz rotation magnetic field. Microrobot with helix angle of 62° propels fastest, so it reaches higher maximum velocity with a low step-out frequency.

Secondly, puncture force is also taken into consideration. The high-speed rotating spiral microrobot performs similar with a microdriller, and the puncture force is a
significant mechanical parameter. Johnson slender body theory is utilized to expose the impact of structure on the force (Figure 4C). The thrust force increases first and then decreases with rising helix angle, and reaches a maximum at approximately 48°. The force also increases as the microrobot rotates at a higher frequency. Besides, similar tendency can be observed from experiment focusing on a scaled-up microhelix (Figure 4D, Parameters can be found in Methods), which is shown in Figure 4D. Given the above, the microhelix provides more puncture force when the helix angle reaches about 50° and microhelix with bigger helix angle is less likely to step out. Based on that, we can enhance the unclogging effect by shape shift real-time.
Figure 4. Enhanced mechanical unclogging effect of microdriller by shape transformation. (A) Schematic indicating that the force and torque generated by the rotation of microrobot. (B) Step-out frequency and corresponding maximum velocity with respect to helix angles under 5 mT magnetic field. The inset shows the velocity of microrobot with different helix angle where the frequency of magnetic field is 3 Hz. (C) Calculation result of the force as a function of helix angle. (D) Experimental results of the force with different helix angle of a scaled-up NiTi helix. The wire diameter is 0.3 mm and the helix diameter is 5 mm. (E) Schematic shows the process of microdriller implement and operation. The microrobot is injected into artery and driven to lesions under rotation magnetic field. The microdriller optimizes the unclogging effect via altering its structure by local heating. (F) Image sequence indicating unclogging performance of helical microrobots in a plump shape, slim shape, and a microrobot transforming from slim to plump shape. The unclogging process is divided into four stages: (i) Reaching the location and beginning to drill in, (ii) drilling into the clot with one body length depth, (iii) drilling through the clot, (iv) repeating drilling for four times. Heating process for shape transformation is conducted at the beginning of stage ii. Scale bar is 500 μm. (G) Statistics of time cost in different stages of three unclogging microrobots.

As studied, microrobot with helix angle of about 53° exerts the biggest thrust, and the larger the helix angle, the smaller the magnetic torque required for motion. Accordingly, we designed the transformable microrobot with helix angle shifting from 53° to 69° and set comparison test with other two microrobot which have constant structure. In order to demonstrate the mechanical unclogging effect, gelatin artificial clot was applied to mimic clogging blockage in blood vessel (Supporting Information, Figure S10). Given that the rigid tail obtains stronger pressure compared to rounded head, all the unclogging experiment were conducted by swimming towards the direction of tail. Microrobots with constant helix angle of 69° (plump shape) and 53° (slim shape) and SMA helical microrobot (helix angle transforms from 53° to 69°) were guided to pass through the artificial clot where all applying rotating magnetic fields set as 20 Hz and 20 mT (Figure 4F and Movie S6). The plump microrobot finishes the whole task in 410 s while the slim one completes in 365 s. In contrast, in the same task implemented by the SMA helical microrobot, transforming from plump to slim shape as soon as drilling into the clogging blockage, the highly effective unclogging process ends in 245 s.

To clearly compare different helical microrobots, we divided the whole unclogging process into four stages as (i) attaching the clot to drill, (ii) drilling in with one body length depth, (iii) drilling through the clot, and (iv) breaking the clot (Supporting Information, Figure S11). To analyze the unclogging performance of each helical microrobot, the time cost in every stage is listed in Figure 4G. It is noticed that the
helical microrobot in slim shape gets faster to thrust into the blockage the start the drilling process, while the plump one performs better in the drilling process. This difference is caused by the different determinants in different stages. The magnitude of puncture force is a critical factor to start the drilling process, while the magnetic torque determines whether the microrobot can keep rotating and meanwhile breaking clots during drilling. By optimizing the thrust and torque magnitude through shape transformation, the SMA helical microrobot realizes the mechanical unclogging function with enhanced performance.

2.5 Self-propelling stent towards plaque problem.
Shape memory alloy, owning advantages of good corrosion resistance and biocompatibility, has been widely implemented in invasive stent implantation surgery to open up clogged arteries.[38] However, the intervention operation might lead to damage in the catheter-placement process, which hugely depends on the operational proficiency of physician. Untethered helical microrobot is regarded as a non-invasive method because of the flow layer generated during propulsion that keeps microrobots from the contact with vessel wall (Supporting Information, Figure S12).

Apart from that, a significant variation in diameter occurs within manageable deformation range of the SMA helices (Figure 5A), based on which we developed a self-propelling stent towards plaque problem. The SMA helical microrobot propels at small helix diameter and transforms to large diameter responding to real-time heating, converting thermal energy into mechanical energy. Ultimately, the high energy density characteristic enables microrobot to expand and open up the plaques in blood vessel wall (Figure 5B). The self-propelling stent can be manufactured in various sizes to be placed in the vasculature and airways. Moreover, they can be coated with diverse drug particles to enable the local delivery of therapeutics through circumferential injections.
Figure 5. Thermal responsive self-propelling stent towards plaque problem.

(A) Schematic showing the helix radius variation occurred during SMA tail deformation. (B) Schematic exhibiting the strategies of shape memory helical microrobot towards self-propelled stent. (C) Simulation model of helices with same wire diameter $d$ and helix angle $\theta$. (D-F) Impact of spring index and deformation ratio of diameter in the model of (C) on cross strain, energy density and elastic strain energy respectively. (G) Simulation model of helices with same helical outer diameter and helix angle. (H-J) Impact of wire diameter and helical radius variation in the model of (G) on cross strain, energy density and elastic strain energy respectively. (K) Image sequence of the realization of a self-propelling stent. The procedure includes pre-design, propulsion, expansion and removal of magnetic head stages. The bottom left panels are the simulation result of the pre-design and expansion process. The color mapping in first two panels refers to the stress and one in last panel refers to radial displacement. Scale bar is 2 mm. (L) Photograph and Statistics recording the diameter change of stent before and after expanding. Scale bar is 4 mm.
The optimized supporting performance of SMA self-propelling stent was investigated by simulation. Two sets of controlled simulation trials were set up to disclose the cross-sectional strain, energy density and stored elastic strain energy as a function of structure parameters during the deformation of SMA stent. Figure 5C shows the schematic of first helices controlled trial made from NiTi wire with same wire diameter $d$ of 0.1 mm. These helices are manufactured with various diameters yet same helix angle of 70°, and deforming with same ratio of helix diameter change in martensitic phase. Spring index ($C$) is written as $C = D/d$, where $D$ is the medium diameter of helix. Deformation ratio of helix diameter (DCR) is written as

$$DRC = \frac{D_O - D'_O}{D_O},$$

where $D_O$ is the outer diameter of initial helix and $D'_O$ is outer diameter of deformed helix. Figure 5D-F are the effect of spring index and deformation ratio of helix diameter on cross strain, energy density and stored elastic strain energy. The results suggest that the cross strain and energy increases almost linearly with the rate of DCR and is hardly affected by spring index, while the stored elastic strain energy is significantly affected by both. Figure 5G is the second controlled trial, including helices with same $D_O$ and helix angle made from different wires. Helix radius variation ($\Delta D_O$) is written as $\Delta D_O = D_O - D'_O$. Evolution of cross strain, energy density and stored elastic strain energy related to helix radius variation and filament diameter is summarized in Figure 5H-J. It can be concluded that both of filament diameter and helix radius impact cross strain, energy density. Besides, for a specific goal diameter to reach, filament diameter provides a greater influence on elastic strain energy.

The realization of a microrobot-based stent includes structure pre-design, propulsion to the target area, self-expansion to dilate the plastic capillary, and removal of magnetic head (Figure 5K and Movie S7). Here, the SMA helical microrobot is designed with the shape transformable from a long helix to short one to obtain an increasement in helix diameter. As the SMA helical microrobot is guided to the target area of the vessel, transient heating triggers the shape transformation. The shrinkage of the SMA helical microrobot leads to the increase in radius, so the plastic capillary is expanded. Besides, the toxic magnetic head is removed by additional magnetic field while the expanded helix tail left in the plastic capillary as a stent due to the confinement of the capillary wall. Further simulation reflects that stress is stored in the stretched helix tail, which is sufficient to expand the outer capillary (bottom left panels in Figure 5K). Figure 5L is the photograph and statistics recording the diameter evolution of the self-propulsive stent. The stent is manufactured with outer diameter slightly higher than inner diameter of the plastic capillary. It is then stretched to longer in length and smaller in diameter, sufficient to swim in the capillary. When the stent is inserted and propel to requisite position,
phase transition is triggered and stent expands the vessel. The diameter in expansion stage exceeds the diameter of the capillary (1.5 mm), reflecting that an effective expansion of capillary wall is obtained by the self-propelled stent. Moreover, we tested the cytotoxicity of shape memory helical microrobot in condition of incubating at 37 °C and 46 °C individually to test its biocompatibility both in normal state and transition state. The test results show that the shape memory microrobot has no potential cytotoxicity in both state. (Supporting Information, Figure S14)

3. Discussion

In summary, we report a biocompatible functionalized shape memory alloy helical microrobot with wide-range active transformation capability providing solution strategies for vascular occlusion problem. The propulsion mechanism based on rotating magnetic field possesses many excellences for biomedical application, including harmless manipulation, low-cost signal generation, stable motion. The shape memory alloy tail provides shape transformation capacity with helix angle ranging from 49.2° to 71.7°, as well as superiorities of great power density, low trigger temperature, maintaining deformation without constant stimuli. We investigated the translational velocity as respect to external magnetic field, surrounding environment and microrobot structure to draw the locomotion manipulation rules triggered by structure transformation. Furthermore, as a key point for practical operation, the step-out occurrence was discussed from the perspective of magnetic torque supply and demand. As for the external rotating magnetic field, larger magnetic intensity generates more magnetic torque while faster frequency requires more magnetic torque to make the microrobot keep up with the rotation. Besides, when viewed by the structure, our SMA helical microrobot with larger helix angle supplies more magnetic torque due to the increasing angle between magnetization direction and propulsion direction. Based on the investigated content, we demonstrate potential application of the SMA helical microrobot towards vascular occlusion diseases. The harden of plaque (also called atherosclerosis) in blood vessels, which is mainly composed of fat, cholesterol and other hydrophobic molecules, leads to the narrow of blood vessel. And blood clots are gel-like clumps in blood vessel that do not dissolve naturally, might completely block the vessel. Compared to the clinical treatment, containing statin therapy to lower low-density lipoproteins (LDL) concentration and conventional percutaneous intervention methods by introducing a manually operated tethered device, our untethered microrobot provides treatment strategies without unnecessary bleeding and damage. The enhanced unclogging performance for blood clot problem benefits from the mechanical properties alteration generated by structure and locomotion transformation, mainly focusing on the thrust and torque distribution. And a
prototype of stent with self-propelled ability takes advantages of the shape memory tail transforming from a propelling component to expanding functional device. In exception to what we have studied above, the complete operation of biomedical microrobot towards in vivo therapy requires other technologies to give real-time position and precisely guide their navigation. We draw a schematic diagram showing medical operation process assisted by microrobot, shown in Figure S15. The doctor could observe the motion and behavior of magnet-driven microrobot on the computer in real time, also make necessary control operations during the whole process. Thus, imaging and tracking technology is indispensable for further implementation of biomedical microrobot application. Until now, several types of imaging techniques has been developed and tested to visualize microrobot in vivo, including fluorescent imaging, optical coherence tomography (OCT), magnetic resonance imaging (MRI), and photoacoustic (PA) imaging [39]. This work is an example of well-functionalized microrobot characteristics by reliable transformation ability towards vascular occlusion treatment, marking a step towards smart microrobots with realistic functions. The microrobot strategy opens a promising pathway for practical artificial microrobot featuring biocompatibility, precise control and cost-effectiveness to carry out sophisticated tasks in biomedical applications.

4. Materials and Methods

Synthesis of magnetic matrix head. Prepolymer (monomer) and curing agent (cross-linker) of a PDMS elastomer were combined in a 10:1 mass ratio during preparation (Sylgard 184, Dow Corning). The mixtures of NdFeB magnetic powders (diameter: ~25 μm, Jiangxi Jinli Permanent Magnet Technology Co. Ltd) and PDMS mixture were poured into a Teflon mold to fabricate a bonded permanent magnet. Before curing, the mixture was vacuumized to remove induced bubbles during mixing. The mixtures were cured at 373 K for 1 h, and then removed from the mold. A uniform magnetic field of 3 T of a vibrating sample magnetometer (VSM, Quantum Design) was applied to program the magnetization of the magnet. The magnetic head with specific size (100×80×60 μm with 40% error range) was constructed by controlling the step blade to cut the cured mixture.

Fabrication of the microrobot. As for the magnetic head, the permanent magnet mixture of NdFeB particles and PDMS was cut into cuboid blocks with the assistance of a stepping motor, and the polarity direction was set as the longest axis direction in order to simplify operation. For helical tail, the original NiTi wire (diameter: 50 μm, nominal transition temperature: 45 °C, Shanghai Shengtong Metal Technology Company) was fixed as helix with diameter of about 250 μm. Then it was annealed (450 °C for 1 hour) to memorize its structure, followed by the magnetic head bonding.
along the helical tail. Strong adhesion glue was employed to assemble microrobot head and tail together assisted by a micromanipulator.

**Characteristics.** The optical images were captured by electronic microscope OLYMPUS BX51 associated with CCD camera. The SEM image and EDS measurement were performed by Nova NanoSem 450 scanning electron microscope. DSC result of NiTi wire was measured and analyzed by DSC Q2000. Heating curve ranges from 10 to 100 °C with rate of 5 °C /min.

**Recording and analysis of microrobot's motion.** The magnetic field control platform (Supporting Information, Figure S2) contains three parts: Helmholtz device composed of three pairs of orthogonal coils and power Amplifiers to generate rotating magnetic field, optical microscope to expose microscale behaviors, and CCD camera to record motion videos of 30 frames per second. PVA solution with different viscosity and dimethylsilicone oil (Macklin) were injected into the capillary tube using a syringe, and then the microrobot was placed into the capillary tube by a micromanipulator. Capillary tube containing microrobot for the motion test was placed on the sample stage in the core of the coils. To analyze the motion and structure transformation, the imageJ with FIJI package which facilitate scientific image analysis was applied.

**Artificial clot.** The artificial clot was made of gelatin mixed with glass fibers and PMMA microspheres to simulate the tissues in a blood clot. 0.27 g gelatin powder (Shanghai Fengwei Industry Company), 0.138 g Congo red dye, 0.21 g glass fiber and 0.02 g microbeads were mixed with 3 ml deionized water. The suspended mixture is heated in a water bath for 20 min at 50 °C. After dissolving completely, the mixed solution was cooled down to 2 °C and kept for two hours to gel sufficiently. In order to set the gelatin clot into capillary for unclogging experiment, the capillary tube was pricked into the gelatin artificial clot to obtain an intact artificial clot segment remaining in the capillary. The clot segment was carefully pushed to specific location by a metal rod and PVA solution was injected into both sides of the clot segment utilizing syringe injection.

**Analysis of Thrust force during rotation.** The thrust force of a rotating helical microrobot was calculated based on Johnson slender body theory.[40] Details can be found in Supplementary Note. The dynamic viscosity of fluid was 5 mPa·s. We fixed the total length of the helical microrobot in order to find out the influence of helix angle on the thrust force. Here, the original shape of the helical robot was set as a helix with 150 μm pitch and 125 μm radius. And the number of turns and the radius of SMA wire were fixed as 3 and 25 μm, respectively.

**Setup of thrust force measurement.** In order to facilitate the measurement, we used a scaled-up helix with diameter of 5 mm and wire diameter of 0.3 mm to rotate at frequency of 0.5 Hz and 1 Hz respectively in viscous environment with dynamic viscosity of 50 mPa-s, and there was no translational speed during the test. One end
of the tested helix is connected to the motor and the rest of the helix is submerged in dimethylsilicone oil (Macklin) filled in a tube. The motor is fixed on a slider, providing constant rotation rate to the helix. Axial force caused by the rotating flagellum in low Reynolds number environment is tracked by the load cell that is touched with the end of a rotating motor (Figure S8).

**Simulation of self-expanded stent.** The simulation of self-propelled stent was conducted by Ansys Workbench. Static structural analysis system was constructed to simulate the pre-design and expansion process. We established a shape memory alloy model for helix and elastic model for capillary tube. The shape memory alloy model includes an isotropic elastic property and shape memory effect data, including Young’s modulus of 35 GPa, Poisson’s ratio of 0.2, hardening parameter of 500 MPa, reference temperature of 38 °C, elastic limit of 120 MPa, temperature scaling parameter of 8.3 MPa/°C, maximum transformation strain of 0.07, martensite modulus of 20 GPa and lode dependency parameter of 0. The tube is conducted with Young’s modulus of 4 MPa. In pre-design process, a radial pressure loading was applied first to create a perturbation on the helix. Then, an axial force loading was added at one end of the helix to stretch it to the deformed shape. In expansion process, the contact between helix and tube was set as frictionless, and the deformed helix was placed into the tube by adding a displacement confinement. Then, the temperature of the helix was raised to trigger the shape memory effect.

**Cell viability test.** Negative control: high density polyethylene; Positive control: zDEC (Manufacturer: TOKYO CHEMICAL CO.); Blank control: MEM medium with 10% fetal bovine serum. Mouse fibroblasts L929, cell line from the American Strain Collection CCL1 (NCTC clone 929) were used for this test. The microrobot samples were extracted using MEM medium containing 10% fetal bovine serum and incubated for 24 hours at 37 °C in a shaker at 60rpm. The extracts were checked for changes at the end of the extraction and implemented immediately in the experiment. After the L-929 cells had grown into a monolayer, the original medium was aspirated and 100 μL of different concentrations of the test sample (100%, 75%, 50%, 25%), empty control solution, negative control solution, and positive control solution were added and incubated at 37 °C for 24 hours with 5% CO₂. 6 parallel samples were made. After 24h incubation, the 96-well plates were removed and the cells were observed morphologically under microscope. After 50 μL of MTT (1 mg/ml) was added to each well and incubated in a CO₂ incubator for 2 hours, the supernatant was discarded and 100 μL of isopropanol was added to each well to dissolve the crystals. Then the microplates were shaken for 10 min and the optical density was measured at 570 nm on an enzyme marker.

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**Conflicts of Interest**
The authors declare that they have no competing interests.

**Data Availability**
All data is available in the main text or the supplementary materials.
Supplementary Materials

This file includes:

- Supplementary Text
- Figs. S1 to S13

Other Supplementary Materials for this manuscript include the following:

- Movies S1 to S7

Supplementary Text

Material properties of Shape memory alloy

Shape memory alloy (SMA) is a traditional smart material that can “memory” its original shape. The behavior is attributed to the microscale transition induced by mechanical stress or temperature changes, which are characterized by shape memory effect (SME) and superelasticity, respectively. The two crystal structures of SMA are called austenite, which is the structure at higher temperatures, and martensite, which is the structure at lower temperatures. The transformation from austenite to martensite is robust and with high energy density, which enables SMA of wide applications in clinical medicine and aerospace. In this work, we utilized the SME of NiTi wire to extend functionalities and optimize effects by precisely control of transformation temperature and structure tuning performance.

In the bottom left panels of Figure 5K, we simulated the stress distribution and displacement of a SMA helical microrobot. Here, the material properties of SMA with shape memory effect is based on the model proposed by Lagoudas [41]. In this model, the strain applied on SMA can be divided into four parts as

\[ \varepsilon = \varepsilon_e + \varepsilon_T + \varepsilon_t + \varepsilon_p \]

Here, \( \varepsilon_e, \varepsilon_T, \varepsilon_t \) and \( \varepsilon_p \) are the elastic, thermal, transformation, and plastic strain component, respectively. And the stress can be expressed as

\[ \sigma = E_\xi \varepsilon_e + \alpha_\xi T + \Omega_\xi \xi + h_\xi \varepsilon_p \]

Here, \( T \) is the temperature and \( \xi \) is the martensite volume fraction. \( E_\xi, \alpha_\xi \) and \( h_\xi \) are the bulk modulus, thermal expansion coefficient and hardening modulus related to the martensite volume fraction \( \xi \). In Lagoudas modulus, \( \alpha_\xi \) is considered as a constant both in martensite and austenite phase. And the bulk modulus \( E_\xi \) can be written as

\[ E_\xi = E_A + \xi (E_M - E_A) \]

where \( E_A \) and \( E_M \) are the bulk modulus of austenite and martensite phase.

As for the transition strain \( \varepsilon_t \) and plastic strain \( \varepsilon_p \), they are given as follows:

\[ \dot{\varepsilon}_t = \Lambda_t \dot{\xi}, \dot{\varepsilon}_p = \Lambda_p \dot{\varepsilon}_p \]
Here, $\bar{\varepsilon}_p$ is a measure of the history of plastic strain evolution given as

$$\bar{\varepsilon}_p = \int_{-\infty}^{t} |\varepsilon_p| d\tau$$

And other two parameters are given as

$$\Lambda_t = \begin{cases} 
3 \frac{\Omega_\xi}{2} \frac{\sigma_t}{\varepsilon_t^\text{eff}} & \dot{\xi} > 0 \\
-\frac{\Omega_\xi}{E_\xi} \frac{\varepsilon_t}{\varepsilon_t^\text{eff}} & \dot{\xi} < 0
\end{cases}$$

$$\Lambda_p = \frac{3}{2} \frac{\sigma_p^\text{eff}}{\bar{\sigma}_p^\text{eff}}$$

Here, $\sigma_t^\text{eff}$ and $\varepsilon_t^\text{eff}$ are the effective stress and strain in transition. And $\sigma_p^\text{eff}$ is the effective stress for plastic strain. $\bar{\sigma}_p^\text{eff}$ denotes the Mises equivalent of effective stress.

**Simulation of heating process.**

To verify the hot water drop heating process capable of triggering transition sufficiently, we derived a model by Heat Transfer in Solids and Fluids component in Comsol Multiphysics (SI Appendix, Figure S6). A silica glass ring hollow pipe body with inner diameter of 0.8 mm and outer diameter of 1 mm was conducted, featuring isobaric heat capacity of 703 J/(kg·K), heat capacity of 1.38 W/(m·K) and density of 2203 kg/m$^3$. The liquid inside was set as Newtonian liquid and the laminar flow module was introduced, taking into account the gravity factor. The coefficient of dynamic viscosity was set as 4.7 mPa·s. The original temperature of this system was 293.15 K. The outer wall of the tube was applied with forced convective heat flux (333.15 K) lasting for 0.2 s. This condition was set based on the assumption that the water droplet keeps 60°C and stays around the capillary tube for 0.2 s. Then the tube was set in natural air convection of 293.15 K and the heat flux can be calculated as,

$$q = h(T_{\text{ext}} - T)$$

In which $q$ is the heat flux, $h$ is heat transfer coefficient, $T_{\text{ext}}$ is the temperature of external experiment and $T$ is temperature of tube.

**Helix model for thrust force analysis.**

The thrust force of a helix (Figure 4C) is calculated based on the Johnson slender body theory [40]. According to the Johnson slender body, the radius of the cross section along the centerline is determined by following equation.

$$r(s) = 2\epsilon \sqrt{s(L - s)}, s \in [0, L]$$

where $s$ is the arclength, and $\epsilon$ is the slenderness ratio defined as $r/L$. Therefore, the average radius in a Johnson slender body theory model is calculated as $r^*\pi/4$. 
The position along the centerline is given by \( \mathbf{x}(s, \varphi) \), in a helical structure, the position can be expressed as following.

\[
\mathbf{x}(s, \varphi) = (s \cos \theta, R \cos \varphi, R \sin \varphi)
\]

Here, \( \theta \) is the pitch angle and \( R \) is the radius of the helix. And \( \varphi \) refers to the phase angle, which is defined as \( 2\pi s/(L/N) \). \( N \) is the number of turns and \( L/N \) refers to the pitch of the helix. Therefore, the position \( \mathbf{x} \) can be expressed only by \( s \) or \( \varphi \). Then, the velocity of a point on the helical surface \( s_0 \) is given by

\[
\mathbf{u}(\mathbf{x}(s_0)) = \frac{1}{8\pi\mu} \{-\Lambda[\mathbf{f}](\mathbf{x}(s_0)) - K[\mathbf{f}](\mathbf{x}(s_0))\}
\]

where \( \mathbf{f} \) refers to the force applied on the unit point. The local operator \( \Lambda \) is given by

\[
\Lambda[\mathbf{f}](\mathbf{x}(s_0)) = [-\ln(e^2 e) \cdot (1 + \hat{s}(s_0)\hat{s}(s_0)) + 2(1 - \hat{s}(s_0)\hat{s}(s_0))\mathbf{f}(s_0)]
\]

and the integral operator \( K \) is given by

\[
K[\mathbf{f}](\mathbf{x}(s_0)) = \int_{s_0}^{L} \left( \frac{1 + \hat{A}(s_0, s)\hat{A}(s, s)}{|\hat{A}(s_0, s)|} \mathbf{f}(s') - \frac{1 + \hat{s}(s_0)\hat{s}(s_0)}{|s_0 - s|} \mathbf{f}(s_0) \right) ds
\]

Here, \( \hat{s}(s) \) is the tangential unit vector at \( \mathbf{x}(s) \), \( \hat{A}(s_0, s) = \mathbf{x}(s_0) - \mathbf{x}(s) \). \( \hat{s}s \) and \( \hat{A}A \) refer to dyadic products. To get the relation between the velocity and force via above equations, we applied finite element method and modified the code provided by Bruce Rodenborn [42]. And the translational velocity was set as zero during the calculation of the thrust force.

**Model of movement capability of helical microrobot.**

First of all, the fluid distribution of a cylindrical channel was carried out. According to related theory and simulation results in Figure S16, it is clear that the fluid velocity follows a parabolic distribution. Here, we only consider the distribution in xz plane as a simplification. Therefore, the distribution can be expressed by following equation as we set the x coordinate of the channel center as zero.

\[
\nu_f(x) = 2\nu_{avg}(1 - \frac{x^2}{R^2})
\]

Where \( \nu_{avg} \) is the average flow velocity, and \( R \) is the radius of the channel. Assuming that the helical microrobot is moving near the channel boundary, we can compute the average fluid velocity affecting the motion of microrobot by

\[
\nu_{avg}^m = \frac{1}{2r} \int_{-r}^{r} (\nu_m - \nu_f) dx
\]

\( r \) is the radius of the helix, and \( \nu_m \) is the velocity of the helical microrobot. Hence, \( (\nu_m - \nu_f) \) refers to the relative velocity distribution. Based on the relative average velocity \( \nu_{avg}^m \), the relation between external force \( F_{ex} \), torque \( T_{ex} \), rotating frequency \( f \), and relative velocity can be expressed as [43]

\[
\begin{bmatrix}
F_{ex}
\end{bmatrix} = \begin{bmatrix}
a & b \\
b & c
\end{bmatrix} \begin{bmatrix}
\nu_{avg}^m \\
2\pi f
\end{bmatrix}
\]

\[
\begin{bmatrix}
T_{ex}
\end{bmatrix} = \begin{bmatrix}
a & b \\
b & c
\end{bmatrix} \begin{bmatrix}
\nu_{avg}^m \\
2\pi f
\end{bmatrix}
\]
Where the constant \(a\), \(b\), and \(c\) are the translation parameters in propulsion matrix, which are determined by the microrobot geometric parameters and fluid properties. In our circumstance, the rotating magnetic field only provides rotating torque \(T_{ex}\) and the rotating frequency is same as the frequency of rotating magnetic field before step-out frequency. Therefore, the equation above can be rewritten as

\[
a \cdot v_{avg}^m + b \cdot 2\pi f = 0
\]

\[
T_{ex} = v \cdot v_{avg}^m + c \cdot 2\pi f
\]

According to resistive force theory, the translation parameters of a helical structure with \(n\) turns is written as [35]

\[
a = 2\pi nr \frac{\xi_\parallel \cos^2 \theta + \xi_\perp \sin^2 \theta}{\sin \theta}
\]

\[
b = 2\pi nr^2 (\xi_\parallel - \xi_\perp) \cos \theta \]

\[
c = 2\pi nr^3 \frac{\xi_\parallel \sin^2 \theta + \xi_\perp \cos^2 \theta}{\sin \theta}
\]

Here, \(\theta\) is the helical angle. \(\xi_\parallel\) and \(\xi_\perp\) can be calculated by the formula provided by Lighthill. [44]

\[
\bar{\xi}_\parallel = \frac{2\pi \mu}{\ln \left(\frac{0.36\pi r}{r_w \sin \theta}\right) - 0.5}
\]

\[
\bar{\xi}_\perp = \frac{4\pi \mu}{\ln \left(\frac{0.36\pi r}{r_w \sin \theta}\right)}
\]

Here, \(\mu\) is the fluid viscosity. \(r_w\) is the wire radius. Based on the equations mentioned above, we calculated the microrobot velocity with respect to the rotating frequency and fluid velocity, and the results are given in Re-Figure 3B. Parameters used in the calculation are given in Table S1. The top left part refers to high velocity area, which reflects that the helical microrobot performs rapid translational motion with high frequency and low fluid velocity. The dashed line points out the situation that microrobot rotates without translational motion. And the bottom left part with blue color refers to a backward motion in which situation the microrobot’s propulsion cannot overcome the flowing fluid. According to this phase diagram, it is confirmed from modeling that our microrobot can move forward in a flowing fluid channel with velocity up to 5 mm/s as the step out frequency is more than 60 Hz as we shown in the manuscript.

Furthermore, we give a computational fluid dynamics (CFD) simulation to observe the fluid distribution of a rotating helical microrobot with forward translational motion in a flowing fluid channel. We build a 3D model in COMSOL Multiphysics with rotating machinery interfaces. The average velocity of fluid is 1 mm/s. The rotating frequency and translational speed of microrobot is 20 Hz and 1 mm/s, respectively.
It is shown that the rotating helical microrobot moves forward together with surrounding fluid, reflecting its effective motion against flowing fluid.

### Table S1 Fluid properties and geometric parameters used in the calculation of microrobot's motion.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
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<td>mm</td>
</tr>
<tr>
<td>$\mu$</td>
<td>5</td>
<td>mPa·s</td>
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<tr>
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<td>$r_w$</td>
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**Measurement of SMA helix work energy**

Evolution of force as response to displacement is measured by Dynamic Mechanical Analysis (TA, Q800). Given that tiny structures tend to produce large errors in clamping operations, we apply helix containing several spirals to test under set procedure. The ends of the helices are clamped and then chamber was closed. Temperature ramps from 20 degrees to 65 degrees and holds for 5 minutes. After that the tensile test begins and data are recorded for further analysis. The data columns of displacement and force of each test were selected in a table. The displacement data is divided by the helix number of the tested helix to obtain the displacement-force curve of a single helix. Integrating the displacement-force curve over a certain range, the output work energy value of helices of different helix index is obtained.
**Figure S1.** Characteristics of magnetic head. (A) Optical image of magnetic matrix for microrobot magnetic head. Scale bar is 50 μm. (B) Magnetization intensity as a function of applied magnetic density for PDMS embedded NdFeB particles.
**Figure S2.** Experimental setup for rotational magnetic field generation.
Figure S3. Characterization of original NiTi wire. (A) Weight ratio of Ti and Ni element. (B) DSC result.
**Figure S4.** Translational velocity responding to applied frequency when operated in liquid with different viscosity.
Figure S5. Analysis of heating process by adding a drop of water. (A) Schematic illustration of transformation triggering process by hot water droplet. (B) Simulation results showing temperature as a function of time at three different positions. The temperature 313.15 K and 318.15 K refers to the austenite peak temperature and phase transition complete temperature respectively. (C) Temperature field distribution of the capillary cross-section at different time.
Figure S6. (A) Schematic showing the real-time locomotion tuning due to shape transformation. (B-E) Velocity modulation by real-time structure transformation via heating. i-iv refers to different types of velocity modulation due to different shape transformation. Graphs present the helix angle and moving velocity of shape-memory helical microrobot (1) before and (2) after heating. In Figure S7B, the SMA helical microrobot recovers to a shorter shape resulting in velocity decreasing by around 140 μm/s. Similar recovery can also lead to increased velocity as Figure S7C. Besides, velocity change can be obtained by transforming to longer shape (Figure S7D). Apart from that, Figure S7E shows that large shape shifting can hardly change the velocity, corresponding to the two sides spanning the maximum value in Figure 3G.
Figure S7. Gaits variation due to shape transformation of SMA helical microrobot. (A) Optical image sequences display that shape transformation leads to transformation both in velocity and wobbling angle. (B) Velocity change with respect to time. (C) Contrast of wobbling angle before and after shape transformation.
**Figure S8.** Experimental setup of various force measurement related to helix angle, including force sensor, motor, spring, and tube filled with silicone oil with dynamic viscosity of 50 mPa·s.
Figure S9. Locomotion of rigid helical microrobot in the capillary containing obstacles. The rigid microrobot reveals different strategies facing the obstacle in different size, including pushing off, passing by and drill across. Scale bar is 500 µm.
Figure S10. Photograph of an artificial clot.
Figure S11. Displacement as respect to time of three unclogging strategies. Stage I to III refers to attaching the clot to drill, drilling in with one body length depth, and drilling through the clot.
Figure S12. Flow field distribution when the microrobot tail rotates in low Reynolds number environment.
Figure S13 Experimental result of evolution of work energy with response to spring index.
Figure S14. Viability of L-929 cells with SMA microrobot. (A) The extract of the test sample was cultured with vigorously growing L-929 cells (37°C, 5% CO₂) for 24 h, then the cell morphology and cell lysis were observed, and the potential cytotoxicity of the test sample was determined by MTT method. Error bars indicate the standard deviation. (B) Cell viabilities of L-929 cells which was cultured with shape memory alloy helical microrobot for 24 h (37°C, 5% CO₂). (C) Cell viabilities of L-929 cells which was cultured with shape memory alloy helical microrobot for 24 h (46°C, 5% CO₂).
Figure S15. Schematic diagram of medical surgery operated by microrobot.
Figure S16. Modeling of microrobot moving against flowing liquid. (A) Fluid velocity distribution inside 1 mm-diameter channel where the average velocity of fluid is set as 1 mm/s. The image of helical microrobot depicts relative position inside the channel. (B) Calculation results of helical microrobot velocity related to the rotating frequency and fluid velocity. Dashed line refers to zero points of microrobot velocity. (C) Simulated results of fluid distribution as the helical microrobot moving against flowing liquid.
**Movie S1.** SMA helical microrobot capable of transformable ability.

**Movie S2.** The three propulsion modes with respect to frequency under same magnetic intensity.

**Movie S3.** Different velocity transformation deduced by different structure transformation.

**Movie S4.** Propulsion modes shifting caused by structure transformation.

**Movie S5.** The adaptive strategy of helical microrobot when faced with sighter clogging area.

**Movie S6.** Demonstration of enhanced unclogging effect of transformable SMA microdrill.

**Movie S7.** Demonstration of self-propelling stent.
References


