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Preformation Characterization of a Torque-Driven Magnetic Microswimmer With Multi-Segment Structure

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ABSTRACT  Magnetically powered microswimmers exhibit various advantages in practical applications, including simplified propulsion mechanism of nonreciprocal motion in a low Reynolds (Re) number environment, high flexibility, and high efficiency. Inspired by the morphological and dynamic analyses of microscale nonreciprocal locomotion, this study characterizes the properties of torque-driven segmented microswimmers that actuated by an external oscillating magnetic field. The proposed microswimmer includes a magnetized head and several non-magnetized rigid body segments fabricated by two-photon lithography. The components of the microswimmer are linked together by rigid mechanical joints with an angle limiting mechanism, thereby forming simplified and discrete wave locomotion in a low Reynolds number environment. The motion of this multi-segment structure with different segment number is analyzed, and swimming locomotion involving segment interaction of the microswimmers and ambient liquid is characterized. Theoretical and experimental studies indicate that a minimum of three segments are needed to enable the microswimmers to move forward, whereas having four segments exhibits the best comprehensive performance. Based on this analysis, the geometric parameters of the four-segment microswimmers are further optimized, and experiments verify the enhancement of its motion capacity in a low Re number regime.

INDEX TERMS  Magnetic microrobot, microswimmer, multi-segment structure.

I. INTRODUCTION  Considerable research attention recently focus on micro-robots that can move in a fluidic environment, especially off-board microrobots driven by external energy sources such as light, thermal, ultrasonic, electrical, or magnetic fields [1]–[6]. Among the reported approaches, magnet-driven microrobots attract particular attention because of its high remote control performance and magnetic field that can penetrate through the body with little absorption and harm to living organisms [7]. These advantages are demonstrated in several experiments such as cell culturing [8], cell transportation [9], articular regeneration [10], and biohybrid targeted immunotherapy [11]. Thus, magnetically powered microrobots are promising for both in vitro and in vivo medical applications [12], [13].

Successful transformation of the input magnetic energy into microrobot motion is a key issue to enable the application of a magnet-driven microrobot. In terms of type, a force-driven microrobot can be directly dragged by a magnetic gradient force [14], whereas a torque-driven swimming microrobot or microswimmers is driven by locomotion force produced by oscillating microrobots and squeezing ambient liquid [15]. In sub-microscale or smaller, torque-driven microswimmers are proven more efficient than force-driven types because the equivalent force from the magnetic torque decreases more slowly with area than the magnetic gradient force that decreases with volume [7]. A torque-driven microswimmers can function in a wider working scope especially with large distance between magnets and the
Various torque-driven microswimmers have been developed, including propulsive component microrobot [16], [17], helical propeller inspired by bacterial flagella [18], elastic tail wiggled inspired by eukaryotic screw shape [19], flexible metal connected nanowire [20], and shifting mass microswimmers [21]. Among these designs, a multi-segment structure with rotary joint connection represents one of the simplest models used in low Reynolds (Re) number regimes [22]. Segmented microswimmers commonly employ relatively simple geometric structures such as tube, sphere, and surface, which can be fabricated with conventional microfabrication techniques and thus exhibit flexible structural design [23]. The multi-segment structure is essentially designed as a simplified discrete flagellum, and has similar propulsion efficiency as the wave motion [24]. Early studies report a segmented swimmer containing small links and flexible joints [25], DNA strands are used to connect superparamagnetic microbeads. Research also reports a microrobot that comprise an elastic eukaryote-like polymer tail and rigid magnetic nickel links that are connected by soft, flexible polymeric hinges [26]. Recently, a microrobot with flexible parts is built entirely with synthetic nanostructures that contain several segments manufactured with different metals [23]. Note that segmented microrobots are difficult to fabricate because of the challenges in flexible manufacturing in micro- and nanoscale. Several mechanical behaviors such as stress concentrations on rigid/soft interfaces may easily fail the segmented microswimmers in motion [27], [28].

Inspired by the morphological and dynamic analysis of wave motion, we recently designed a torque-driven four-segment microswimmer with a rigid joint structure, which can be electromagnetically driven in low Reynolds (Re) number regimes [29], [30]. The proposed four-segment microswimmer is easy to manufacture and assemble, and its rigid joint structure can improve durability and reliability compared with other magnet-driven microswimmers. However, a systematic understanding of the propulsion mechanism and influence of the segment number on the motion performance is still unclear. For example, how the microswimmer generates propulsion, how the number of segments affects the microswimmer’s athletic ability, and how to evaluate the kinematics and dynamic characteristics. If these problems cannot be clarified, the parametric design of the multi-segment microswimmer will be very difficult. This paper aims to fill in the gap by characterizing the driven mechanism and motion performance of the microswimmer with different segment number, based on which the ideal number of segments is recommended for the first time. Both theoretical and experimental studies demonstrate that the microswimmers requires a minimum of three segments to move forward but attains the best comprehensive performance with four segments. It is worth noting that similar macroscopic joint structures have been used in the literature for snake-like robots, such as the work of Kim [31], where the driving mechanism is based on the difference in friction between the tangential and normal directions. In contrast, the swimming microrobot proposed in our study is based on vibration, asymmetric motion and viscous resistance [32].

The remainder of this paper is organized as follows. First, the propulsion mechanism of a multi-segment magnetic microswimmers based on geometric motion gaits in a low Re number regime is analyzed. Second, the kinematic and dynamic models of the multi-segment microswimmers is established, based on which its properties with different numbers of segment are characterized. Then, parameters of the microswimmers with the ideal number of segments are designed and optimized, which is followed by experimental studies of microswimmers with different segment numbers. The conclusions of the work are finally given.

II. PROPULSION MECHANISM OF MULTI-SEGMENT MICROSWIMMERS

Unlike the force-driven magnetic actuation that can directly drag the magnetized microrobot, the torque-driven magnetic microrobot squeezes ambient liquids and generates the interaction counterforce between the microrobot and ambient liquid to provide propulsive power. Reynolds number (Re) is the ratio of inertial force to viscous force in a liquid environment, and it is an important factor for studying the propulsion mechanism of microswimmers. The Re number can be calculated by Re = ρVL/µ, where V is the speed, L is the characteristic length, ρ and µ are the density and viscosity of the fluid, respectively. When the Re number is considerably less than one, viscous force predominates the inertial force and the Navier–Stokes equation is linear and independent of time. This scenario indicates that when a microorganism or artificial microswimmers executes a geometrically reciprocal motion in an incompressible, Newtonian and low-Re fluid, net displacement cannot be generated because forward and backward movements cancel each other [22]. A segmented microswimmer with 1–2 segments has motion states that are less than two, and thus cannot execute a geometrically reciprocal motion to overcome the liquid resistance to move forward. In specific liquid environments, a two-segment microswimmer can move under a special motion strategy [33], but that is not considered in this study.

With three segments, the microswimmer structure is similar to Purcell’s three-link swimmer [22], which has been proven to be one of the most concise and durable locomotion structures in a low Re number regime. The three-link swimmer is a fore-aft symmetric linkage with three links and two revolute hinges. Each hinge can generate clockwise (CW) and counter CW (CCW) motions. Accordingly, the microswimmer can LO form a nonreciprocal motion squeeze with the four motion steps (CW and CCW rotation of each hinge). This feature enables the swimmer to move forward in low Re number regime by following the sequence of front link CW
rotation, rear link CCW rotation, front link CCW rotation, and rear link CW rotation in one circle. This sequence is also described as the alternating movements of front and rear links, each characterized by the independent and temporal CW and CCW rotations. Thus, each link must be controlled independently and synchronously. To achieve the described motion sequence, actuators such as linear actuator, servo motor, and piezoelectric actuator are placed in the front and rear links [27], [34], [35]. However, these actuators are difficult to use at micro-scale. Figs. 1(a) to 1(f) illustrate that a three-segment microswimmer can form a nonreciprocal periodic motion and move forward by using a specific pattern in an oscillating magnetic field, where the red arrows represent the direction of oscillating magnetic field. Fig. 1(a) shows the initial state of the three-segment microswimmer, where the segment with triangle is the head and red arrows represent the direction of the magnetic field. When the magnetic field rotates CW from the equilibrium position, the magnetized head follows the magnetic field rotation, whereas the two rigid body segments remain at their positions. Fig. 1(b) shows that when the active joint reaches its limit, the middle segment starts to move following the head motion. Fig. 1(c) displays that when the passive joint also reaches its limit, the head starts to rotate in the opposite direction. At this point, active and passive joints temporally lose function, the two rigid body segments remain in their positions whereas the head rotates CCW. Fig. 1(d) shows that when the active joint reaches its limit on the other side, the head rotation affects the middle segment. Fig. 1(e) and (f) are the chiral symmetry motions of Fig. 1(c) and (d), respectively, following the motion circle of (c)-(d)-(e)-(f).

When a microswimmer swims in a low Re number regime, nonreciprocal and periodic motion is a necessary condition. After the state in Fig. 1(f), the microswimmer naturally moves to its state of Fig. 1(c), indicating that the motion sequence (c)-(d)-(e)-(f) can fulfill the requirement of a periodic motion. The chiral symmetry motions in Fig. 1(d) and (f) indicate that the forward circulation (c)-(d)-(e)-(f) differs from the backward circulation (c)-(f)-(e)-(d). Thus, the nonreciprocal motion requirement is also fulfilled. Note that this study does not consider the force and torque between different segments, because the internal interaction only affects the position and orientation of the microswimmer but not the motion patterns. Based on the above analysis, a torque-driven microswimmer requires a minimum of three segments to move forward in a low Re number regime.

As the number of segments increases, the number of motion states also increases. This is a straightforward way to use the wave locomotion method to analyze the moving gait of a microswimmer. Figs. 1(g), (h), and (i) illustrate the moving gait [36] of microswimmer with three, four, and five segments, respectively. The microswimmer produces an approximate s-shaped standing wave when the horizontal displacement of each segment is considered along the vertical line, which is different from the traditional snake-shaped robot on the macro scale. The motion of the snake-shaped robot is based on the frictional motion generated by the anisotropic contact between the snake-shaped body and the ground, and the contact is directional [37], [38]. The horizontal displacement shows that the oscillation transmits from the head to the last segment, which is similar to a propagating wave. Here, the propulsion of a multi-segment microswimmer can be described as a discrete, undulating propulsion similar to bacterial flagella, which is regarded as an efficient propulsion mechanism in a low Re number regime.

The prototype of this multi-segment microswimmer can be fabricated with commercial two-photon lithography technology, which is found effective in producing a complex microstructure with functional mechanism [29], [39]–[41].
The details of prototype fabrication are described in appendix of this paper.

III. MATH PERFORMANCE CHARACTERIZATION OF SEGMENTED MICROSWMERS

A. NUMERICAL MODELS

In this study, the rotating magnetic field is generated by a Helmholtz magnetic coil system, which can generate a uniform magnetic field to prevent the influence of gradient magnetic flux. For simplicity, only 2D motion is considered in this study. In a low Re number regime, the microswimmer has negligible inertial force and moves in a quasi-equilibrium state. This finding implies that when the external magnetic force and torque changes, the acceleration is completed in a short time, and the external magnetic power and external liquid interaction is balanced during almost all the time period, which is expressed as

\[ L_m = L, \]

where \( L_m \) and \( L \) denote the external magnetic power and external liquid interaction, respectively. When the microswimmer is located inside the region of interest (ROI), the external magnetic power \( L_m \) can be regarded as the combination of external magnetic force \( F_m \) and torque \( T_m \), which are expressed as follows:

\[
L_m = \begin{bmatrix} F_m \\ T_m \end{bmatrix} = \begin{bmatrix} \mathbf{V} (\mathbf{M} \cdot \nabla) \mathbf{B} \\ \mathbf{VM} \times \mathbf{B} \end{bmatrix},
\]

where \( \mathbf{V} \), \( \mathbf{M} \), and \( \mathbf{B} \) denote the volume of the magnetic material, magnetization vector, and magnetic flux density of the external magnetic field, respectively, and \( \nabla \) denotes the Hamiltonian operator representing the gradient of field.

The interaction \( L \) represents the resistance force and torque between the microswimmer and ambient liquid, which can be treated as a peristaltic flow-structure interaction in a low Re number regime, governed by N–S equation. Defining \( L_i \) as the interaction of the \( i_{th} \) segment from ambient liquid, which includes the resistance force \( f_i \) and torque \( \tau_i \) on the \( i_{th} \) segment, we then obtain

\[
L = \sum_{i=0}^{n} L_i,
\]

\[
L_i = \begin{bmatrix} f_i \\ \tau_i \end{bmatrix} = \begin{bmatrix} -v_i f_0 (t_i, n_i) \left[ \begin{array}{cc} c_{t_i} & 0 \\ 0 & c_{n_i} \end{array} \right] & (t_i, n_i)^T d l_i \\ -\frac{1}{12} c_{n_i} l_i^3 \omega_i \end{bmatrix},
\]

where \( v_i \), \( \omega_i \), and \( l_i \) denote the microswimmer velocity, angular velocity, and length of the \( i_{th} \) segment, respectively, \( t_i \) and \( n_i \) are unit vectors in the axial and normal directions, which can be calculated as \( t_i = (\cos \phi_i, \sin \phi_i)^T \) and \( n_i = (-\sin \phi_i, \cos \phi_i)^T \); \( c_{t_i} \) and \( c_{n_i} \) are the \( i_{th} \) tangential local force coefficient in the axial and normal directions, which are represented as \( c_{t_i} = -2\pi \mu / [\ln(l_i/r_i) - 0.807] \) and \( c_{n_i} = -4\pi \mu / [\ln(l_i/r_i) + 0.193] \), where \( \mu \) is the dynamic viscosity of the liquid and \( r_i \) is the equivalent character radius of the \( i_{th} \) segment [42]–[44]. For simplicity, \( c_{t_i} = 2c_{n_i} \), based on the resistive force theory [45], the interaction \( L_i \) on the \( i_{th} \) segment can be expressed as

\[
L_i = -R_i \begin{bmatrix} v_i \\ \omega_i \end{bmatrix},
\]

where \( R_i \in \mathbb{R}^{3\times3} \) denotes a resistance matrix. The dynamic property of the microswimmer depends on shape only and the velocity follows gauge symmetry property theory [46]. \( R_i \) represents a resistance tensor, which is known to be symmetric and positive definite, expressed as

\[
R_i = c_{t_i} \cdot l_i \begin{bmatrix} 1 + \sin^2 \phi_i & -\cos \phi_i \sin \phi_i & 0 \\ -\cos \phi_i \sin \phi_i & 1 + \cos^2 \phi_i & 0 \\ 0 & 0 & 0 \end{bmatrix}
\]

where \( \phi_i \) denotes the orientation of the \( i_{th} \) segment.

We now derive the velocity and angular velocity of each segment. Fig. 2 shows the schematic of a n-segment microswimmer. The position and orientation are expressed as \( \mathbf{q} = (x, y, \phi_0)^T \), where \( (x, y) \) denotes the head position and \( \phi_0 \) denotes the rotating angle between the head and its equilibrium position. The shape of the microswimmer is represented by coefficient \( \phi = (\phi_1, \phi_2, \ldots, \phi_{n-1})^T \), where \( \phi_i \) denotes the angle between the \( i_{th} \) segment and \((i+1)_{th} \) segment. Given the position vector \( \mathbf{q} \) and the shape coefficient \( \phi \), the velocity and angular velocity of the \( i_{th} \) segment can be derived as

\[
\begin{bmatrix} v_i \\ \omega_i \end{bmatrix} = T_i (\mathbf{q}, \phi) \dot{\mathbf{q}} + E_i (\mathbf{q}, \phi) \dot{\phi},
\]

where \( T_i \in \mathbb{R}^{3\times3} \) and \( E_i \in \mathbb{R}^{3\times(n-1)} \) are defined as the two coefficient matrices representing the weighting functions of the body and shape velocity [47], respectively, which are determined by the geometric parameters of the microswimmer. Taking a three-segment microswimmer as an example, we obtain

\[
T_1 = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad \text{and} \quad E_1 = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 1 & 0 \end{bmatrix},
\]

\[
T_2 = \begin{bmatrix} 1 & 0 & -l_1 \sin \theta_1 + l_2 \sin \theta_2 / 2 \\ 0 & 1 & (l_1 \cos \theta_1 + l_2 \cos \theta_2) / 2 \\ 0 & 0 & 1 \end{bmatrix}
\]
and $E_2 = \begin{bmatrix} -l_1 \sin \theta_1 & 0 \\ l_1 \cos \theta_1 & 0 \\ 1 & 0 \end{bmatrix}$, 
$T_3 = \begin{bmatrix} 1 & 0 & (l_1 \sin \theta_1 + 2l_2 \sin \theta_2 + l_3 \sin \theta_3) / 2 \\ 0 & 1 & -(l_1 \cos \theta_1 + 2l_2 \cos \theta_2 + l_3 \cos \theta_3) / 2 \\ 0 & 0 & 1 \end{bmatrix}$, 
and $E_3 = \begin{bmatrix} 0 & -l_2 \sin \theta_2 \\ 0 & -l_2 \cos \theta_2 \\ 0 & -1 \end{bmatrix}$.

where $\theta_i = \varphi_0 + \sum_{j=1}^{i-1} \phi_j$. When the position and orientation of head is expressed as $q = (x, y, \varphi_0)^T$, the rotating angle $\phi_1$ between the head and the second segment, $\phi_2$ between the second segment and the third segment (or the tail), the velocity and angular velocity of all the three segments can be solved by using (7). For a four-segment microswimmer, the first three items $T_1, T_2, T_3$ remain as above and the fourth item $T_4$ is represented as

Thus, $E_i$ ($i = 1–4$) are represented as

$$E_1 = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}, \quad E_2 = \begin{bmatrix} -l_1 \sin \theta_1 & 0 & 0 \\ l_1 \cos \theta_1 & 0 & 0 \end{bmatrix},$$

$$E_3 = \begin{bmatrix} 0 & -l_2 \sin \theta_2 & 0 \\ 0 & -l_2 \cos \theta_2 & 0 \\ 0 & -1 & 0 \end{bmatrix}, \quad E_4 = \begin{bmatrix} 0 & 0 & l_3 \sin \theta_3 \\ 0 & 0 & -l_3 \cos \theta_3 \end{bmatrix}.$$

When the segments increase, $T_i$ and $E_i$ can be deduced accordingly. Finally, the relationship between the liquid resistance and the microswimmer motion is represented as

$$L = \sum_{i=0}^{n} L_i = -\sum_{i=0}^{n} R_i \begin{bmatrix} v_i \\ \omega_i \end{bmatrix} = -\sum_{i=0}^{n} (T_i^T R_i T_i \dot{q} + T_i^T R_i E_i).$$

Combining (1), (2), and (8), we obtain

$$\begin{bmatrix} V (M \nabla) B \\ VM \times B \end{bmatrix} = -\sum_{i=0}^{n} (T_i^T R_i T_i \dot{q} + T_i^T R_i E_i) = -\dot{q} \sum_{i=0}^{n} T_i^T R_i T_i - \sum_{i=0}^{n} \left( T_i^T R_i E_i \right) \phi \cdot \left( \sum_{i=0}^{n} T_i^T R_i T_i \right)^{-1}.$$

From (9), the microswimmer velocity is derived as

$$\dot{q} = \left( \sum_{i=0}^{n} T_i^T R_i T_i \right)^{-1} \cdot \left( -\sum_{i=0}^{n} \left( T_i^T R_i E_i \right) \phi - \left[ V (M \nabla) B \right] / VM \times B \right).$$

Then, the position and orientation of the microswimmer can be solved by integrating $\dot{q}$ in (10)

$$q = -\int_{t_0}^{t} \left( \sum_{i=0}^{n} T_i^T R_i T_i \right)^{-1}.$$

where the two coefficient matrices $T_i, E_i$, and the resistance matrix $R_i$ are all determined by the geometric characteristics of the microswimmer. $V$ and $M$ are determined by the magnetization of the head. As a result, the microswimmer state, represented by the state coordinate of head $q$, can be solved by using (11).

### B. NUMERICAL PERFORMANCE ANALYSIS

The motion performance of microswimmers with segment numbers from three to seven are examined through a series of numerical analysis. The microswimmers are assembled with the components as is shown in Fig. 10 of appendix. In the simulations, the strength of magnetic field $B$ increases from 0 to 40 mT (the maximum magnetic intensity) at a step of 10 mT, and the frequency increases from 0 to 10 Hz at a step of 1 Hz. Oscillating or on–off magnetic field is used to swing the magnetizing head of the microswimmer. The analysis used a planar oscillating magnetic field generated by two orthogonal sinusoidal magnetic coils, with the magnetic field flux density described as

$$B = \| B \| \begin{bmatrix} \cos (\psi \sin (2 \pi f t)) \\ \sin (\psi \sin (2 \pi f t)) \end{bmatrix},$$

where $\psi, f$, and $t$ are the swing angle, oscillating frequency, and time, respectively. At the beginning of the motion, the swing angle of the magnetic field is $90^\circ$, and $q$ and $\phi$ are set to zero. Based on (11), the velocity can be solved iteratively by using MUMPS solver in COMSOL Multiphysics. Table 1 provides the adopted parameters used in the simulation.

Note that in many practical applications, the magnetic field strength of the alternating magnetic field is usually below 40 mT for safety reasons. Therefore, in our study, the magnetic field strength is limited to 40 mT. Previous studies have analyzed the size of the microscanner and proposed the range of 100 µm to 200 µm used in this study. In addition, some other design principles are also considered in the modeling, such as the ratio of the length of the head to the segment and the equivalent diameter of the microswimmer.

The microswimmers with different segment numbers are evaluated in terms of the performance of forward velocity, efficiency, and carrying capacity. Forward velocity reflects the propulsion performance, which is largely dependent on frequency and torque of the magnetic actuation system. The microswimmer must achieve a sufficiently large velocity to overcome resistance. Fig. 3 shows the forward velocity performance of the microswimmers with different segment numbers. Fig. 3(a) illustrates the trajectory of a four-segment microswimmer, where the head position is used to represent the microswimmer position. The frequency and strength of the oscillating magnetic field are 1 Hz and 40 mT, respectively. The red dash line denotes the defined trajectory under

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TABLE 1. Key parameters of multi-segment microswimmer modeling.

<table>
<thead>
<tr>
<th>ITEMS</th>
<th>Value</th>
<th>Unit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>(B)</td>
<td>0 to 40 at step 10</td>
<td>mT</td>
<td>Strength of magnetic field</td>
</tr>
<tr>
<td>(f)</td>
<td>0 to 10 at step 1</td>
<td>Hz</td>
<td>Frequency</td>
</tr>
<tr>
<td>(q)</td>
<td>0</td>
<td>(\mu m)</td>
<td>Position vector</td>
</tr>
<tr>
<td>(\phi)</td>
<td>0</td>
<td>degree</td>
<td>Shape coefficient</td>
</tr>
<tr>
<td>(V)</td>
<td>253.323</td>
<td>(\mu m^3)</td>
<td>Volume of magnetic material (coating thickness is 100 nm)</td>
</tr>
<tr>
<td>Coating layer Material</td>
<td>Ni</td>
<td>N/A</td>
<td>The parameters of the Ni layer are provided by the supply company</td>
</tr>
<tr>
<td>Body Material</td>
<td>IP-L 780</td>
<td>N/A</td>
<td>The parameters of IP-L 780 Photore sist are provided by the supply company</td>
</tr>
<tr>
<td>(\rho)</td>
<td>1000</td>
<td>kg/m(^3)</td>
<td>Density of liquid</td>
</tr>
<tr>
<td>(\mu)</td>
<td>0.001</td>
<td>N·s/m(^2)</td>
<td>Dynamic viscosity of liquid</td>
</tr>
<tr>
<td>(l_i(1))</td>
<td>40</td>
<td>(\mu m)</td>
<td>Length of head</td>
</tr>
<tr>
<td>(l_i(l+1))</td>
<td>20</td>
<td>(\mu m)</td>
<td>Length of segments (except head)</td>
</tr>
<tr>
<td>(r_i(1))</td>
<td>1.46</td>
<td>(\mu m)</td>
<td>Equivalent character radius of head [47]</td>
</tr>
<tr>
<td>(r_i(l+1))</td>
<td>3.63</td>
<td>(\mu m)</td>
<td>Equivalent character radius of segments (except head) [47]</td>
</tr>
<tr>
<td>(\theta_{max})</td>
<td>20</td>
<td>degree</td>
<td>Angle of shaft rotating limiter</td>
</tr>
</tbody>
</table>

an open-loop control, and the black solid line denotes the desired trajectory. The microswimmer moves from position a to b by following a horizontal line, then changes the heading direction to move from b to c, and finally moves from c to d. Here, the forward velocity is calculated as the moving distance of the microswimmer, which is \((ab+bc+cd)\) in Fig. 3(b), divided by the time spent. Fig. 3(b) illustrates the position \([q(x), q(y)]\) of the microswimmer head when the magnetic intensity and frequency are set at 40 mT and 1 Hz, respectively. The magnetized direction is along the head orientation. The positive and negative torques represent the magnetic directions are CW and CCW, respectively. Fig. 3(d) illustrates the calculated forward velocity of the microswimmers with three to seven segment numbers when the magnetic intensity is 40 mT. The forward velocity dramatically decreases when the segment number is larger than five. When the segment number increases, the resistance of the liquid increases, whereas the driving magnetic energy remains the same. These results preliminarily reveal that the segment number is ideally five and below. Thus, Figs. 3(e), (f), and (g) illustrate the relationships among the frequency, magnetic strength, and forward velocity of the three-, four-, and five-segment microswimmers, respectively. The velocity increases as the intensity of the magnetic field increases, and no inflexion is observed in the power range of 0–40 mT. In all the follow-up experiments, a maximum intensity of the magnetic field is set as 40 mT.

Efficiency (denoted by \(\epsilon\)) is dependent on the magnetic energy transformation, which can be defined as the ratio of the power propelling the microswimmer and the total power from the magnetic actuation system. Given that the acceleration is neglected in the low Re number regime, the microswimmer moves in a quasi-equilibrium state. As a result, efficiency can be defined as the output energy, a kinetic energy of the microswimmer, divided by the input energy of the coil system. The input energy can be treated as a constant because the input current and voltage remain the same. Therefore, the kinetic energy at the given current level mainly determines the microswimmer efficiency.

The microswimmer also functions as a platform for either sensing or loading biological samples such as astrocytes, neurons, or cells; thus, its carrying capacity represents another important criterion [13], [48]. Considering that microswimmer delivers a certain number of cargos in a given time period, its carrying capacity can be represented by its velocity multiplied by the number of cargos. Thus, given its planar structure, the microswimmer surface area can be used to represent the loading capability.

Fig. 4 illustrates the evaluation results of the microswimmers with three-, four- and five-segments based on the three criteria of forward velocity, efficiency, and carrying capacity. Apart from a swing angle of 90°, a smaller swing angle of 45° is also considered in the oscillating magnetic field. Fig. 4(a) illustrates the velocity–frequency curves of the three types of microswimmers at maximum intensity (40 mT) of the magnetic field when the swing angle is 90°. Overall, the four-segment microswimmer exhibits better velocity performance than the three- and five-segment microswimmers, except at the certain range of low frequency where the three-
FIGURE 3. Performance evaluation of microswimmers with different segment numbers: (a) Trajectory simulation of a four-segment microswimmer driven by oscillating magnetic field (frequency = 1 Hz and strength = 40 mT); (b) Position $q(x, y)$ of the microswimmer head when the magnetic intensity and frequency are set at 40 mT and 1 Hz; (c) Magnetic torque applied on the microswimmer head when the magnetic intensity and frequency are set at 40 mT and 1 Hz; (d) Velocity of the microswimmers with three, four, and five segment numbers as the frequency changes; (e) Relationship of velocity, frequency, and magnetic intensity of the three-segment microswimmer; (f) Relationship of velocity, frequency, and magnetic intensity of the four-segment microswimmer; (g) Relationship of velocity, frequency, and magnetic intensity of the five-segment microswimmer.

A segment microswimmer appears to have better performance. Fig. 4(b) also illustrates that the four-segment microswimmer performs the best when the swing angle of the oscillating magnetic field is 45°. Figs. 4(c) and (d) illustrate the relationship between the different swing angles of the oscillating magnetic field. For simplicity, the input energy...
remains constant, and the kinetic energy of the microswimmers is calculated as $E_k = \frac{1}{2}mv^2 = \frac{1}{2}V \cdot v \cdot c_m$, where $v$, $V$, and $c$ denote the microswimmer velocity, volume, and mass coefficients, respectively. Efficiency is defined as $\eta = V \cdot v^2 \cdot c / E$. Fig. 4(c) shows that among the three types of microswimmers, the four-segment microswimmer exhibits the overall best efficiency when the swing angle of the magnetic field is 90°. Fig. 4(d) depicts that when the swing angle decreases from 90° to 45°, the actuation efficiency of the four- and five-segment microswimmers are similar, whereas that of the three-segment microswimmer is the lowest. Figs. 4(e) and (f) show the carrying capacity of the three types of microswimmers with different frequencies under the two magnetic fields with swing angles 90° and 45°, respectively. Here, the carrying capacity depends on how many cargos a microswimmer can carry in one-time travel and how fast the magnetically driven system can transfer microswimmers, which is calculated as $C = s \cdot v \cdot c_n$, where $s$, $v$ and $c_n$ denote the microswimmer surface area, velocity, and capacity coefficients, respectively. The surface area is calculated by the microswimmer’s height multiplied by its length (seen Fig. 10). The results show that the three-segment microswimmer has the weakest carrying capacity and the four- and five-segment microswimmers have similar capacities. As the frequency increases, the carrying capacities of all the microswimmers decrease.

Based on the above analysis, the three-segment microswimmer has a comparable velocity performance but worse efficiency and carrying capacity in comparison with the four-segment microswimmer. The five-segment microswimmer has better carrying capacity because of its larger surface area but has much lower velocity than those of the three- and four-segment microswimmers. The four-segment microswimmer exhibits the overall best comprehensive performance. Moreover, the four-segment microswimmer shows good redundancy and dependability, which are also very important in practical applications. Table 2 summarize the comparison results of the three microswimmers.

### TABLE 2. Comparison of microswimmers with three, four, and five segments.

<table>
<thead>
<tr>
<th>CHARACTERISTICS</th>
<th>Three-segment</th>
<th>Four-segment</th>
<th>Five-segment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum speed</td>
<td>Fast</td>
<td>Medium</td>
<td>Slow</td>
</tr>
<tr>
<td>Oscillating 90°</td>
<td>45° Oscillating</td>
<td>Medium</td>
<td>Fast</td>
</tr>
<tr>
<td>Efficiency</td>
<td>Medium</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Oscillating 90°</td>
<td>45° Oscillating</td>
<td>Low</td>
<td>Medium</td>
</tr>
<tr>
<td>Carrying capacity</td>
<td>Low</td>
<td>Medium</td>
<td>High</td>
</tr>
<tr>
<td>Oscillating 45°</td>
<td>Low</td>
<td>Medium</td>
<td>High</td>
</tr>
<tr>
<td>Redundancy</td>
<td>Low</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Dependability</td>
<td>Low</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Complexity</td>
<td>Low</td>
<td>Medium</td>
<td>High</td>
</tr>
</tbody>
</table>

### C. PARAMETER DESIGN OF THE FOUR-SEGMENT MICROSWIMMERS

The above analysis shows that the four-segment microswimmer is preferable than the other two types. In this subsection, the geometric parameters of the four-segment microswimmer are designed, including the head length, non-magnetized segment length, and angle of shaft rotating limiter, which are independent of each other. These parameters can highly affect the microswimmer performance in low Re number regimes. Fig. 4 shows the results, indicating that the velocity, efficiency, and carrying capacity are all highest when the magnetic frequency is approximately 3 Hz. Therefore, in the following analysis, the frequency of the magnetic field is set at 3 Hz.

The microswimmer length is a combination of head length ($L_h$) and segment length ($L_f$), which is $L_{total} = L_h + 3L_f$ for a four-segment microswimmer with equal lengths of rigid body segments. Ideally, the total length of the microswimmer should not be too large to ensure accessibility in the body, but also not too small so as to retain its loading capacity. To this end, a total length of 100–200 µm may be appropriate [30]. Figs. 5(a), (b), and (c) illustrate the velocity, efficiency, and carrying capacity of the four-segment microswimmer with different segment and head lengths. The segment lengths are chosen as 10, 20, 30, and 40 µm, whereas the head lengths range from 10 µm to 80 µm. The microswimmer exhibits
the highest velocity and efficiency when the head length is 40 μm and the segment lengths are 20 μm or 30 μm, and thus the total microswimmer length is 100 μm and 130 μm, respectively. Eventually, the microswimmer with 20 μm segment lengths and 40 μm head length, which has a smaller total length of 100 μm, is selected for prototype fabrication.

Fig. 5(d) illustrates how the angle of shaft rotating limiter affects the microswimmer velocity. Changing the angle does not affect the other parameters such as the volume or surface area. The angle of the limiter changes from 10° to 35° at a step of 5°. At approximately 25°, the microswimmer velocity reaches the maximum, which agrees with a previous report [29]. Finally, Table 3 shows the designed parameters of the four-segment microswimmer.

IV. EXPERIMENTS

A series of experiments are performed to verify the theoretical analysis and design of the segmented microswimmers. The microswimmers are placed in a custom-designed container which is manufactured with glass-polydimethylsiloxane plasma bonding and filled with 1% (w/v) Tween 20 solution (Sigma Aldrich). The magnetic actuation system used in the experiments consists of two pairs of magnetic coils, two DC power supplies (DF1731SB5A), and two electrical signal amplifiers controlled by ATMEL MEGA32U4 that can transform DC current to sinusoidal wave signals. The maximum current is set to $I_{\text{max}} = 5$ A. An inverted optical microscope with a 3× objective is integrated with the magnetic system. Fig. 6(a) shows the schematic of the microswimmer driven by the magnetic coil system. The ROI is located in the center of the coil system, which is a square with side length of 5 mm. Microswimmers with three, four, and five segments, with a total length of 80, 100, and 120 μm, respectively, were
TABLE 3. Optimized key parameters of the four-segment microswimmer.

<table>
<thead>
<tr>
<th>Item</th>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Numbers of segments</td>
<td>4</td>
<td>One head and three segments</td>
</tr>
<tr>
<td>Height (µm)</td>
<td>20</td>
<td>Distance between the top and bottom positions of segments disregarding the supporting structure</td>
</tr>
<tr>
<td>Head length (µm)</td>
<td>40</td>
<td>Distance between the head front and joint center</td>
</tr>
<tr>
<td>Middle: distance between the centers of two joints</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Segment length (µm)</td>
<td>20</td>
<td>Tail: distance between the joint center and segment tip</td>
</tr>
<tr>
<td>Total length (µm)</td>
<td>100</td>
<td>Distance between the head front and the tip of tail segment</td>
</tr>
<tr>
<td>Angle of limiter (degree)</td>
<td>25</td>
<td>Value of shaft rotation limiter in Fig. 10</td>
</tr>
</tbody>
</table>

Fig. 7 shows the motion capacity of the segmented microswimmers. Figs. 7(a), (b), and (c) show the gait of the microswimmers in a time series with three, four, and five segment numbers. The described moving gaits is also shown in Supplementary Video. The oscillation transmits from the head to the segments, indicating that the microswimmer motion can be described as an approximate propagating wave.

These wave-like motions demonstrate that the described s-shaped undulating propulsion can be generated under the tested. All microswimmer motions were restricted within the ROI. Fig. 6(b) shows the field strength distribution of the designed magnetic system calculated by using FEM method [49]. The difference between the upper limit and lower limit of the magnetic field strength distribution in ROI is under 5%, implying that the magnetic field can be regarded as a uniform field area. One pair of coils generates the maximum magnetic field of approximately 40 mT at the center area. The magnetic strength is measured by using a GM-500 fluxmeter tindun testmeter.
actuation of a rotating magnetic field, thereby verifying the wave propulsion mechanism. The distance between the starting red dash line and the ending blue solid line shows that the microswimmer moves forward under the net force. The mobility of microswimmers with three and four segment numbers are shown in figs. 7(d) and (e), and supplementary video. Fig. 7(d) illustrates that when the first segment of the three-segment microswimmer #1 malfunctioned, the microswimmer could not move and was oscillated at its original position. Only when all three segments functioned normally, as seen on microswimmer #2, can it move forward. Fig. 7(e) shows that the four-segment microswimmer #3 can move even when one of the joints stopped working, demonstrating that the four-segment microswimmer exhibits stronger moving adaptability and capability than the three-segment microswimmer.

Fig. 8 shows the motion performance of the three types of segmented microswimmers. Fig. 8(a) shows the traveling trajectories of the microswimmers with three, four and five segments. For simplicity in comparison, the moving trajectory is designed as a straight line, where the microswimmer moves from a starting position in the left to an ending position in the right. The frequencies of magnetic field are set as 1 Hz, 3 Hz and 5 Hz. For both three- and four-segment microswimmers, the moving distances under 3 and 5 Hz frequency are larger than those under 1 Hz within the same time spent (20 s). Under the same frequency of 3 or 5 Hz, the four-segment microswimmer moves longer distances and shows a better moving capacity than the three- and five-segment microswimmers. For the five-segment microswimmer, the moving distance is much shorter, which indicated slower movement, than those of the three and four-segment microswimmers. Fig. 8(b) illustrates the statistical results of the velocities of the three types of microswimmers under different frequencies. Clearly, the four-segment microswimmer exhibits the best motion performance. The detailed comparison can be seen in Supplementary Video.

Finally, we test the four-segment microswimmer with the designed optimized parameters in Table 3. Fig. 8(a) shows that the microswimmer is required to move along a straight line. Fig. 9(a) illustrates the velocity of the designed four-segment microswimmer prototype as the oscillating frequency of the magnetic field changes from 0 to 10 Hz. Since the multi-segment microswimmers usually swim at a low flapping frequency, a more detailed analysis of the test in the low frequency range is carried out. Here the oscillating frequency increases from 0 to 6 Hz with a step of 0.5 Hz, and increases from 6 to 10 Hz with a step of 1 Hz. The velocity is calculated by dividing the moving distance by the spent time. Here, the swing angle of the magnetic field orientation is fixed at 45°. The solid and dash lines represent
the theoretical and experimental results, respectively. The velocity increased as the frequency increased in the low frequency range (under 4.5 Hz) and then decreased after 4.5 Hz. The experimental result well matched the theoretical analysis in the low-frequency region, indicating that the four-segment structure exhibits good performance particularly in this range. In the high-frequency region, the deviation between the theoretical and the experimental results is clearer. This result is caused by the rapid decrease of driving energy provided by the magnetic field due to the influence of inductive reactance, and the increased severity of environmental effect such as non-uniform distribution of magnetic field. The microswimmer velocity generally reaches the maximum in the frequency range of 3–5 Hz, and then decreases as frequency increases. When the frequency is larger than 10 Hz, speed is only 2–3 μm/s, which is slightly larger than the Brownian motion, indicating that the magnetic field provides a weak driven energy. The four-segment microswimmer can overcome the viscosity resistance from ambient liquid by increasing the intensity of magnetic field or using advanced materials to enhance the maximum magnetic torque. Fig. 9(b) illustrates the position \([q(x), q(y)]\) of the designed four-segment microswimmer driven by oscillating magnetic field with the strength of 40 mT and a frequency of 3 Hz. The red solid and black dotted lines denote the x- and y-coordinates of the microswimmer head, respectively. Fig. 9(c) illustrates the head trajectory of the designed four-segment microswimmer which is required move along a straight line over a time period of 10 s, the x- and y-axis represent the position \([q(x), q(y)]\) of the four-segment microswimmer, the z-axis represents the time. The red solid line denotes the trajectory and the grey semitransparent plane denotes the plane of \(y = 0\). After the above tests, the microswimmer is further required to move along a desired Z-shape trajectory as shown in Fig. 9(d) and Supplementary Video. Fig. 9(d) shows the blue dash line that denotes the actual trajectory under an open-loop control, and the red solid line that denotes the defined trajectory. The results show that the designed four-segment microswimmer successfully moves along the given trajectory.

V. CONCLUSION
This study presents the propulsion mechanism and performance characterization of segmented microswimmers driven by an external oscillating magnetic field, inspired by morphological and dynamic analyses of wave locomotion. The motion pattern analysis shows that the multi-segment
microswimmers can form a nonreciprocal motion and move forward under an oscillating magnetic field in a low Re number regime. Both the theoretical analysis and experimental study demonstrate that the segmented microswimmer with a minimum of three segments can move forward smoothly under an external magnetic field, and the microswimmer with four segments exhibits the best comprehensive performance. A series of experiments further validate the theoretical analysis and the design. Future study can focus on the application of the designed microswimmers to 3D motion navigation in the in vivo environment.

APPENDIX A

The microswimmer prototype used in this study includes one lathy plane head and several lathy plane segments connected with a solid joint structure to prevent failure of rigid/soft interface [27], [28], as shown in Fig. 10. At each joint, a shaft rotation limiter is installed to constrain the relative rotating angle between two adjacent segments. The designed microswimmers are fabricated with a high-precision two-photon lithography system [Photonic Professional (GT), Nanoscribe GmbH, Germany] equipped with a 63 x, NA (numerical aperture) = 1.4 oil-immersion objective lens. Fig. 10 illustrates a proof of concept of three-, four-, and five-segment microswimmer prototype, which includes a magnetized head (coated with 100 nm Ni layer) and several nonmagnetic rigid body segments [29], [30]. Microswimmers with other segment numbers can also be made in a similar process. The key parameters of the segmented microswimmers include head length, body segment length, height, and shaft rotating angle. Here, the rotating angle of the shaft represents the maximum relative rotation of each joint.

REFERENCES

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