A Review on the Motion of Magnetically Actuated Bio-Inspired Microrobots

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Abstract: Nature consists of numerous solutions to overcome challenges in designing artificial systems. Various actuation mechanisms have been implemented in microrobots to mimic the motion of microorganisms. Such bio-inspired designs have contributed immensely to microscale developments. Among the actuation mechanisms, magnetic actuation is widely used in bio-inspired microrobotic systems and related propulsion mechanisms used by microrobots to navigate inside a magnetic field and are presented in this review. In addition, the considered robots are in microscale, and they can swim inside a fluidic environment with a low Reynolds number. In relation to microrobotics, mimicry of bacteria flagella, sperm flagella, cilia, and fish is significant. Due to the fact that these biological matters consist of different propulsion mechanisms, the effect of various parameters was investigated in the last decade and the review presents a summary that enhances understanding of the working principle of propulsion mechanisms. In addition, the effect of different parameters on the various speeds of the existing microrobots was analyzed to identify their trends. So, the swimming speeds of the microrobots show an upward trend with increasing body length, frequency, magnetic flux density, and helix angle. Microfabrication techniques play a significant role in the microscale because the device designs are highly dependent on the availability of the techniques. The presented microrobots were manufactured by 3D/4D photolithography and rapid prototyping techniques. Proper materials enable effective fabrication of microrobots using the mentioned techniques. Therefore, magnetically active material types, matrix materials, biocompatible and biodegradable materials are presented in this study. Utilizing biocompatible and biodegradable materials avoids adverse effects to the organs that could occur otherwise. In addition, magnetic field generation is significant for the propulsion of such microrobots. We conclude the review with an overview of the biomimicry of microrobots and magnetically actuated robot propulsion.

Keywords: microrobots; microswimmers; bio-inspired; magnetic actuation; propulsion; microfabrication; lab on a chip

1. Introduction

At present, microfluidics is widely used in clinical diagnostics and biomedical research due to the significant advantages in high throughput, miniaturized device size, simplicity, low cost, and portability [1,2]. Microfluidic devices are developed to perform fluidic and particle manipulations [3]. A prominent direction of microfluidics for medical diagnostics is the lab-on-a-chip (LOC) technology [4], which is the study of performing laborious and time-consuming laboratory tasks in a single chip [5]. To perform particle manipulations such as mixing, separation, and delivery in a microfluidic environment, various approaches have been investigated [6–8]. A promising approach is the development of microrobots that act as individual robot modules and, as a collective microrobotic swarm. In addition, targeted drug delivery is one of the key applications of microfluidics. Nanoparticles, cells,
genetic materials, and imaging agents are also required to be delivered to a target location in the biomedical field for medical diagnostics and treatments [9,10]. Nanomedicine [11] and microrobotics are two approaches that can be utilized for targeted drug delivery. Therefore, microrobotics is an important field of study in microfluidics research.

A microrobot is an intelligent, reprogrammable, microscale robotic system fabricated using microfabrication techniques to move, sense, and operate inside a microenvironment [12]. Most commonly, microrobots used in medical applications are operated inside a fluidic environment in the microscale [13]. Therefore, the microrobots discussed in this review are related to the microfluidic domain. Various classifications of microrobots are reported based on their make-up, operating region, actuator placement, and propulsion method [12]. According to the make-up, microrobots are classified as cellular microrobots, synthetic microrobots, and hybrid microrobots [14]. Cellular microrobots are based on cell-made components and synthetic microrobots are made of man-made components [15]. Hybrid microrobots contain both cell made components and man-made components [16]. Microrobots are divided into two groups such as microswimmers and surface walking robots according to the operating region. Microswimmers [17] can propel and move inside a bulk fluid. Conversely, surface walking robots can walk [18], slip [19], or roll [20] on the fluidic walls. According to the actuator placement, microrobots are categorized as on-board and off-board robots [21]. On-board microrobots have the capability to move, sense, and operate independently without any external interaction whereas off-board microrobots require external interference [12]. In classification according to the propulsion method, the actuation technique is significant.

Microrobots are actuated using magnetic [22], acoustic [19], optical [23], chemical [24], and mechanical [25] actuation methods. From the mentioned actuation methods, magnetic actuation is a widely used actuation method, which is used to mobilize microrobots in biomedical applications [26]. In magnetic actuation, the use of external magnetic fields is considered the most successful approach [3]. This is because low-frequency and low-strength magnetic fields are not harmful to biological matters including the vital organs in the human body [27], providing the magnetic environment near the microrobot can be achieved using a permanent magnet or an electromagnet. However, the magnetic field strength decreases at a greater rate with the distance from the source [28]. This is a challenge in designing and choosing the magnetic propulsion method. However, this approach is suitable for both in vitro and in vivo applications [29]. The major challenge in exploring the fluid and particle behavior in the microenvironment is that the fundamental theories differ from that of the macroscale [30,31]. For example, viscous forces dominate the inertial forces in the microscale [32]. This happens in the low Reynold’s number fluid regime of Newtonian fluids. Reynold’s number can be calculated using the density of the fluid, length of the microrobot, swimming speed of the microrobot, and the dynamic viscosity of the fluid [33]. For microrobots, length and swimming speed are in microscale. Therefore, the flow regime of a microrobot always has a low Reynold’s number. According to the scallop theorem, microrobots that do not have a non-reciprocal motion cannot propel in Newtonian fluids [34]. Mimicry of natural matter is a promising approach in addressing this challenge and various bio-inspired systems have been investigated [35]. Bio-inspired mechanisms have been implemented for microrobots and various propulsion methods have been investigated [36]. In this review, biological systems which are capable of generating non-reciprocal motion are focused on. Specifically, the motion of bacteria flagella, sperm flagella, cilia, and fish have given inspiration in propelling microrobots [35]. For propulsion, bacteria flagella use a cellular level motor, sperm flagella use a beating tail-like motion, cilia use dynein motors, and fish use undulatory motion generated by the body and caudal fin locomotion.

While the major mimicking feature investigated has been the propulsion method [37], the appearance of the microorganisms or the animal has also been mimicked in a few studies [38]. However, in cases such as mimicking fish, only the undulatory motion has been mimicked. In addition to the review on the bio-inspired propulsion methods of
magnetically actuated microrobots, important parameters related to different motions, fabrication techniques, and materials are presented in the review. The parameters that affect the velocity of the microrobot are further analyzed to identify whether they have an upward or downward trend. Generating the magnetic field is also important in developing such microrobotic systems, therefore, the available techniques are discussed in the later section of the review.

2. Bio-Inspired Mechanisms Used in Locomotion

Macro-scale robots have mimicked the shape and locomotion of biological species [39]. This mimicry is challenging when the size of the robot is reduced [40]. Due to space limitation, placing an actuator inside the robot is very challenging [41]. This challenge has been addressed by using an untethered actuation mechanism such as magnetic actuation [42]. Apart from that, the domination of viscous force highlights the requirement of non-reciprocal motion for a Newtonian fluid. Mimicry of the motion of bacteria flagella, sperm flagella, cilia, and fish has shown promising solutions to control microrobots in the low Reynolds’s number flow regime. In this section, mechanisms behind the motion of living organisms and the microrobots which adapt to these mechanisms are discussed.

2.1. Bacteria Flagella

Bacteria is a living organism that can move inside a low Reynolds number fluidic environment. A helical-shaped filament called flagellum is used by bacteria for locomotion. This flagellum can be rotated at about 100 Hz by a rotary motor connected to the cell body. The rotary motor and flagellum are connected through a short flexible hook as shown in Figure 1 and the arrangement operates as a universal joint. In general, the diameter and the length of the helical flagellum are about 20 nm [43] and 3–10 μm [44].

![Figure 1. Placement of rotary motor, hook, and flagellum or filament.](image)

Bacteria have one or many flagella located at the pole or lateral side of the cell body. Accordingly, bacteria are categorized into four categories as shown in Table 1 [45].

| Type              | No. of Flagella | Placement of Flagella | Layout       | Examples         |
|-------------------|-----------------|-----------------------|--------------|------------------|
| Monotrichous      | One             | One pole              |              | Pseudomonas      |
| Amphitrichous     | Two             | Two poles             |              | Campylobacter    |
| Lophotrichous     | More than two   | One pole              |              | Helicobacter     |
| Peritrichous      | More than two   | Lateral               |              | Escherichia coli |
A helical microstructure is used to mimic the bacteria flagella, but in some cases, a head is attached to the helical structure to act as the magnetically active part or to perform micromanipulations [46]. Therefore, microrobots that mimic Monotrichous bacteria can be again classified as microrobots with heads and without heads. In the literature, rectangular [47], circular [48], spherical [49], and cylindrical [50] shaped heads are used in helical microrobot designs, and several designs are shown in Figure 2a–c. In addition, the microholder shown in Figure 2d was also used as the head of the helical microrobot to perform micromanipulations [51]. It is significant that, when the performance of the microrobots with different rectangular head sizes is compared with the rotating frequency of the magnetic field, microrobots with larger heads can achieve higher maximum velocities when operated at high frequencies [52]. When the helical tail is fabricated with a non-magnetic material, a magnetically active head is essential to control the microrobot [53]. Microrobots having both head and tail fabricated using magnetic materials have also been reported because it improves the magnetic effect [54].

Figure 2. Helical microrobots: (a) With a soft magnetic head; (b) having a head with a microholder; (c) with a spherical head; (d) with a circular head; (e) without a head.

In comparison to helical microrobots with heads, microrobots without heads are less complex in fabrication due to the geometry as shown in Figure 2e [55]. Because of the nature of the helical structure, these microrobots can swim inside a fibrous environment which leads to in vivo experiments [56]. In addition, drugs can be coated on the helical microstructures to perform targeted drug delivery [57]. These capabilities have been further improved by culturing and transporting stem cells on a helical microrobot with holes in its body [58]. Their bodies are fabricated or coated using soft magnetic materials which can be activated using a rotating magnetic field [59]. Artificial helical microrobots pose challenges in fabrication therefore, an alternative approach of coating magnetic particles on naturally available helical structures which are available on Spirulina [60], Raphiolepis indica [61], and self-assembled liposomes [28] is performed. In addition, hollow helical microrobots can be fabricated, removing the Spirulina template by annealing, after coating the magnetic particles [62].

A microrobot which has two flagella similar to the geometric appearance of the Amphitrichous bacteria has been reported. However, the propulsion was performed using planar wave propagation which is not similar to the propulsion of a bacteria flagella [47]. A helical microrobot with two, three, or four flagella fixed to its head mimics the shape of the Lophotrichous bacteria as shown in Figure 3a. These microrobots can rotate their flagella separately whereas the mimicking helical microrobots can only rotate all the flagella at once inside a rotating magnetic field. Even though the motion is not identical, having multiple helical structures increases the torque applied to the microrobot [46].
Apart from the above types, helical microswimmers which have mastigonemes (flagella covered with appendages perpendicular to the main flagella) have been presented and the effect of the length/space ratio of mastigonemes on the speed of the microrobot has been investigated [64]. In addition, nanowires are used to mimic the motion of the Monotrichous bacteria. They are also maneuvered inside a rotating magnetic field similar to the helical microrobots [65]. A swarm of microrobots that mimic the motion of Monotrichous bacteria as shown in Figure 3b has been successfully tested in vitro and in vivo in the intraperitoneal cavity of a 4-week-old Bulb-C mouse [63].

The geometry of the helix, properties of the coated magnetic layer, viscosity of the fluid, wettability of the helix in the fluid, and step-out frequency are several factors that affect the swimming performance of helical microrobots [66]. Mathematical modeling and computer-based simulations have been widely used to investigate the effects of geometric parameters of the helix on the microrobot’s swimming performance [67,68]. When increasing the helix angle and number of turns, the velocity of the microrobot also increases [44]. Similarly, the velocity of the microrobot increases with the thickness of the magnetic layer [66] and decreases with the viscosity of the fluid [48]. When increasing the frequency of the magnetic field, the rotating speed and linear velocity of the microrobots increase up to a certain point and then start to decrease. For microrobots, the frequency which gives the highest velocity is taken as the step-out frequency [69]. The wettability of the helix mainly depends on the contact angle. Therefore, hydrophilic surfaces have a low step-out frequency compared to hydrophobic surfaces in water [70]. In addition to these factors, the biodegradability of the microrobot was investigated to avoid material accumulation inside the organs [71]. To achieve biodegradability, helical microstructures are first fabricated using biodegradable materials and then, coated with magnetic [72] or magnetoelectric [73] nanoparticles to control them using a rotating magnetic field.

In terms of controlling the microrobots, most of the helical microrobots utilize an open-loop controlling system [74]. This controlling method can be used to follow a straight path with velocity controlling and so avoid lateral motion due to gravity [75]. In addition, a millimeter scale helical microrobot was studied with a closed-loop controlling system using position-based visual servoing which requires multiple calibrated cameras [76]. Due to the refractions caused at low Reynold numbers, the accuracy of the 3D reconstruction procedure drops in this method [77]. This challenge is addressed by introducing a closed-loop in controlling a millimeter scale helical microrobot using image-based visual servoing which, directly calculates the control sequence using image features [78]. Even though it is
possible to manipulate a single microrobot using a magnetic field, selective manipulation of multiple microrobots is difficult. This was investigated by manipulating two types of helical microrobots that had a bar-shaped head and a cross-shaped head, using an external magnetic field [79]. Another way to perform selective control is the use of hydrophobic surfaces which exhibit larger step-out frequencies and hydrophilic surfaces which exhibit lower step-out frequencies. Then, the microrobots having a step-out frequency larger than the applied frequency, are able to move inside the fluid [80].

2.2. Sperm Flagella

Animal sperms are the motile male reproductive cells. The motile sperms have a beating tail-like flagellum to propel through fluids. A human sperm cell beats at a frequency of 10–30 Hz, which varies depending on the environmental conditions [81]. Human sperm also have a swimming velocity of around 50 µm/s, a beat amplitude of around 5 µm, and a beat wavelength of about 12 µm [82]. The fluid regime encountered for sperm propulsion is in the low Reynolds domain. Because the low Reynolds number in their environment renders reciprocal motion inefficient, such microscale creatures require a specific approach to move to positions in fluids [83]. The swimming tactics of microorganisms are based on helical rotation with more than one degree of freedom and a time-reversal asymmetry. Thus, a complex helical motion is achieved through flagella to generate traveling waves. These waves are of two main types, helical traveling waves, and planar traveling waves [84]. With the increase of fluid viscosity, the tail of the sperm cell can switch from a planar waveform to a helical waveform [35].

The shape and propulsive performance of the tail depend on viscous forces and bending forces. Sperm number $Sp = L(\xi_\perp \omega / A)^{1/4}$ can be used to describe the relative magnitudes of these forces. Here, $L$, $\xi_\perp$, $\omega$ and $A$ are the length, transverse viscous drag, angular frequency of the driving action, and bending stiffness of the flexible tail respectively. Transverse viscous drag can be calculated using $\xi_\perp = 4\pi\mu / [\log(2L/d) + C]$, where $\mu$ is dynamic viscosity, $d$ is tail diameter and $C$ is a constant (0.5 often used). The bending stiffness of the flexible tail can be calculated using $A = EI$, where $E$ is Young’s modulus and $I$ is the second moment of inertia of the tail [35]. When $Sp \ll 1$, bending forces dominate and the motion of the tail is almost reciprocal, which results in negligible swimming speeds. Conversely, when $Sp \gg 1$, viscous forces dominate and the amplitude of the motion of the tail is reduced, causing inefficient swimming [85]. In nature, sperms have a $Sp \sim 7$ [86]. However, the propulsion of a flexible filament in a fluid has been optimized at $Sp \sim 1$ [87].

Sperm-shaped microrobots are fabricated to study their swimming performances. Out-of-plane wobbling of the magnetic head of a robotic sperm has been used for helical wave propagation while in-plane wobbling has been used for planar wave propagation as shown in Figure 4 [88]. A flexible nanowire with a nickel head and a porous silver tail was propelled under a combination of rotating and gradient magnetic fields [89]. Similarly, a nanowire with a gold head and a nickel tail connected using a porous silver link was also controlled using a rotating magnetic field [90]. An oscillating magnetic field and a closed-loop control system with a feature tracking algorithm were also used to propel sperm-shaped microrobots [91]. In addition, a soft microrobotic sperm is used to study the effect of the concentration of the immersed particles in a viscous heterogeneous medium, on propulsion of the robot. It was experimentally proven that the speed of the microrobot increases in a small range of particle concentration [92]. The motion of sperm was mimicked by using a head created using the accumulation of iron oxide nanoparticles and a tail created by dissolving polystyrene in dimethyl formamide [84]. Apart from that, sperms were coated with magnetic nanoparticles and experimented with using an external magnetic field [93,94].
2.3. Cilia

The core structure of a cilium was identified as the axoneme [95]. The axoneme consists of dynein motors which are assembled onto a scaffold of nine cylindrically arranged doublet microtubules. Dynein motors can generate a linear motion, which makes the neighboring doublet microtubules slide over each other and create an oscillatory beating pattern [96]. However, the exact mechanism causing the beating pattern is still unclear [97]. The search for any chemical modification which regulates the dynein motors was unsuccessful over the past decade. Therefore, this beating pattern must be regulated by the intrinsic physical properties of the axoneme [98]. A single cilium can beat rhythmically and its motion can be divided into two stages; effective stroke and recovery stroke as shown in Figure 5a [99]. During the effective stroke, the cilium is straight and pushes a large amount of fluid and in the recovery stroke, it pulls a small amount of fluid as it is closer to the cell surface [100]. When cilia arrange in an array, the hydrodynamic interactions make the adjacent cilia beat out-of-phase [101]. This motion is similar to a wave-like motion and is known as a metachronal wave which is shown in Figure 5b [102].

![Figure 4. Helical and planar wave propagation initiating mechanisms](image_url)

**Figure 4.** Helical and planar wave propagation initiating mechanisms [88].

The slender shape of the cilium and time-varying bending moments ensure the generation of non-reciprocal motion required to propel in a low Reynolds number regime [103]. The dynamics of cilia can be analyzed using the rotor and rower models [104]. In addition, the effect of metachronal waves on the flow has been numerically analyzed using super-paramagnetic cilia actuated by a rotating magnetic field [105]. Similar to flagella, several microorganisms use cilia to generate drag-based propulsion within a fluid. Paramecium and stentor are such microorganisms that use cilia for propulsion [106]. ParaLikers (shown in Figure 6a) mimics the motion of Paramecium and has two arrays of cilia with an in-plane beating action [107]. The maximum velocity of a microrobot with two cilia arrays as shown in Figure 6b, was measured in both silicon oil and DI water and it was proved that the maximum velocity and the step-out frequency in silicon oil are smaller due to its high viscosity. This robot was demonstrated for particle transportation in microenvironments [108].

![Figure 5. Cilium motion: (a) Effective and recovery stroke of a cilium; (b) metachronal wave generated by an array of cilia](image_url)

**Figure 5.** Cilium motion: (a) Effective and recovery stroke of a cilium; (b) metachronal wave generated by an array of cilia.
Nickel Polypyrrole (flexible hinges used in b-Metachronal Wave Hinge)

The flexibility of the PPy allows the tail of the nanoswimmer to break the time reversibility of the motion and the performance of the nanoswimmer increases when the number of links is increased. In addition, the four-link hydrogel-based biodegradable microrobot

2.4. Fish

Most fish use body and caudal fin (BCF) locomotion to generate thrust force to move forward. Few fish families use median and paired fin (MPF) locomotion to move forward. BCF locomotion involves the bending of the body and MPF generates thrust by using only median and paired fins. Both BCF and MPF locomotion can be further categorized as undulatory and oscillatory motions. Magnetically actuated microrobots use BCF locomotion with undulatory motion as the moving mechanism. In BCF locomotion with undulatory motion, a moving wave is passed from the body to the caudal fin of the fish. The main parts involved in the locomotion of a fish and the waves generated during BCF locomotion of different fish are shown in Figure 7. This wave creates wakes in the neighboring fluid. The behavior of the neighboring fluid of the fish during its BCF locomotion is considered important to understand the propulsion mechanism of fish and can be numerically analyzed using computer-based simulation methods. BCF locomotion is performed using the muscles of the fish. Therefore, an electromyogram (EMG) was used to analyze the muscles’ response of the fish toward the undulatory motion.

The undulatory motion generated during the BCF motion is mimicked in microrobots which use nanowires for locomotion. Four link nanowire which is shown in Figure 8a was used to mimic the BCF locomotion. The undulatory motion was generated by activating the two nickel segments with a planer oscillating magnetic field. Similar nanowires were fabricated using one link, two links, and three links. In these nanoswimmers, a relatively long polypyrrole (PPy) link was used as the caudal fin as shown in Figure 8b. The flexibility of the PPy allows the tail of the nanoswimmer to break the time reversibility of the motion and the performance of the nanoswimmer increases when the number of links is increased. In addition, the four-link hydrogel-based biodegradable microrobot.

Figure 6. Ciliary microrobots: (a) Schematic of a microrobot inspired by cilia; (b) a SEM image of a ciliary microrobot.

Figure 7. Fish locomotion: (a) Main parts of a fish that involves locomotion; (b) BCF motion of 4 different types of fish families.
shown in Figure 8c used the undulatory motion to propel in a fluidic environment [114]. Flexible hinges are critical in nanowires because of their involvement in combining the links and maintaining the flexibility of the microrobot. The flexible hinges used in nanowires are porous silver hinges [84], concentric layers of polyallylamine chloride (PAH) and polystyrene sulfonate (PSS) [85], and microsprings [114].

**Figure 8.** Nanowires for locomotion: (a) Nanoswimmer which uses two gold segments to mimic the head and caudal fin of the fish; (b) nanoswimmer which uses one PPy segment as the tail [113]; (c) four link hydrogel-based biodegradable microrobot which uses microsprings [114].

3. Parameters Related to the Motion of Microrobots

The swimming speed of a microrobot is a significant parameter to investigate its performance [115]. The speed depends on the parameters such as the length of the microrobot, the strength, and the frequency of the applied magnetic field [116]. A summary of the swimming speed of the microrobots is presented in Table 2. The data presented in Table 2 was analyzed further to identify the effect of the related parameters on the speed of the microrobot and is represented in Figure 9.

**Figure 9.** Performance analysis of microrobots: (a) Variation of maximum speed against body length; (b) variation of relative speed against frequency; (c) variation of dimensionless maximum speed against magnetic flux density; (d) variation of the dimensionless maximum speed of helical microrobots against helical angle. (Blue color dots represents the data points and red color dotted line represents the regression line.)
Table 2. Important parameters of bio-inspired magnetically actuated microrobots.

| Inspired from | Body Length L (µm) | Maximum Speed U (µm/s) | Relative Speed U/L (1/s) | Frequency f (Hz) | Dimensionless Maximum Speed U/Lf | Helix Angle (Degrees) | Magnetic Flux Density | Ref. |
|---------------|--------------------|------------------------|-------------------------|----------------|---------------------------------|----------------------|----------------------|-----|
| B             | 8.8                | 127.0                  | 14.43                   | 40             | 0.3608                          | 65.0                 | (R) 1.5 mT           | [51]|
| B             | 35.0               | 320.0                  | 9.14                    | 40             | 0.2286                          | 65.0                 | (R) 1.5 mT           | [51]|
| B             | 1.5                | 40.0                   | 26.67                   | 150            | 0.1780                          | -                    | (R) 6.0 mT           | [117]|
| B             | 30.0               | 140.0                  | 4.67                    | 30             | 0.1560                          | 32.7                 | (R) -                | [118]|
| B             | 2.0                | 2.0                    | 1.00                    | 10             | 0.1000                          | 51.5                 | (R) 2.0 mT           | [44]|
| B             | 16.0               | 45.0                   | 2.81                    | 34             | 0.0827                          | 71.3                 | (R) 5.0 mT           | [55]|
| B             | 50.0               | 250.0                  | 5.00                    | 70             | 0.0710                          | 41.0                 | (R) 1.0 mT           | [61]|
| B             | 121.0              | 821.2                  | 6.79                    | 95             | 0.0710                          | 49.0                 | (R) 5.0 mT           | [60]|
| B             | 16.0               | 8.4                    | 0.53                    | 9              | 0.0580                          | 71.3                 | (R) 3.0 mT           | [57]|
| B             | 224.0              | 2613.8                 | 11.67                   | 205            | 0.0570                          | 53.4                 | (R) 5.0 mT           | [60]|
| B             | 8.0                | 4.0                    | 0.50                    | 10             | 0.0500                          | 47.7                 | (R) 2.0 mT           | [44]|
| B             | 30.0               | 3.9                    | 0.13                    | 2.6            | 0.0500                          | 62.0                 | (R) 2.0 mT           | [48]|
| B             | 16.0               | 70.4                   | 4.40                    | 90             | 0.0490                          | -                    | (R) 9.0 mT           | [63]|
| B             | 16.0               | 48.9                   | 3.06                    | 72             | 0.0420                          | -                    | (R) 9.0 mT           | [119]|
| B             | 30.0               | 15.0                   | 0.50                    | 16             | 0.0313                          | -                    | (R) 8.0 mT           | [71]|
| B             | 47.0               | 1.2                    | 0.03                    | 1              | 0.0255                          | 36.8                 | (R) 2.0 mT           | [47]|
| B             | 30.0               | 6.0                    | 0.20                    | 10             | 0.0200                          | 45.7                 | (R) 2.0 mT           | [44]|
| B             | 50.0               | 10.0                   | 0.20                    | 10             | 0.0200                          | -                    | (R) 1.0 mT           | [65]|
| B             | 38.0               | 18.0                   | 0.47                    | 30             | 0.0158                          | 46.2                 | (R) 2.0 mT           | [52]|
| B             | 10.0               | 3.7                    | 0.25                    | -              | -                               | (R) 80.0 T, (G) 40.0 T/m | [28]|
| S             | 260.0              | 103.0                  | 0.40                    | 1              | 0.3960                          | -                    | (R) 70 mT           | [92]|
| S             | 358.0              | 39.0                   | 0.11                    | 1              | 0.1080                          | -                    | (R), (O) 70.0 mT     | [88]|
| S             | 5.5                | 20.8                   | 3.78                    | 35             | 0.1080                          | -                    | (R) 0.95 mT, (G) 1.0 mT | [89]|
| S             | 316.0              | 158.0                  | 0.50                    | 45             | 0.0110                          | -                    | (O) 5.0 mT           | [91]|
| C             | 400.0              | 4500.0                 | 11.25                   | 167            | 0.0675                          | -                    | -                    | [107]|
| C             | 220.0              | 340.0                  | 1.55                    | 60             | 0.0258                          | -                    | (G) 12.0 mT          | [108]|
| F             | 4.8                | 30.9                   | 6.90                    | 11             | 0.6300                          | -                    | (O) 10.0 mH          | [37]|
| F             | 15.5               | 14.4                   | 0.93                    | 20             | 0.0465                          | -                    | (O) 8.4 mT           | [113]|

R—Rotating magnetic field, O—Oscillating magnetic field, G—Magnetic field gradient, B—Bacteria flagella, S—Sperm flagella, C—Cilia, F—Fish.

The speed of the microrobot is important for microscale applications. Both maximum speed and average speed can be examined to evaluate the performance of the microrobot [37]. In this review, the maximum speeds of the microrobots were collected to analyze the performance of the microrobots. According to Figure 9a, it can be observed that the maximum speed of the microrobots increases with the body length. The effect of the body length can be eliminated by calculating the relative speed (speed per unit body length). The frequency of the rotation or oscillation of the microrobot is another factor that affects the speed of the microrobot. This rotation or oscillation is generated due to the frequency of the applied magnetic field. The variation of the relative speed with the frequency is clearly illustrated in Figure 9b. According to the graph, the relative speed increases with frequency. Using a similar method, the effect of the frequency can be removed by dividing the relative speed by the frequency to obtain the dimensionless maximum speed [37]. In Figure 9c, the variation of the dimensionless maximum speed with the magnetic flux density is analyzed. According to the variation, it can be observed that the dimensionless maximum speed increases when the applied magnetic flux density is increased. Apart from the body length, frequency, and magnetic flux density, the helix angle is an important parameter for helical microrobots. Figure 9d shows the variation of the dimensionless maximum speed of helical microrobots against helical angle. This graph also has an upward trend.
4. Materials and Fabrication Methods

When microrobots are actuated using a magnetic field, it is essential to fabricate at least one part of the microrobot using a magnetically active material [120]. Apart from that, other non-magnetic materials are also required to maintain other features of the microrobot such as the structural rigidity, flexibility of fins, transparency, etc. Therefore, several materials used to fabricate the microrobots are summarized with their key features in Table 3.

| Material/s | Key Features |
|------------|--------------|
| Pure iron, ferric oxide, ferro-ferric oxide, nickel, cobalt | Used as the magnetic particles or magnetic material to generate a magnetic moment [38]. |
| Polydimethylsiloxane (PDMS) | Used as the matrix material [121]. Flexible and transparent material used for biomedical applications [122]. |
| Polyurethane (PU), polystyrene (PS), polymethyl methacrylate (PMMA), epoxy | Used as the matrix material [122]. |
| Titanium | Improves biocompatibility [63]. Prevents oxidation of nickel [119]. Facilitates the surface functionalization of the structures with other medical and biological substances such as liposomes [57]. |
| Silver | Used to fabricate hinges by partially dissolving in hydrogen peroxide [37]. |
| Polypyrrole (PPy) | Flexible material and used to fabricate tails of nanowires [113]. Biocompatible [123]. |
| Gold | Used to fabricate solid linkages in nanowires [84]. |
| Hydrogels | These are used to fabricate biodegradable microrobots [114]. |

Photolithography and rapid prototyping are the most common fabrication techniques used in fabricating microrobots [124]. Expensive equipment, complex facilities, and tedious tasks are required to perform photolithography processes whereas rapid prototyping techniques have a less complicated approach [125, 126]. In terms of mimicking the bacteria flagella, helical microrobots are used. Due to the 3D nature of the helical structure, conventional 2D photolithographic methods are not suitable [127]. However, the self-scrolling technique enables the creation of 3D helical structures using 2D fabrication techniques [20]. That apart, glancing angle deposition [28] and direct laser writing [15] can be used to fabricate helical structures at the microscale. Glancing angle deposition is a physical vapor deposition method and can be performed in one step [69] whereas direct laser writing is performed on a negative photoresist where it is required to remove the unpolymerized materials using a developer [51]. In glancing angle deposition, magnetic materials can be deposited but in direct laser writing, magnetic materials should be coated [55]. In addition, helical microrobots are created by modifying the naturally available helical structures by coating magnetic nanoparticles, and this method is known as the bio-template method [60, 61]. Electrochemical co-deposition using molds is also used to fabricate helical microrobots in the nanoscale. These microrobots need to be coated with magnetic nanoparticles at a later stage of the process [128]. Nanowires are another type of frequently used microrobots that mimic the propulsion mechanism of living organisms. Molding is widely used to fabricate these microrobots at large scale due to their 2.5D shape [37]. For magnetically actuated microrobots, magnetically active materials are required to generate a propulsive force or torque. Therefore, there are two ways to embed magnetic materials in microrobots. The first method is to fabricate the structure of the microrobot using magnetic materials. The second method is to coat the microrobot using magnetic nanoparticles. E-beam deposition [89] and electroless deposition [60] methods are two methods used to deposit soft magnetic materials on non-magnetic materials. In addition to coating, fabrication of hinges to combine the linkages of nanowires is also important.
when developing such microrobots. Porous silver hinges prepared by dissolving silver in hydrogen peroxide solution [37], concentric layers of polyallylamine chloride (PAH) and polystyrene sulfonate (PSS) [113], and microsprings [114] are three approaches used to fabricate hinges of nanowires.

The repeatability of the fabrication process and control over the design parameters are the main challenges when fabricating microrobots [26]. In addition, the requirement of materials to perform in vivo experiments and the availability of magnetic response materials are the challenges with the materials used in medical applications. Biocompatibility and biodegradability are important when considering the above challenges. Microrobots are coated with titanium to improve their biocompatibility [63]. This can also prevent the oxidation of nickel if nickel is used in fabricating the microrobot [119]. Apart from that, titanium is a good candidate to support the surface functionalization of structures with other medical and biological substances such as liposomes and cells [57]. Furthermore, biodegradability is important to avoid material accumulation inside organs [71]. Materials such as hydrogels are suitable candidates to fabricate biodegradable microrobots [114]. Response to a magnetic field was created by coating magnetic nanoparticles on biodegradable microrobots [72].

5. Magnetic Field Generation Techniques

A controllable external magnetic field is required to control magnetically actuated microrobots. Usage of a magnetic field to control microrobots has key advantages such as long-range, fast response, precise actuation, high dexterity, high actuating force or torque, minimal interactions with tissues, high penetration depth, and 2D and 3D actuation capability [129]. The requirement of a complex setup to generate a magnetic field is a disadvantage of magnetically actuated microrobots [130]. Since microrobots are most commonly used in biomedical applications, the static magnetic field strength for clinical procedures should be less than 2 T, according to the United States Food and Drug Administration (FDA) Agency [16].

Magnetic torque-based and magnetic gradient-based are the two actuation methods that are used to actuate magnetic microrobots [131]. Among them, torque-based actuation is the most efficient actuation method [132]. Torque-based actuation requires a uniform magnetic field that can be generated using a Helmholtz coil system [133]. Due to the nature of the coil arrangement, this system has limited space. However, a weak rotating magnetic field can be generated over a relatively long distance, such as inside the living organisms [44]. This generates a lateral screwing motion, which deviates the original moving direction of the microrobot due to the applied torque on the microrobot [28]. Gradient-based actuation can be performed using a convergent magnetic field. Two independent coils [91], four independent coils [48], eight independent coils [88], a permanent magnet attached to a robotic manipulator [134], and a magnet array [135] can be used to generate a convergent magnetic field. These types of actuation methods cannot generate a large magnetic gradient over a long distance [28].

6. Discussion and Future Directions

Even though the microorganisms such as bacteria and cilia do not have a central nervous system, they demonstrate a form of intelligence during locomotion. Therefore, the locomotion techniques used by such living organisms are mimicked to propel microscale robots. Since bacteria can move their flagellum on a helical path, helical microstructures are used to mimic the motion inside a rotating magnetic field. Sperm can also move its flagellum on a helical path in addition to its oscillation on a 2D plane, but the mechanism used to move the flagellum is different from that of the bacteria. Cilia has a similar working principle to sperm, but its locomotion is performed by generating a metachronal wave. Even though the fish is a macro-scale living organism, its propulsion pattern can be mimicked in the microscale. Therefore, nanowires have adopted the BCF locomotion pattern inside an oscillating magnetic field. The length of the microrobot, frequency of the rotation or
oscillation of the microrobot, and the magnitude of the magnetic field are analyzed with the swimming speed of the microrobot. In addition to these parameters, the helix angle is analyzed with the swimming speed of the helical microrobots. Swimming speed has shown an upward trend with all the parameters and both frequency and magnetic flux density have higher steepness. Apart from the analyzed parameters, the viscosity of the fluid and the wettability of the microrobot can also affect the swimming speed of the microrobot. In terms of fabrication, nickel, cobalt, and pure iron have been widely used to fabricate the structure of the microrobot and these materials also have magnetic properties. PDMS and PMMA are used as the matrix material and PDMS is popular in microfluidic applications due to its flexibility, transparency, and biocompatibility. For nanowires, flexible hinges are very important to generate undulatory motion. Porous silver is a good candidate for fabricating these hinges.

Due to the challenges in fabrication techniques on the micro- and nanoscale, the exact mechanism used by the living organisms cannot be mimicked, but their propulsion method or pattern can be mimicked using an alternative actuating principle. For example, actuation using a magnetic field has ensured the untethered actuation inside the human body while reaching targeted locations. Helmholtz coil systems are widely used to generate the magnetic field due to their capability to generate a uniform magnetic field. In terms of magnetically actuated microrobots, multiple challenges have been identified. Namely lack of materials to fulfill biocompatibility and biodegradability, difficulty in selective control of multiple microrobots, and challenges in implementing a closed-loop control system are a few. At present, the microrobot is fabricated or coated with titanium to maintain biocompatibility, and hydrogels are used to fabricate biodegradable microrobots. In addition, implementing fully autonomous microrobots along with a closed-loop control system is currently being investigated and that challenge has not yet been addressed successfully. Therefore, novel research directions are still being introduced to address these challenges in the field of microrobotics amongst which most of these directions tend towards biomedicine.

Advancements in the microrobotic field have directly influenced the medical sector. As a result, microrobots are most commonly designed to perform in vivo treatments and their locomotion is inside a fluidic environment. The movement of microrobots inside a fluidic environment involves a low Reynold’s number fluidic regime. Therefore, non-reciprocal motion is essential to propel these fluidic environments. In conclusion, nature is a good resource to search for new reciprocal motions, and mimicry of such motions in microrobots has provided successful solutions for microrobotic propulsion inside microscale fluidic environments.

7. Conclusions

In this review, naturally available propulsion mechanisms and movement patterns that can be used to propel microrobots inside a microfluidic environment were presented. Accordingly, bacteria flagella, sperm flagella, cilia, and fish have been inspirational in fabricating and controlling microrobots. Parameters extracted from the literature have shown that the velocity of the microrobots depends on the body length, rotating or oscillating frequency, and magnetic flux density. In terms of helical microrobots, velocity depends on the helix angle. By observing the requisite graphs, it can be concluded that the velocity of the microrobot has an upward trend with the considered parameters. In general, microrobots are developed for implementation in the medical field due to their significant advantages. Biocompatibility and biodegradability are the major challenges in selecting materials and suitable fabrication processes. That apart, magnetic actuation has enabled the possibility of untethered actuation. In terms of magnetic field generation, the Helmholtz coil system and a set of electromagnetic coils are used. Finally, it can be concluded that the identification of propulsion mechanisms and motion patterns available in nature have enhanced the possibility to fabricate novel microrobots.
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