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Flow Tweezing of Anisotropic Magnetic Particles in a Dynamic Magnetic Trap

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Abstract: Unravelling the dynamics of anisotropic particles in fluids is critical for a range of applications in micro-robotics, lab-on-chip biochemical assays, environmental remediation, and purification. However, controlled transport of an anisotropic particle in a fluidic flow has proven nontrivial owing to the coupling of the particle’s rotation movement with the hydrodynamic flow, leading to complex flow trajectories and motion dynamics. Here, we report the dynamic tweezing of an anisotropic magnetic particle structure in a rotating magnetic trap. We reveal a series of unconventional motion modes and dynamics of the particle transporting in a confined fluidic flow, which manifest themselves as transitions from on-trap centre rolling to large-area revolution and off-trap centre rolling with varying rotating frequencies. The revolution of a particle is observed to shift to off-centre rolling at varied flow velocities, which is absent for the common scenario when the particle is purely trapped in a medium flow. Our findings unlock a new strategy to determine local magnetic tweezing force profile and flow conditions in arbitrary flow channels, revealing strong potential for microfluidics, chemical reactors and in-vivo endovascular flow measurement.

Controlled transport of microscale objects in fluidic flows has key applications in lab-on-chip microfluidic devices,\(^12\) chemical reactors,\(^34\) and in-vivo physiological systems featuring hierarchical networks of capillaries, arteries and veins.\(^5\)–\(^7\) Traditional wired devices (e.g., differential pressure flowmeter and cantilever-based flowmeter) face difficulties in their manipulation in small and confined spaces.\(^8\)\(^9\)\(^10\) Magnetically responsive microstructures with programmed shape and anisotropy have shown significant potential due to their miniaturised fingerprints and untethered manipulation capability.\(^11\)\(^12\) Equipped with motion capabilities, such systems function as mobile robotic platforms for applications, including localized sensing,\(^13\)\(^14\) drug delivery,\(^15\)\(^16\) and cargo transport.\(^17\)\(^18\) However, most of the existing systems focus on locomotion in static fluids.\(^19\)\(^20\) The efficient control and transport of the systems in dynamic fluidic flows remain elusive.\(^21\)\(^22\)

Magnetic tweezers possess the trapping capability to physically confine a magnetically responsive object in fluids.\(^22\) They are widely established by using a pair of permanent magnets,\(^23\) a single magnet,\(^24\) or a cylindrical magnet.\(^22\) The trapping magnetic fields of tweezers feature a local maximum of field strength to trap magnetic particles.\(^25\) It has been reported that a rotating magnetic field can drive magnetic particles of various morphologies (e.g., magnetic microsphere\(^26\),\(^27\) and dimer-shaped microstructures\(^28\),\(^29\)) into synchronous rotation at low frequencies and further to large-area revolution at high frequencies in unconfined fluids.

Here, we report the dynamic magnetic field tweezing of anisotropic magnetic particle structures in a confined fluidic flow (Fig. 1). The coupling between the magnetic trapping field, confined fluidic flow field and the particle, results in intriguing in-flow locomotion characteristics. The magnetic particle can switch its locomotion mode from “on-trap centre rolling” to “large-area revolution” with varying rotating magnetic field frequency. The revolution of the particle
can be further modulated from “on-trap centre rolling” to “off-trap centre rolling” at varied flow speeds. The manipulation strategy for anisotropic particles leveraging a dynamic rotating magnetic trap holds potential in lab-on-chip microfluidic systems, micro-robotic control and endovascular flow measurements.

FIG. 1 Tweezing a magnetic microparticle in a fluid-filled capillary using a pair of rotating permanent magnets. (a) Schematic illustration of the experimental scenario. (i) Photo of a glass capillary laden with a magnetic microparticle. (ii) Image of an anisotropic magnetic particle fabricated by photolithography. (b) Distributions of magnetic field and magnetic force. Inserted curves (coloured red) are the profile of the Y-axis components of the magnetic field gradient and magnetic force, respectively.

We chose an exemplar magnetic anisotropic particle structure for our study, which is consisting of lined-up magnetic nanoparticles embedded in a polymer matrix. The microparticle structure was fabricated utilizing a magnetic field-assisted photolithography approach, as illustrated in Fig. 1a. In brief, this methodology involved the application of a magnetic field to guide the assembly of superparamagnetic nanoparticles (7 wt%) through short-range dipolar interactions in the PEG-DA hydrogel, thereby establishing magnetic anisotropy axis, commonly referred to the chaining direction of nanoparticles, in alignment with the direction determined by the applied magnetic field. The shape of the microparticle structures was defined through computer-aided design, specifying geometry features on a photomask. The dimensions of the resulting particles ranged from dozens of microns to millimetres. For the tweezing study, we used a pair of permanent magnets, each with a diameter of 3 cm and positioned 5 mm apart to produce the desired magnetic field patterns. COMSOL simulations were conducted to ascertain the magnetic field distribution, revealing that the in-plane component, \( B_y \), exhibited a local maximum field strength at the field centre, measured at 50 mT (Fig. 1b), which enables trapping the structure toward the field centre.

To study the locomotion in confined fluidic flow, we injected a particle in a capillary tube with a 2 mm inner diameter at the magnetic field (B) centre of the magnets. One side of the tube was connected with a fluidic pump for liquid injection (0~100 µL/s). It was shown that the particle exhibited two primary motion modes as illustrated in Figure 2a. The particle was trapped at the centre of the rotating magnetic field and rotating under a low-frequency magnetic field. At zero flow rates, the particle experiences a magnetic centripetal force, a rolling friction force, and a centrifugal force (Fig. 2b). The magnetic (centripetal) force scales within 1 cm-distance away from the magnetic field centre and its value at the field centre is zero. With the increasing rotation rate of the field, the increasing centrifugal force pushes the particle off the centre position, leading to the swing of the structure around the symmetry centre of the field. For instance, the microstructure measured with a dimension of 400 µm *600 µm *150 µm can rotate around its centre at low frequencies of 0~1000 rpm. When the frequency increases to 1000 rpm, the microstructure experiences a centrifugal force of over 4.52 nN (\( F_c=mrw^2 \), in which \( m \) is weight, \( r \) is the off-axis radius, and \( w \) is angular speed). This force can overcome the magnetic force and rolling friction force, leading to the particle to swing off the centre with modulated trajectory ranges (~2.5 mm for 1100 rpm and ~4 mm for 1500 rpm) (Fig. 2c). When the particle does the revolution locomotion, the trajectory is elliptical rather than circular due to space limitations.
FIG. 2 Locomotion transition between on-centre rolling and revolution based on cycling field. (a) Schematic of transition between on-centre rolling and large-area revolution under the modulation of centrifugal force. (b) Forces exerted on the magnetic particle, including magnetic centripetal force, rolling force and centrifugal force. (c) Motion dynamics of the magnetic particle at varying magnetic field frequencies. $d_1 \approx 2.5$ mm, and $d_2 \approx 4$ mm. Colored dots indicate the motion trajectories of the particle.

To investigate the influence of fluidic flow, we monitor the motion dynamics of particles at varying flow rates with and without magnetic fields. Figure 3a shows that without applying a rotating magnetic field, a statically trapped particle was suddenly washed off from the centre at a higher flow rate of 80 µL/s when the flow rate is gradually increased from 0. The fluidic drag force is expressed as:

$$F_d = \frac{1}{2} \rho v^2 C_D A$$

where $\rho$ is the density of the fluid, and $v$ is the speed. $A$ is the cross-section area, and $C_D$ is the drag coefficient. At the low $Re$ (i.e. close to 1 for flow rate varying from 0 to 50 µL/s (0–16 mm/s)), the drag coefficient is asymptotically proportional to $Re^{-1}$:

$$C_D \sim Re^{-1} = \frac{\mu}{\rho v D}$$

Thus, the fluidic drag force is directly modulated by the flow speed as $F_d \propto v$. Based on the fluidic drag force, the static frictional force is estimated as high as 70 nN.

When the particle was set to roll, the fluidic drag force pushes the particle away from the centre until an equilibrium position is achieved, as shown in Figure 3a. The particle structure with a 200-rpm rolling speed at the field centre experiences a centrifugal force of up to 0.2 nN. To propel the particle away from the centre, 4.52 nN force is needed. A flow rate of 5 µL/s generates a drag force of about 4.32 nN to push the particle to a new position that is 0.55 mm distance away from the centre. In this respect, the off-centre distance was observed to scale with the flow speed ($d \sim v$) (Fig. S1). Interestingly, such a scaling relationship between the fluidic drag and off-centre distance of a particle only holds when the particle is set to roll, which is absent for a static unrolling particle.
We identified four major modes of motion with respect to varying flow rates and rotating field frequencies, which include “on-centre rolling”, “off-centre rolling”, “large-area revolution” and “flown off” (Fig. 3b and 3c). At zero rotating field, the particle is either trapped at the centre or being flown off. With a rotating magnetic field, the particle rolls in the centre of the magnetic potential well and may undergo a “large-area revolution”. The particle with 1500-rpm speed switches from “large-area revolution” to “off-centre rolling” at the flow of 30 μL/s. In a confined fluidic flow field, the particle exhibits a dynamic form of “off-centre rolling” at the flow rate range of 5~55 μL/s at the 400-rpm rolling speed. When the drag force overcomes the magnetic force and the frictional force, the particle is washed off at the flow rate of 55 μL/s. We further found that a higher rotating speed leads to smaller off-centre distance and renders a smaller magnetic force exerted on the particle, as the magnetic force scales with the off-centre distance ($F_m \sim d^2 \nu$). For example, the particle with a 200-rpm rotation speed travelled 6.5 mm at a flow rate of 40 μL/s, while it only travelled 3.5 mm in distance at a rotation speed of 800 rpm. As the magnetic force is reduced, a small flow speed is sufficient to transit the particle from an “off-centre rolling” state to a “flown off” state. The transition speed for 200 rpm is about 62 μL/s, while the transition speed for 800 rpm reduces to 48 μL/s. The scaling relationship between the particle’s off-centre distance and the flow speed equips the particle a flow-sensing capability, the range of which can be modulated by the rotation frequency of the magnetic field.

Figure 4 shows that the dynamic magnetic trap may serve as a driving source for the in-flow directional movement of anisotropic particles. The particle was observed to propel upstream, and the motion distance scales with the rotation speed from 200 rpm to 800 rpm (Figure 4a). The particle walked 2.24 mm at 1000-rpm rolling speed and the propelling force can reach 25.51 nN at 1000-rpm rotation frequency (0 μL/s flow speed, Figure 4b). To further confirm the origin of the propelling force, we exchanged the flow direction and found that the propelling force exhibits a directional bias towards the right and is independent on the flow direction (defined in Fig. 4b, c). This suggests that the origin of the propelling force could be stemming from a non-reciprocal “rolling-walking”-like movement of the particle. Indeed, when the directions of the fluidic flow and propelling force align or opposes, the propelling force may augment or attenuates the flow effect, resulting in longer/shorter displacement distances towards the field centre, respectively (Fig. 4e). Our results (Figure 4f and 4g) further show that the relative directions between the flow drag force and propelling
force could be leveraged to acquire a large flow responsive range. The maximum flow rate is 61.9 μL/s with a 7.8-mm distance (200 rpm distance) for flow from the right to left.

FIG.4 Directional movement of a particle in the dynamic magnetic trap. (a) Micrograph showing the directional motion of a particle at varying rotating field frequencies in static fluid. (b) Off-centre distance of the particle as a function of the rotation frequency of the magnetic fields at zero flow rates. (c)-(d) Micrograph showing a particle at varying rotating field frequencies in flows of different directions. (e) Off-centre distance of the particle as a function of the rotation field frequency for different flow directions. R to L: right to left; L to R: left to right. (f) Maximum flow rate to flush away the particle and (g) the maximum off-centre distance of the particle for different flow directions.

In all, we have reported the unconventional motion modes of magnetic particle structures under the effect of dynamic magnetic tweezing fields in confined fluidic flows. The interplay between the rotating magnetic trap and the flow fluid results in the elastic displacement of the particle from the field centre, the distance of which can be modulated by the magnetic field frequency and flow speeds. The manipulation scheme leads to an intriguing flow field responsive characteristic that is promising for localised sensing in micro-scale and confined spaces and in-vivo localized endovascular blood velocity measurement.

References
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DATA AVAILABILITY

Data available on request from the authors.