Supplementary information

Design of a magnetically responsive artificial cilia array platform for microsphere transport

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Other additional documents:

Video-S1: The dynamic reciprocating beating effect of the captured cilia array in the presence of a circulating magnetic field.
Video-S2: Results of the SPH numerical simulation for the transport of the spheres by synchronous beating mode.
Video-S3: Results of the SPH numerical simulation for the transport of the spheres by metachronous beating mode.
Video-S4: Results of the SPH numerical simulation for the position change of the sphere, its own rotation, and the flow field.
Video-S5: The sphere transport process captured by the high-speed camera.
Video-S6: the efficacy of artificial cilia to remove 100 μm diameter spheres in different fluid environments at a beating frequency of 15 Hz.
Supporting Data: Original data from simulations and experiments in the paper.
Supporting Code: Code for numerical simulation methods.

Beating equations of the cilia

The beating cycle of the cilia is T, which is divided into two oscillation phases, the first phase is the effective stroke, and the time is $t_1 = \frac{2}{3}T$; the second phase is the recovery stroke, and the time is $t_2 = \frac{1}{3}T$. Therefore, the equation for the oscillation of each cilium is

$$\Theta_1(t) = \frac{\pi}{9}(1 - \cos(\frac{\pi t}{t_1}))$$

$$\Theta_2(t) = \frac{\pi}{9}(1 + \cos(\frac{\pi t}{t_2}))$$

The mathematical expression for the corresponding angular velocity is

$$\Omega_1(t) = \frac{\pi^2}{9t_1}\sin(\frac{\pi t}{t_1})$$

$$\Omega_2(t) = -\frac{\pi^2}{9t_2}\sin(\frac{\pi t}{t_2})$$

Calculations of the Reynolds number around the cilia

The cilia are 60 μm long, with an average beat amplitude of 40°. At a beating frequency of 15 Hz, the average angular velocity is 2π/9 and the velocity at the ciliary tip is approximately 42 μm/s. Using the ciliary length as the characteristic length, the Reynolds number of ciliary motion in water is calculated to be approximately 0.00252.

Calculations for the Sperm Number

The Sperm Number, is the ratio of the viscous to the bending forces on a cilium

$$\mathrm{Sp} = L\left[\frac{8\pi^2\mu_g\omega}{EI}\right]^{\frac{1}{4}}$$

Where L is the length of the cilia (60 μm), μ_g is the viscosity of the fluid (1 mPa·s for water, 0.26 Pa·s for 68% w/w glycerol-water solution and 1.5 Pa·s for pure glycerol), ω is the beating frequency of the cilia (from 1 to 15 Hz in the experiments), E is the Young's modulus of the cilia (50 MPa) and $I = \pi D^4/4$ is the area moment of inertia of the cilia with D =15 μm the diameter of the cilia.

Table S1 The calculated Sperm Number for different fluid

ω (Hz)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
water	0.10	0.12	0.13	0.14	0.15	0.16	0.17	0.17	0.18	0.18	0.19	0.19	0.19	0.20	0.20
glycerol-water solution	0.41	0.49	0.54	0.58	0.61	0.64	0.66	0.69	0.71	0.73	0.74	0.76	0.78	0.79	0.80
pure glycerol	0.63	0.75	0.83	0.89	0.95	0.99	1.03	1.06	1.10	1.12	1.15	1.18	1.20	1.22	1.24

Distribution of magnetic field calculated by ANSYS method

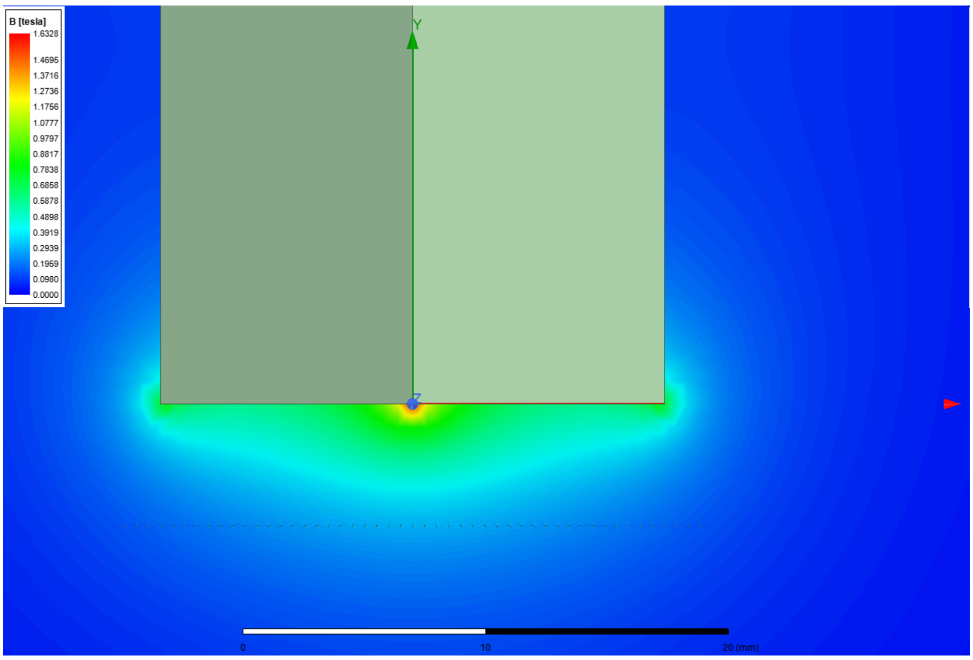

Fig. S1 Magnetic field strength distribution. The permanent magnet has a rectangular structure with dimensions of 30mm × 20mm × 10mm and model 52 N with a residual flux density of 1.4 T.

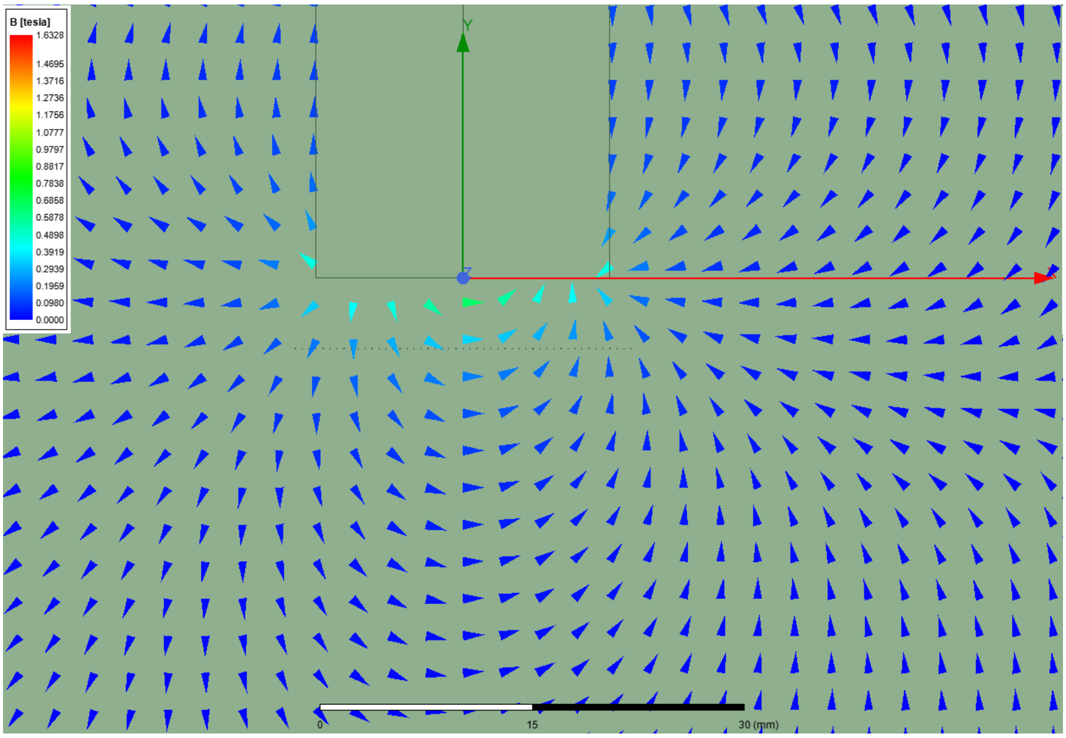

Fig. S2 Distribution of magnetic field directions.

Small-scale cilia modelling simulations

To demonstrate that the motion and transport mechanisms of real cilia can be reasonably referenced using our existing setup, we complemented our study with a small-scale cilia model that closely matches the dimensions of real cilia (10 µm in length, 1 µm in diameter), with a smaller distance between cilia and a higher packing density. The results show that the microsphere motion (rolling forward) and vortex generation induced by the metachronal wave in the small-scale model are highly consistent with those observed in our current larger-scale model. Therefore, despite the larger size of our artificial cilia, the entire ciliary layer at the bottom of the microchannel replicates similar microsphere transport functions. This provides valuable insights into the transport mechanisms of natural cilia and helps us to better understand these processes through in vitro experiments.

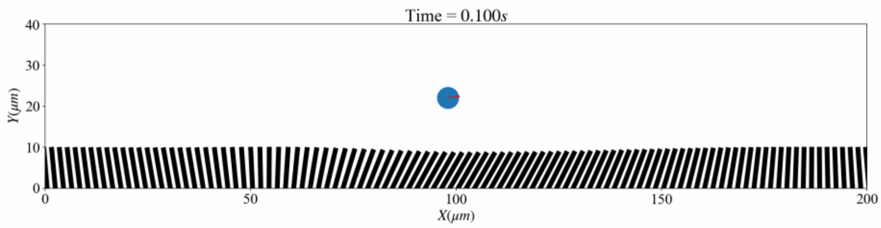

Fig. S3 A more realistic SPH model of cilia with a length of 10 µm, a diameter of 1 µm and a distance of 2 µm between adjacent cilia. The thickness of the fluid layer over the cilia is 40 µm. A microsphere with a diameter of 5 µm is suspended in the fluid.

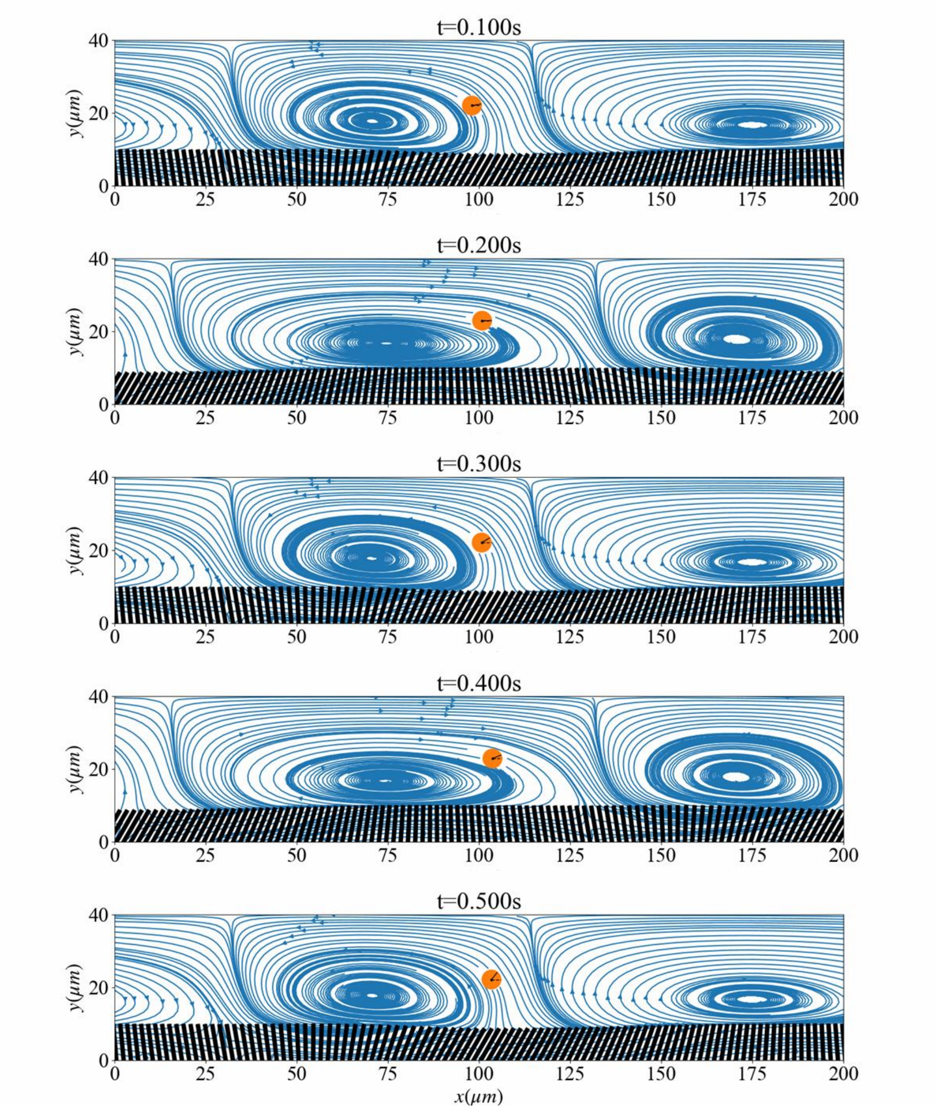

Fig. S4 Position changes, rotation, and surrounding streamlines of the microsphere.

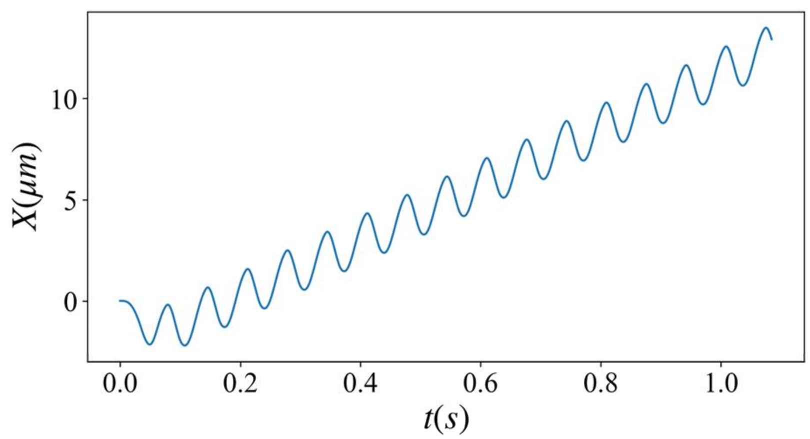

Fig. S5 Displacement of the microsphere in the x-direction.

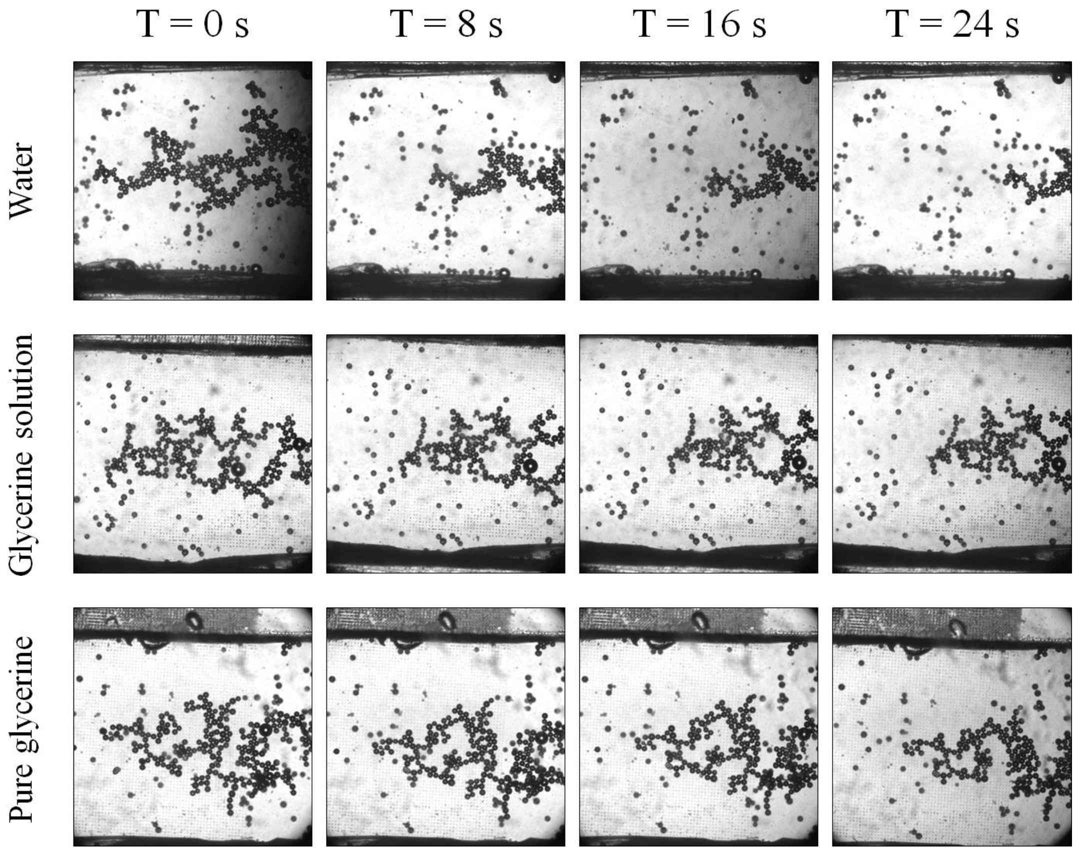

Fig. S6 Unprocessed original photographs of artificial cilia to remove 100 μm diameter spheres in different fluid environments at a beating frequency of 15 Hz.

High-frame-rate data on the microsphere motion

To provide a more detailed view of microsphere motion, we incorporated high-frame-rate photographic data into our analysis. This data helps to characterize microsphere displacement patterns, revealing a reciprocal forward motion. Despite the back-and-forth motion driven by ciliary beating, the microspheres ultimately move in the direction of the metachronal wave, which is in close agreement with our simulation results and provides robust empirical support for the predictive accuracy of our model.

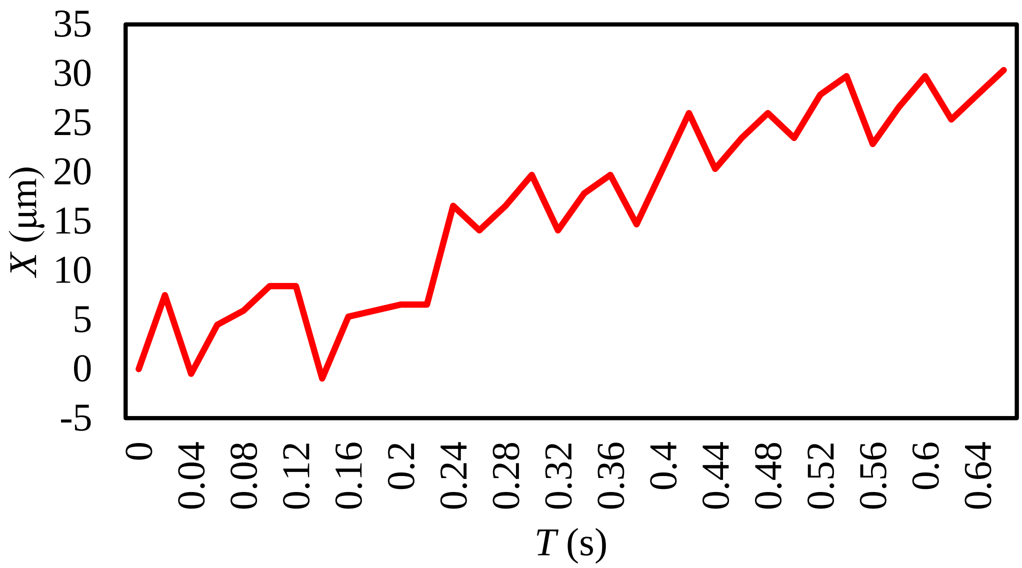

Fig. S7 High-frame-rate data on the microsphere motion

Determination of length and phase difference of simulated cilia arrays

In our experimental model, the total width of the cilia array is L0 = 5000 μm. However, due to the influence of the rotating magnetic field, which decreases with height, we assume that the magnetic field acts uniformly along a horizontal region of 1000 μm width. In our simulations, we idealize the ciliary wave as periodic and focus on a 1000 μm segment of the ciliary array, implementing periodic boundary conditions. This setup is shown in Figure S8.

We assumed that the phase difference between the cilia at either end of this 1000 μm segment is equal to one full cycle (2π), leading to a wavelength of λ = 1000 μm. Since the distance between adjacent cilia is 40 μm, this results in a total of 25 cilia within this segment, resulting in a phase difference of 2π/25 between adjacent cilia.

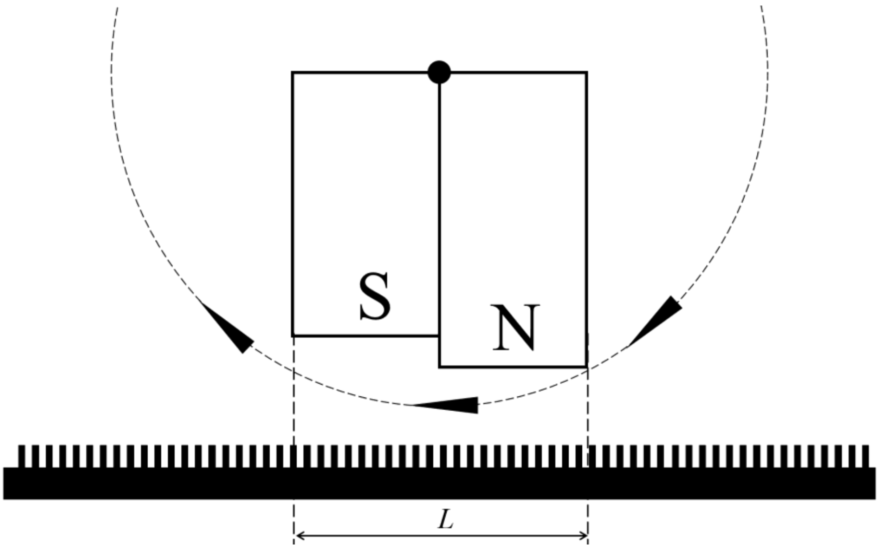

Fig. S8 The magnetic actuation system and the cilia. Note that the height difference between the S and N poles in the figure does not represent the difference in the actual experiment.

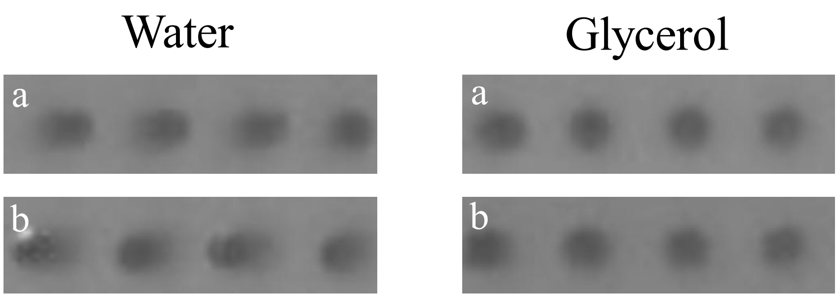

Fig. S9 Cilia beating amplitude in different fluids. The cilia show a reduced beating amplitude in glycerol compared to water. Panels (a) and (b) show the maximum deflection positions of the cilia in each direction.