Supplementary Information

A Numerical Simulation and an Experimental Study on the Steady-State Levitation Characteristics of a Magnetic Ball Driven by External Electromagnets in a Fluid Tube: Applications to Micromachines in Human Blood Vessels

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In the electromagnetic field simulation results, Fig. S1 presents the vector diagram of the magnetic field distribution under different conditions. The magnetic field lines form closed loops that pass through the ball and the electromagnet.

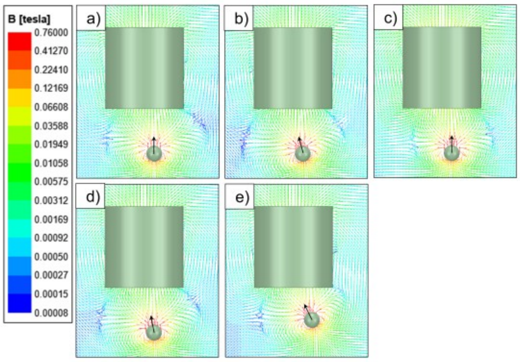

Fig. S1. Magnetic vector distribution diagram of magnetic ball and electromagnet in y-O-z plane where ball positions, magnetic pole orientation, and current are: a) [0, 8, -36], θ = 0, I = 1 A; b) [0, 8, -36[, θ = -20, I = 1 A; c) [0, 8, -36], θ = 0, I = 2 A; d) [0, 8, -36], θ = -11, I = 1 A; and e) [0, 15, -26], θ = 0, I = 1 A

In the fluid simulation, the turbulence intensity of the fluid is calculated by the Eq. (S1) [1]:

$$I = 0.16Re^{-1/8} = 0.16\frac{(vd\rho)^{-1/8}}{\eta}, \quad , \qquad \textbf{(S1)}$$

where Re is the Reynolds number, v is the velocity of the fluid relative to the obstacle, d is the hydraulic diameter, ρ is the density of the fluid, and η is the dynamic viscosity coefficient of the fluid. In the absence of obstacles within the blood vessels, the blood flow rate is 0.08 m/s to 0.24 m/s. The turbulence intensity is 6.4% to 7.3 % which is input in the simulation settings.

Fig. S2 shows the relationship between the fluid force acting on the ball in the vertical direction and the blood flow velocity within the blood vessel.

Fig. S3 presents the results of the sensitivity analysis for the optimized parameters in the MOGA optimization, specifically the Spearman correlation coefficient. This analysis identifies the influence weights of the driving current, blood flow velocity, the y-coordinate and the z-coordinate of the ball on the resultant force acting on the ball. The results indicate that several parameters are positively correlated with the resultant force of the ball. Within the range of parameters discussed in this paper, the driving current and the y-coordinate position of the magnetic ball significantly influence the force exerted on the magnetic ball during the co-simulation of the electromagnetic field and the flow field.

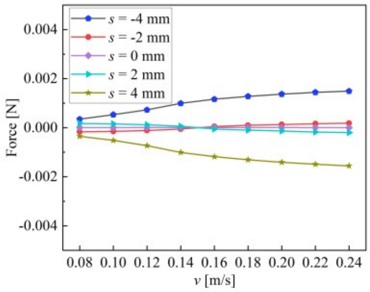

Fig. S2. The relationship between the fluid force exerted on the ball in the vertical direction and the blood flow velocity

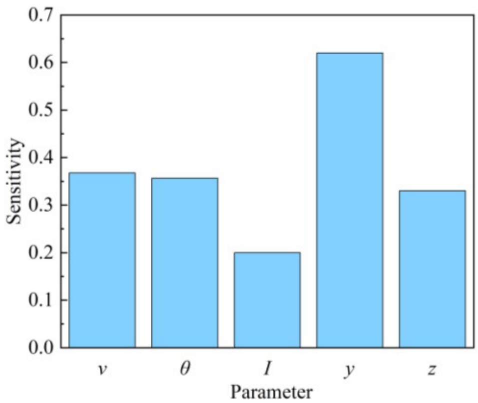

Fig. S3. Parameter sensitivity

REFERENCES

[1] Prasanth, T.K., Behara, S., Singh, S.P., Kumar, R., Mittal, S. Effect of blockage on vortex-induced vibrations at low Reynolds numbers. *Journal Fluid Struct* 22, 865-876 (2006) **DOI:10.1016/j.jfluidstructs.2006.04.011**