Supporting Information for

Controllable Pump-Free Electrokinetic-Driven Microdevice for Single-Cell Electrorotation

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S1. Zeta potential values for different materials

Since the velocity of EOF is dependent on zeta potential, the zeta potential values for some materials are listed in table S1.

Table S1. Zeta values for Glass-PDMS, and PDMS-PDMS [1]

Materials	Zeta-potential value
Glass-PDMS	-66 to -88 mV
PDMS-PDMS	-68 to -110 mV

S2. Yeast cell, particle, colon cancer cell electrical parameters

Fig. S1 shows the equivalent model of PS particle, HCT16 cell and yeast cells.

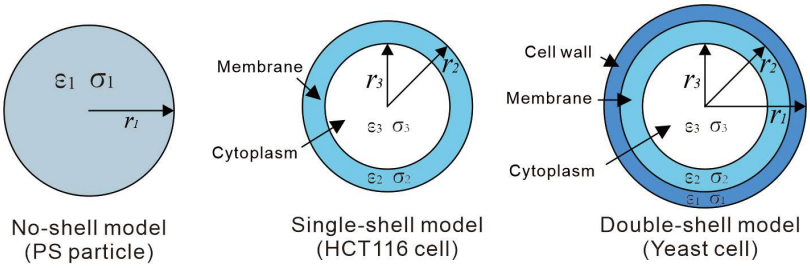

Fig. S1. The equivalent model of PS particles, HCT116 and yeast cell

The table S2 lists the parameters use in simulation models.

Table S2. The electrical parameters of yeast cells, particles and HCT116

	r_1(μm)	r_2(μm)	r_3(μm)	ε_1	ε_2	ε_3	σ_1(mS/m)	σ_2(mS/m)	σ_3(S/m)
Particles	5/7.5			$2.55\varepsilon_0$			0.4		
Yeast cells	3	2.78	2.772	$60\varepsilon_0$	$6\varepsilon_0$	$50\varepsilon_0$	14	2.5×10^{-4}	0.2
HCT116		7.5	7.492		$7\varepsilon_0$	$100\varepsilon_0$		1×10^{-3}	0.4

Where r1, r2 and r3 are the radius of the wall, membrane and cytoplasm, respectively. ε_1^*, ε_2^* and ε_3^* are the complex permittivity of the wall and membrane and nucleus, respectively. The values of the radius r, conductivity σ,

and permittivity ε for each of the three layers and the permittivity εm and viscosity η of medium are listed in the Table S1.

S3. Transmembrane voltage

Mammalian cells are composed of cell membrane and the intracellular cytoplasma, and the membrane is basically treated as an insulator. In the cell suspension, both sides of the cell are immersed in electrolyte solution with lentiful ions. Extracellular electrolyte solution is the cell suspension, and the intracellular is cytoplasm., The electrolyte ions on both sides induced by an applied electric field can be polarized to generate some membrane potential difference V_m, which is given by [2]:

$$V_m = 1.5\alpha E_{ext}\cos\theta/[1 + (\omega\tau)^2]1/2 \quad (1)$$

Where, E_{ext} is the applied electric field intensity, θ is the angle between the radial direction at an arbitrary point on the membrane and the electric field direction, τ is the relaxation time constant of the membrane. When the frequency of the applied alternating electric field is low enough, Eq.(1) can be approximated by Eq.(2), assuming $\omega\tau << 1$:

$$V_m = 1.5\alpha E_{ext}\cos\theta \quad (2)$$

For two cellular extremum points, $\theta = 0°$ or $180°$, the membrane potential difference induced by the applied electric field is further simplified as:

$$V_m = 1.5\alpha E_{ext} \quad (3)$$

The potential difference between these two points is the largest. The induced membrane potential increases with the strength of the applied electric field. In cell electroporation, when the intensity reaches a specific value Ecr, the cell membrane begins to perforate. The higher the intensity of the applied electric field, the more holes appear in the membrane. When the V_m is larger than 0.5 V, the cells will be electroporated.

Fig. S2(a,b) presents numerical simulations of the transmembrane voltages induced by ROT and EOF signals. Fig S2(c) displays the voltage distribution profile along the A-A cross-section. The results demonstrate that both ROT and EOF stimulation generate peak transmembrane voltages of approximately 0.01V, which remains significantly below the membrane breakdown threshold of 0.5V.

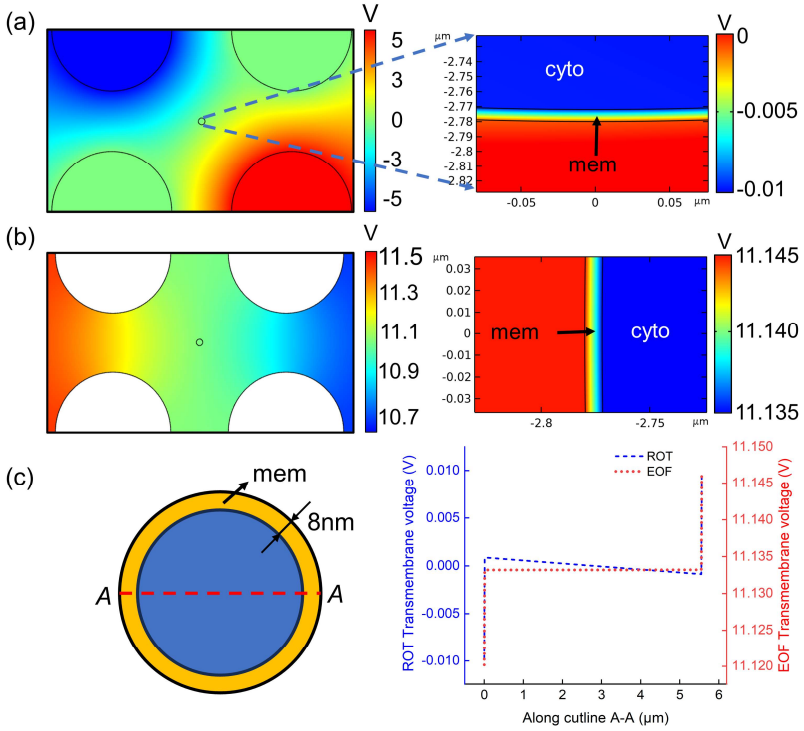

Fig. S2. ROT and EOF transmembrane voltage simulation. Voltage simulation on both sides of the cell membrane

under ROT (a) and EOF (b). (c) The voltage distribution along the cutline A-A of cell.

S4. Velocity of particles with different size under EOF

To quantify the velocity in the channel in more detail, we added a velocity function of a particle with a diameter of 15 μm to the flow channel. And we woke up with a 10 μm particle. From Fig.S3, we find that the velocity of the two particles is almost the same when the voltage is lower than 20 V, which may be due to particle sedimentation, and the friction between the particles and the PDMS hinders the particle movement. When the voltage is greater than 20 V, the velocity of the 10 μm particle will be slightly greater than 15 μm, and it is precisely because the 15 μm particle is more tolerant of sedimentation, and the resistance will be greater than that of 10 μm.

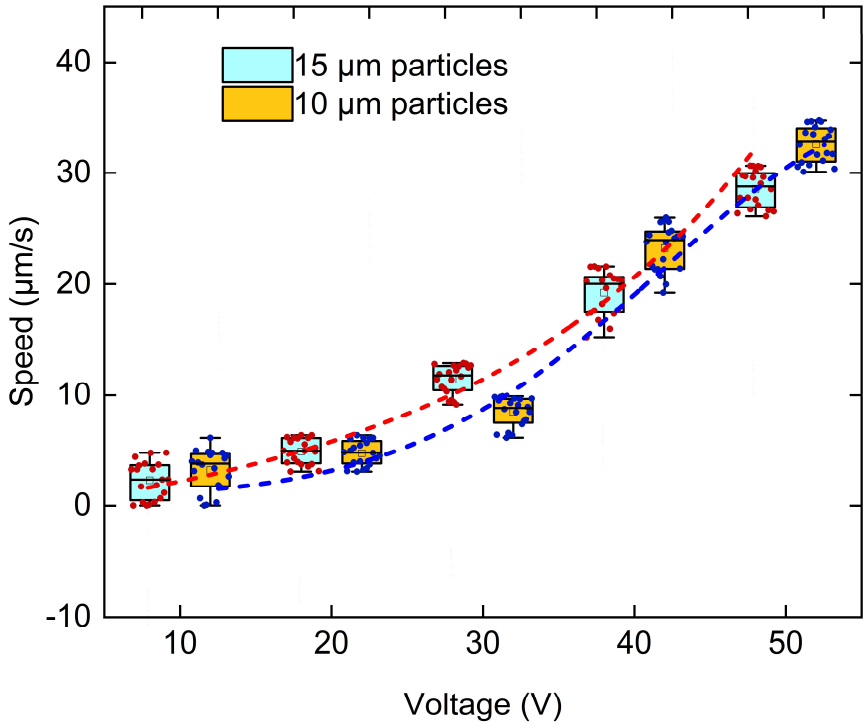

Fig. S3. Comparison of velocity of particles with different size under EOF.

References

[1] M.F. Al-Rjoub, A.K. Roy, S. Ganguli, R.K. Banerjee, Improved flow rate in electro-osmotic micropumps for combinations of substrates and different liquids with and without nanoparticles, J. Electron. Packaging. 2015, 137(2): 021001.

[2] J.C. Weaver, Y.A Chizmadzhev, Theory of electroporation: a review, Bioelectrochem. Bioenerg. 1996, 41(2): 135-160.