Collective Ratchet Transport Generated by Particle Crowding under Asymmetric Sawtooth-Shaped Static Potential

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Herein, the ratchet transport of particles under static asymmetric potential with periodicity is investigated. Ratchet transport garners considerable attention due to its potential for application in smart transport techniques on a micrometer scale. In previous studies, either particle self-propulsion or time-varying potential has been introduced to realize unidirectional transport. The ratchet transport through particle interactions during crowding without utilizing these two factors is experimentally demonstrated. Such ratchet transport induced by particle interaction has not previously been experimentally demonstrated, although some theoretical studies have suggested that particle crowding enhances ratchet transport. In addition, a model for such transport in which the potential varies depending on the particle density is constructed, which agrees well with the experimental results. The development of transport techniques on a micrometer scale is accelerated.

1. Introduction

Increasing attention has been focused on techniques for transporting micrometer-sized particles using asymmetric periodic potential. Generally, such transport is called ratchet transport, in which an asymmetric ratchet-shaped potential rectifies particle motion, resulting in unidirectional particle motion even if the particles intrinsically exhibit nondirectional motion. Thus, ratchet transport enables unidirectional transport without macroscopic field gradients, including microflow and electric potential, along the transport direction, and is expected to be applicable for smart transportation methods in lab-on-a-chip devices. To date, ratchet transport has been proposed for various types of particles, including self-propelled particles (e.g., migrating cells) and passive (non-self-propelled) particles (e.g., molecules). Recently, techniques to rectify the motion of self-propelled particles are being developed using static asymmetric potential. Generally, although self-propelled particles such as migrating cells and micromotors exhibit ballistic motion on a short timescale, they lose directionality after rotational diffusion time. Thus, the motion of such self-propelled particles must be guided. Solid barriers fabricated using lithography have frequently been used in previous studies as the static asymmetric potential. Microparticles suspended in a bath of swimming bacteria have been driven by collisions with the bacteria and their nondirected motions rectified using 3D fabricated patterned asymmetric solid barriers. Furthermore, the unidirectional motions of catalytic micromotors and kinesin-driven microtubules have been successfully extracted using arrowhead-shaped microchannels.

In contrast, techniques to rectify the motion of passive particles have been studied using dynamic asymmetric potential. Although the particles themselves do not exhibit ballistic motion, unidirectional motion is extracted through time dependency and asymmetricity of the potential. Typical examples for varying the potential have been proposed in a flashing ratchet, the asymmetric potential switches between the on/off states, whereas in a rocking ratchet, the asymmetric potential is tilted by an oscillating force. It has been experimentally demonstrated that passive small particles can be transported based on these principles. For instance, thermally fluctuating colloidal particles and large DNA molecules have been transported by the on/off switching of asymmetric potential. In addition, a recent study has realized the transportation of gold spheres under asymmetric potential tilted by an applied oscillating electric field. Several theoretical studies regarding ratchet transport have reported that interaction during particle crowding causes nontrivial and complex effects, for example, the reinforcement of the transport flux. This phenomenon generated by crowding has been theoretically observed in the transport of passive particles under dynamic potential as well as self-propelled particles under static potential. As an example, 1D models that forbid the overlapping of particles show that particle interaction enhances the transport of passive particles under dynamic potential.
Furthermore, examination through computer simulation of the behavior of sterically interacting self-propelled run-and-tumble particles in the presence of a quasi-1D asymmetric substrate indicates that the particle flux can be increased.\cite{18}

In this study, we experimentally demonstrate the ratchet transport of passive particles under static asymmetric potential, utilizing the effect of particle interaction. Herein, interacting passive microparticles are transported under a static asymmetric electric potential generated using 2D sawtooth-shaped electrodes. In this system, transport occurs depending on the microparticle density, as predicted by theoretical studies.\cite{14,15} Our results can enhance the development of smart applications in lab-on-a-chip devices and electrically controlled molecular robots.

2. Results and Discussion

2.1. Microparticle Motion in a Sparsely Populated Area

We generated an electric field using sawtooth-shaped Au microelectrodes patterned on a 2D xy-plane (Figure 1a). Constant direct current (DC) power was supplied to the microelectrode (the applied voltage \( \phi \) was \( \approx 300 \) V), i.e., the electric field was stable over time \( t \). In all the experiments, the electrode on the left was positive, whereas the one on the right was negative. The direct distance \( d \), horizontal distance \( d_h \), and vertical distance \( d_v \) between the tips of the sawtooth were 53, 40, and 70 \( \mu \text{m} \), respectively (Figure 1a). The asymmetricity of the field along the \( y \)-axis was varied by changing the angle of the sawtooth \( \theta \); \( \theta = 60^\circ \) (Figure 1a and Figure S1a, Supporting Information), \( \theta = 30^\circ \) (Figure S1b, Supporting Information), and \( \theta = 0^\circ \) (Figure S1c, Supporting Information) were used. Figure 1b,c shows the calculated electric potential \( \Phi \) when \( \theta = 60^\circ \) and \( \theta = 0^\circ \). In both cases, the total gradient along the \( y \)-axis is zero. The symmetricity of \( \Phi \) at \( \theta = 60^\circ \) and \( \theta = 30^\circ \) is broken along the \( y \)-axis (Figure 1b and Figure S2, Supporting Information), whereas \( \Phi \) at \( \theta = 0^\circ \) is symmetric along the \( y \)-axis (Figure 1c). The asymmetricity of \( \Phi \) is remarkable near the electrode. Similarly, the calculated electric fields are asymmetric when \( \theta = 60^\circ \) and \( \theta = 30^\circ \) (Figure S3, Supporting Information). The linear profile of the electric potential is shown in Figure S4, Supporting Information. The profile of the electric potential along the connecting line between one electrode and its two neighboring counter electrodes is symmetric for all \( \theta \), whereas it is asymmetric along the connecting line between one electrode and vertically neighboring electrodes (for \( \theta = 60^\circ \) and \( \theta = 30^\circ \)). In this study, we observed the motion of polystyrene microparticles (20 \( \mu \text{m} \) diameter) between the microelectrodes. These microparticles were dispersed in liquid paraffin containing 0.1% w/w Span80 (sorbitan monooleate), filling a polydimethylsiloxane (PDMS) chamber (\( \approx 1 \) mm height) placed on a glass slide with sawtooth-shaped Au electrodes (Figure 1d). Figure 1e shows the typical top-view image of experiments.

Figure 2a shows the motion of a single microparticle (indicated by arrowheads) between the tips of the electrodes (Movie S1, Supporting Information). As shown in the maximum intensity projection (Figure 2b) and by the relative position from the initial position, \( x(t) - x(0) \) and \( y(t) - y(0) \) (Figure 2c,d),

![Figure 1. Experimental setup and calculated electric potential.](image-url)
the microparticles exhibited back-and-forth oscillatory motion between the two points P and Q shown in Figure 2b. We speculate that this back-and-forth motion can be attributed to a combination of electrophoretic and dielectrophoretic forces, which is the same mechanism we have previously reported. When DC voltage was applied to the electrodes, the microparticles were attracted to the tip of the sawtooth (point Q) by the dielectrophoretic force, obtaining electric charge. Immediately after obtaining the charge, the microparticles were repelled from the tip by electrostatic repulsion and attracted to the opposite electrode (point P). After electrostatic repulsion from point P, the microparticles were attracted to the opposite tip (point Q) again by the dielectrophoretic force. In the case where there are two microparticles between the electrodes, the two microparticles collide with each other at the center of the electrode, eventually exhibiting back-and-forth motion (Figure 2c-g and Movie S2, Supporting Information). The colors of the arrows in Figure 2c-g and lines in Figure 2h identify each microparticle. When the microparticles having positive and negative charges collide between the electrodes, the charge of the microparticles is neutralized by the collision, and then the microparticles are attracted to the closer electrode by dielectrophoretic forces. Thereafter, the microparticles in contact with the electrode receive the repulsive force from the electrode and collide again with the other microparticle. In this study, we observed only this motion mode when two microparticles were placed between the electrodes, although there might be another possibility that the two particles continuously move together without collision similar to the case of the single microparticle shown in Figure 2b. We consider that the deformation of the electric potential due to the presence of the second microparticle affected the motion of individual microparticles and may have inhibited the motion similar to Figure 2b. This type of motion mode may appear if the size of the microparticle were so small that the deformation of the field is negligible. Figure 2h shows the maximum intensity projection of Movie S3, Supporting Information, which depicts the case with three microparticles between the electrodes. The time variations $x(t) - x(0)$ and $y(t) - y(0)$ of each microparticle are shown in Figure 2i,j. The color of the arrows in Figure 2h and lines in Figure 2i,j identify each microparticle. In this situation, the three microparticles were aligned between points P and Q due to dielectric polarization; therefore, the x- and y-coordinates of each microparticle hardly changed (Figure 2i,j). The results in Figure 2 suggest that microparticle motion was confined along line PQ (Figure 2b,e,h) when the microparticles were sparsely distributed; i.e., net transport along the y-axis was not observed. In addition, the results suggest that the line PQ was the stable position for the microparticles.
2.2. Collective Microparticle Transport Generated during Particle Crowding

Figure 3a shows the snapshots of the collective transport of microparticles between the electrodes at $\theta = 60^\circ$ for each $t$ (Movie S4, Supporting Information). The arrow colors identify each microparticle. To understand the collective transport, we calculated the position change $\Delta y(t) = y(t) - y(0)$ for all microparticles in Movie S4, Supporting Information, averaged $\Delta y(t)$, and then obtained $\Delta y(t) = (y(t) - y(0))$ as the mean displacement for the system (black line in Figure 3b). Unlike the case of the sparse microparticles (Figure 2), some microparticles were transported along the $y$-axis. Collective transport was also observed when $\theta = 30^\circ$ (blue line in Figure 3b, Figure S5a and Movie S5, Supporting Information); however, the speed of transport was slower than the speed when $\theta = 60^\circ$. In contrast, a distinct increase in $\Delta y(t)$ was not observed when the electrode with $\theta = 0^\circ$ was used (red line in Figure 3b, Figure S5b, and Movie S6, Supporting Information). We speculate that the collective transport under an asymmetric electric field was generated by the electrostatic interaction and collision among the crowding microparticles. When the microparticles were sparsely dispersed between the electrodes (Figure 2), the microparticle motion was confined between points P and Q, which was a stable position; hence, transport along the $y$-axis was not observed. However, during crowding (Figure 3a), all the microparticles could not exist on line PQ (snapshot at $t = 27.1$ s in Figure 3a) due to the microparticle volume. In the periphery of line PQ, these microparticles interacted and received randomly directed forces. Eventually, when the electric field was asymmetric, some microparticles were stochastically transported along the $y$-axis due to the locally biased potential (black and blue lines in Figure 3b, and Movies S4 and S5, Supporting Information). In contrast, when the electric potential was symmetric, although microparticle interaction was observed, net transport was not observed (red line in Figure 3b and Movie S6, Supporting Information). Based on the observation of Movies S4 and S5, Supporting Information, collective transport was generated when 4–6 microparticles were present between points P and Q on the electrodes. Thus, it is difficult to define the threshold value for the number of microparticles that gives rise to transport distinctly. We consider this ambiguity of the threshold value to originate from the fluctuation of the force applied to the microparticles such as electrostatic repulsion. For example, in our system, it is considered that the reverse micelles of the surfactant are ubiquitous in the medium oil. These micelles could act as carriers to transport the charge to the microparticles and eventually may affect the magnitude of the electrostatic force.

When the charged microparticles were crowded, the electric potential near them should be deformed and different from...
the calculated geometries (Figure 1b,c, and Figure S2, Supporting Information). We consider that microparticle crowding deforms the original electric potentials and affects existing asymmetricity (counter lines in Figure 1b and Figure S2 and S4c, Supporting Information) importantly to generate the transport.

Next, we conducted numerical simulations considering the forces exerted on the microparticles. A microparticle receives an electrostatic force, a dielectric force, and a force through the interaction with other microparticles. Then, the equation of motion of the $i$th microparticle is described as follows

$$\eta \frac{dR_i}{dT} = \sum_j \sum_k \left( F_{EP_{ijk}} + F_{DE_{ijk}} \right) + \sum_l F_{PP_{il}} \tag{1}$$

where $\eta$ is the viscous constant, $R_i = (X_i, Y_i)$ is the position of the $i$th microparticle in a dimensionless $X$–$Y$ coordinate system, and $T$ is the time. Here, we represent the electrodes as a patterned cluster of fixed dots with charge; i.e., the positively charged dots and the negatively charged dots are patterned along the shape of the electrodes (Figure S6a, Supporting Information). $F_{EP_{ijk}}$ and $F_{DE_{ijk}}$ represent the electrostatic and dielectricforces between the $i$th microparticle and the $j$th positively charged dot and $k$th negatively charged dot representing the electrodes (see Equation (5) and (6) in Experimental Section), and $F_{PP_{il}}$ describes the interaction force between the $i$th and $i$th microparticles attributed to the electrostatic force and collision (see Equation (7) in Experimental Section). In addition, each microparticle has charge, and the charge changes on contact with the charged dots or other microparticles. The details of this model are explained in Experimental Section. Figure 3c shows the images of numerical simulation using Equation (1) under the condition that the positive and negative dots are patterned along the electrode with $\theta = 60^\circ$ (Movie S6, Supporting Information). Each image is a cropped snapshot from an original simulation window (Figure S6b, Supporting Information). Each arrow in Figure 3c shows that some microparticles are transported with time $T$. Figure 3d shows the plot of the mean displacement of all the microparticles, $\Delta Y(T) = (Y(T) - Y(0))$. The black squares and blue triangles denote $\Delta Y(T)$ at $\theta = 60^\circ$ and $30^\circ$, respectively, indicating that net transport is generated when the potential is asymmetric (Figure 3c and Figure S7a and Movie S6 and S7, Supporting Information). In contrast, when the potential is symmetric ($\theta = 0^\circ$) (Figure S7b and Movie S8, Supporting Information), there is no significant change in $\Delta Y(T)$, as shown by the red circles in Figure 3d, which is consistent with the experimental results (red line in Figure 3b). Figure 3d also suggests the dependence of transport speed on potential asymmetricity, meaning that an increase in asymmetricity enhances the transport speed. In addition, to determine the threshold value for the potential asymmetricity that gives rise to transport, we carried out the calculation in the cases of $\theta = 5^\circ$ (green inverted triangle in Figure 3e) and $1^\circ$ (Figure S8, Supporting Information). In both cases, the microparticles are transported, although the transport is small in comparison with the cases of $\theta = 30^\circ$ and $60^\circ$. This implies that there is no explicit threshold of asymmetricity in our system; the transport continuously responds to the change of asymmetricity; thus, slight asymmetricity can induce transport in the presence of a sufficient number of microparticles. Figure 3e shows the dependence of the net transport on the number of particles $N$ in the simulation. Although an increase in $\Delta Y(T)$ is clearly observed when $N = 30$ (black squares in Figure 3e), when $N = 15$ and 5 (blue triangles and red circles in Figure 3e, respectively), $\Delta Y(T)$ is less than half of that for $N = 30$, indicating that the crowding of particles induces transport. Also, the transport speed depends on the number of particles, that is to say, a large number of microparticles generates higher transport speed. These results qualitatively agree with our experimental results. The cases when $N = 5$ and 30 might correspond to the experimental observation of sparse microparticles (Figure 2) and crowding (Figure 3a), respectively, and $N = 15$ may correspond to an intermediate situation. Thus, we conclude that the collective transport in our system (Figure 3a) can be attributed to the asymmetricity of the potential and the crowding of microparticles.

2.3. Modeling of the Collective Transport Generated by Crowding

Our experimental and simulation results indicate that microparticle crowding generates net mass transport under asymmetric periodic potential. Because the possible number of microparticles confined at minimum potential is limited, some of the microparticles are stochastically pushed out along the $y$-axis, resulting in microparticle transport. This manner of transport is the same as that in the previous theoretical study that depicts the mass transport of microparticles under an asymmetric potential, where spatial overlapping is forbidden.[19] From another point of view, it can also be argued that the crowding of microparticles forces the field “flashing.” In this study, we modeled the collective transport as the system whose potential “flashes” depend on the number of particles in the period. The calculations were carried out along a one-1D line that included three periodic potentials with a period length of unity under a periodic boundary condition (Figure 4a).

The nondimensional model is described as

$$\zeta \frac{du_i}{d\tau} = - \frac{dU(u_i)}{du} \cdot S(P_{num}) + \xi(\tau) \tag{2}$$

where $\zeta$ represents the viscous constant, $u_i$ is the position of the $i$th microparticle, $\tau$ is the time, and $\xi$ is a random force that follows a Gaussian distribution. A periodic boundary condition is assumed, i.e., $0 < u < 1$. $U$ is the periodic potential, as shown in Figure 4a, with the following form

$$U(u_i) = \begin{cases} \frac{U_{\text{max}}}{\delta} (\delta - u_i) & (0 \leq u_i \leq \delta) \\ \frac{U_{\text{max}}}{1-\delta} (u_i - \delta) & (\delta < u_i < 1) \end{cases} \tag{3}$$

where $\delta$ is the asymmetricity parameter indicating the position where the potential is minimum, and $U_{\text{max}} > 0$ is the maximum value of the potential. In our model, $U(u_i)$ is weakened depending on a sigmoid function (Figure 4b) described as

$$S(P_{\text{num}}) = \frac{1}{1 + \exp \left( \frac{1}{r} \left( P_{\text{num}} - \frac{N_{\text{max}}+1}{2} \right) \right)} \tag{4}$$
where \( P_{\text{num}} \) is the number of microparticles existing in the periphery of the minimum potential, represented as \( \delta - \epsilon < u < \delta + \epsilon \) (Figure 4a). The range of the periphery of the minimum potential is determined by \( \epsilon \); in all the simulations, \( \epsilon = 0.2 \). \( \gamma \) is the gain, and \( N_{\text{max}} \) is the maximum number of microparticles that can occupy the minimum potential, \( \delta - \epsilon < u < \delta + \epsilon \). To evaluate the transport, we define the flux \( J = (1/N) \sum_{i=0}^{S} j_i(\tau) \), where \( N \) is the total number of microparticles in the simulation, \( S \) is the final time, and \( j_i(\tau) \) is defined as \( j_i(\tau) = \sum_{l=0}^{N} j_{i,l}(\tau) \), where \( j_{i,l}(\tau) \) characterizes the transport of the \( i \)th microparticle at time \( \tau \). When the \( i \)th microparticle moves into the subsequent period of the potential on the left, \( j_i(\tau) = 1 \); when it moves into that on the right, \( j_i(\tau) = -1 \); when it remains at the same period, \( j_i(\tau) = 0 \).

Figure 4c shows a plot of \( J \) against \( N_D/N_{\text{max}} \). \( N_D \) denotes the number of microparticles per period of the asymmetric potential \( (N_D = N/3) \). \( J \) is small when \( N_D/N_{\text{max}} \) is small \( (N_D/N_{\text{max}} < 1) \), and it begins to increase significantly when \( N_D/N_{\text{max}} = 1 \). This nonlinear response is observed in both cases, where \( N_{\text{max}} = 3 \) and 6 (black circles and red squares in Figure 4c, respectively). \( N_D/N_{\text{max}} = 1 \) indicates that a sufficient number of microparticles exist to weaken the potential force at all the periodic potentials. These results reproduce our experimental results well. The small \( J \) at small \( N_D/N_{\text{max}} \) corresponds to the back-and-forth motion with alignment on line PQ in the sparsely populated areas, and the increase in \( J \) in \( 1 < N_D/N_{\text{max}} < 2 \) corresponds to the collective motion generated by crowding. When \( N_D/N_{\text{max}} > 2 \), \( J \) gradually decreases. In addition, it should be noted that \( J \) of \( N_{\text{max}} = 6 \) is always lower than that of \( N_{\text{max}} = 3 \). We speculate that the decrease in \( J \) may be caused by excessive crowding. When there are too many particles in the system, the potential force is weakened at all the periods of the potential, and the motions of the particles are randomized, causing a decrease in \( J \). This nonlinear relationship between the particle number and transport efficiency can be beneficial, for example, to estimate the appropriate sample density in an actual transport system.

Figure 4d shows the plot of \( J \) against \( \delta \), indicating that asymmetry in the periodic potential is essential for transport. In the presence of asymmetricity \( (0.05 \leq \delta < 0.5) \), transport is always generated; however, \( J \) decreases with a decrease in the amplitude of the asymmetricity. Further, when \( \delta = 0.5 \), the potential is symmetric and transport is not generated. Similar phenomena are experimentally observed, as shown in Figure 3; transport is not observed when the electric field is symmetric \((\theta = 0^\circ)\), whereas collective transport is observed when \( \theta = 60^\circ \) and \( 30^\circ \).

3. Conclusions

In this study, we demonstrated the collective transport generated by the crowding of microparticles under a periodic asymmetric potential. When the microparticles were sparsely distributed, they exhibited back-and-forth motion (Figure 2b–g) and stable alignment on a line between the electrodes (Figure 2h–j); the microparticles were confined in the minimum of the periodic potential. In contrast, when the microparticles were crowded and the field was asymmetric, they moved into the next period of the potential due to electrostatic and collision interaction (Figure 3a,b). The results of the 2D simulation agree well with the experimental results, indicating that both crowding and an asymmetric potential are necessary for mass transport (Figure 3c–e). Finally, we constructed an abstract model of the collective transport generated by crowding. In the model, the amplitude of the potential is assumed to vary depending on...
the number of microparticles. This simpler abstract model succeeds not only in reproducing the dependence of transport speed on the number of microparticles and the potential asymmetry but also in showing nonlinear response due to the crowding effect (Figure 4c,d). This work verifies the theoretically expected phenomenon of the generation of ratchet transport by microparticle interaction. To date, methods of electrotransports on a micrometer scale have been developed; for instance, it is known that electrokinetic transports with liquid crystal fluids can provide higher-order applications including pumping, mixing, and sensing.[23] In contrast, our electrotransport is a technique that becomes effective not by using specific materials (e.g., molecules) but by harnessing self-organized collective motion through individual interaction.[5,24–26] This concept can be used to apply the self-organized intelligent phenomena to engineering applications on micrometer scale such as transports. Our study can lead to the development of transport techniques on a micrometer scale with sophisticated functions such as changes in the transport direction and sorting in accordance with the particle shape and size.[27–29]

4. Experimental Section

Preparation and Experimental Setup: Polystyrene microparticles (without coating, size: 20 μm, 01-00-2045, micromod, Germany) dispersed in liquid paraffin (K-350, Kaneda, Japan) with 0.1% w/w Span80 (Sorbitan Monoooleate, Tokyo Chemical Industry, Japan) were sonicated for 60 min and filled in a PDMS chamber (height: ≈1 mm), which was placed on a glass slide with the electrode. The open top was sealed with cover glass (1.8 cm × 1.8 cm, Matsunami Glass, Japan) to prevent convective flow in the liquid paraffin. Static DC voltage was then applied to the electrode using a constant-voltage power supply (CPU-301H100, GW Instek, Japan). The motions of the microparticles were observed using an inverted microscope (CKX-41, Olympus, Japan) and recorded using a digital camera (EOS D60, Canon, Japan) at a frame rate of 30 fps. The recorded video was analyzed using image processing software, Image J (National Institutes of Health, USA).

2D Numerical Simulation: Each force in Equation (1) is described as follows

\[ F_{\text{EPFj}} = a Q(s_i) \left( \frac{d_{ij}}{d_{ij}^2} - \frac{d_{ik}}{d_{ik}^2} \right) \]  
\[ F_{\text{D\text{EN}Pj}} = b \left( \frac{d_{ij}}{d_{ij}^2} + \frac{d_{ik}}{d_{ik}^2} \right) \]  
\[ F_{\text{PPV}} = -c \frac{d_i}{d_{ij}} m_i |d_i| - a (2R_i - |d_i|) \frac{d_{ij}}{d_{ij}^2} \]  
\[ a, b, c, d = \text{const.} \]  

\[ F_{\text{EPFj}} \] in Equation (5) is described as the force inversely proportional to the square of the distance from the electrode, which corresponds to the electrostatic force. \( d_{ij} \) and \( d_{ik} \) are the distances from the \( j \)th microparticle to the positive and negative dots, respectively. \( Q(s_i) = m_i^\beta \) is defined as the charge of the \( i \)th microparticle. \( Q(s_i) \) exponentially dissipates with elapsed time \( s \) on contact with either dot, and \( m_i \) is a discrete variable representing the sign of the charge (\( m_i = -1, 1 \); \( \beta < 1 \) is the dissipation parameter). The contact of the \( i \)th microparticle of radius \( R_i \) with the positive and negative dots is determined by \( |d_{ij}| \leq R_i \) and \( |d_{ik}| \leq R_i \). After contact, \( m_i \) is updated to \( m_i = -1 \) (the case where contact occurs with the positive dot) and \( m_i = 1 \) (the case where contact occurs with the negative dot), and \( s \) is reset to \( s = 0 \). \( F_{\text{D\text{EN}Pj}} \) in Equation (6) is described as the force inversely proportional to the fifth power of \( d_{ij} \) and \( d_{ik} \), which corresponds to the dielectrophoretic force. Here, we assume that the dielectric constant of the polystyrene microparticle is larger than that of liquid paraffin; therefore, \( F_{\text{D\text{EN}Pj}} \) acts in the direction in which the microparticles are attracted to the electrode. \( F_{\text{PPV}} \) in Equation (7) describes the interaction among the particles, attributed to the electrostatic force and collision. The first term on the right of Equation (7) represents the electrostatic force acting between the \( i \)th and \( j \)th microparticles. \( F_{\text{PPV}} \) represents the distance between the \( i \)th and \( j \)th microparticles. The second term is the repulsive force that prohibits the overlapping of the \( i \)th and \( j \)th microparticles, and it repels them when \( |d_{ij}| \leq 2R_i \). Furthermore, we consider the charge transfer among particles parallel to the interaction force (Equation (7)). When the microparticles make contact, the change of the contacting microparticles changes to \( Q(s_i) |d_{ij}| \leq 2R_i \), meaning the average of the contacting microparticle charge. In addition, \( s \) is reset to \( s = 0 \). The equation of motion and the force formulas were normalized into a dimensionless system. In all the simulations, \( \eta, R_c, \beta \), and \( (a, b, c, d) \) were set to 1.0, 0.091, 0.996, and (0.01, 0.000015, 0.01, 50.0), respectively, and the distance between the electrodes (\( d_0 \) in the experiments) was 0.456. The calculation was carried out for 50,000 steps.

Calculation of the Abstract 1D Model: The equation of motion was normalized into a dimensionless system. In the simulations shown in Figure 4c, \( \gamma = 2 \) when \( N_{\text{max}} = 3 \) (black circles), and \( \gamma = 1 \) when \( N_{\text{max}} = 6 \) (red squares). In the simulations shown in Figure 4d, \( \gamma = 2 \) and \( N_{\text{max}} = 3 \). In these simulations, \( \epsilon = 0.2 \), and the calculations were carried out for 100,000 steps.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest

The authors declare no conflict of interest.

Keywords

collective motions, ratcheting, smart particle transports, swarm behaviors

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