Rectification of self-propelled translational bacterial motors

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Introduction

Escherichia Coli (E. coli) is a rod shaped, typically non-pathogenic bacterium that naturally lives in the guts of several animals, including the human being. It is easily cultured in the laboratory and has been intensively studied and used in the laboratory as a model for microbiology and as a tool in biotechnology. When E. coli cells are placed in a diluted aqueous suspension, they self-propel using their long flagella of about 10 µm in length, with an average speed of about 10 µm/s. When placed in a dense suspension, the interaction between many swimming bacteria produces complex behaviors at length scales of several body lengths, such the active turbulence [1].

Past studies have shown that such a dense suspension, when confined in an aqueous droplet immersed in oil produces movement of the whole drop. We call these systems a translational bacterial motor. The drop movement exhibits a persistent movement at short times, but zero mean displacement at long times, behaving in a diffusive fashion when it is posed over a flat substrate [2]. That is, the mean square displacement (MSD) is well fitted by the equation

$$\mathrm{MSD} = 4D\tau\left(\frac{t}{\tau} - 1 + e^{-\frac{t}{\tau}}\right), \tag{1}$$

where τ is a characteristic timescale and D is the diffusion coefficient (see Fig. 1). The former results indicate that the long-term movement of the translational bacterial motor is random, thus resembling a Brownian particle. The objective of this work is to rectify the movement of the drops to achieve a directed motion. Due to the dominance of viscous forces at the microscale, the extraction of useful work from these motors requires to break both the temporal and spatial symmetry. For that, we designed and fabricated ratchet type substrates and studied how translational bacterial motors behave when posed over it, showing that it is possible to rectify the motion of translational bacterial motors.

Results

Rectified translational bacterial motor are fluctuating systems that can be understood by a Langevin equation. Peter Hanggi proposed theoretically a mechanism to rectify the motion of a Brownian particle, through the application of an asymmetric potential $V_R(x)$, and a fluctuating forcing $f(t)$. The motion of such a particle is governed by the over-damped equation of motion given by [3]

$$\gamma\dot{x} = -V_R'(x) + f(t) + \sqrt{2D}\zeta(t), \tag{2}$$

where x is the position of the particle, and γ the drag coefficient. The effect of the thermal noise has been included in $\zeta(t)$. Importantly, the fluctuating force $f(t)$, which represents the effect of the bacterial collective motion in the drop movement, is random but exponentially auto-correlated, which allows the temporal symmetry breaking.

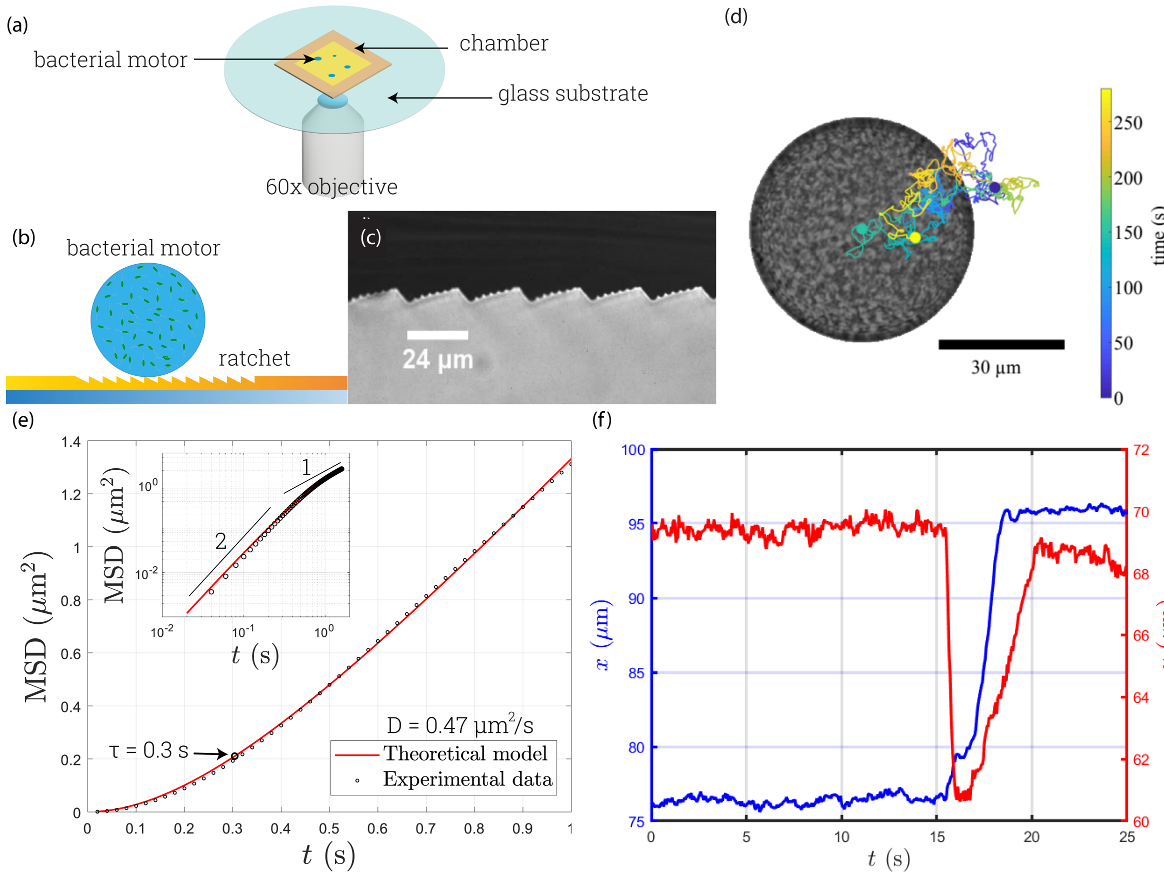

Figure 1: (a) Experimental setup. (b) Schematic of a translational bacterial motor over an anisotropic ratchet type substrate. (c) Examples of real ratchet type substrate fabricated in positive photoresist AZ-10XT. (d) Real translational bacterial motor and its motion in time. (e) MSD as a function of time for a TBM posed in an isotropic substrate. Theoretical model is given by Equation (1). (f) Position *x* and *y* as a function of time of a translational bacterial motor in a ratchet substrate.

Using optical lithography techniques, we designed and fabricated anisotropic ratchet type substrates controlling precisely their aspect ratio (see Fig. 1). With that we can break the spatial symmetry, i.e., we generate the potential $V_R(x)$, and produce a non-reciprocal motion in the translational bacterial motors that generates discrete rectification in the direction of the ratchet. We characterized the optimal geometry to enhance the rectification and quantified the statistics of the movement of the bacterial motors in these substrates.

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