Swimming force and behavior of optically trapped micro-organisms: supplement

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Swimming force and behavior of optically trapped micro-organisms: supplementary material

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This document provides supplementary information to “Swimming force and behavior of optically trapped micro-organisms,” https://doi.org/10.1364/OPTICA.394232. Information contained within this document provides further details on parameters used for both simulations and experimental measurements. This includes discussion of how optically trapped particles are simulated, unfiltered power spectrum and time-series force data, as well as discussion of how swimming and tumbling periods of cells may be determined during experimental measurements.

1. SIMULATION OF OPTICALLY TRAPPED CELL

Supplementary Movie S1 shows the time-trace of Figure 3 in the main text. The simulation shows an E. coli moving in a Gaussian beam optical trap. A Gaussian beam tends to align the E. coli with the beam axis. When the trap stiffness transverse to the beam axis is significantly stronger than along the beam axis, and the particle is strongly aligned to the beam axis, the swimming cell can be approximately modelled by a one-dimensional linear trap. In this case, the differential equation describing the particles motion along the beam axis is

\[
m \ddot{z} = -kz + F_{\text{swim}} + F_{\text{BM}} + F_{\text{drag}}
\]  

(S1)

where \(m\) is the particle mass, \(k\) is the optical trap stiffness along the beam axis, \(F_{\text{swim}}\) is the swimming force, \(F_{\text{BM}}\) is a stochastic term for the Brownian motion and \(F_{\text{drag}}\) is the drag force. This equation is relatively straightforward to simulate numerically [1]. For the simulation we ignored the inertial effects and used approximate values for the particle drag, trap stiffness and swimming force.

2. UNFILTERED POWER SPECTRUM AND TIME-SERIES DATA

In Figure 2 of the main text, the power spectrum for a motile E. coli and the associated time-series force measurements are provided. This data has been averaged using a moving window to better visualise the power spectrum peaks associated with body and flagellum rotation, as well as better visualising changes in the measured forces in the time-series data. The unfiltered data is provided here in Figure S2.

3. DETERMINING RUN AND TUMBLE PERIODS

This section is provided to present better understanding of Figure 4 in the main text. This figure shows a histogram with two distinct peaks, which are said to correspond to running and tumbling motion of the cell. It is initially unclear as to whether or not the larger peak corresponds to running or tumbling, and the video of this process does little to help visually distinguish these movements. We can, however, determine that this particular cell spends the majority of its time swimming by looking at the continuous wavelet transformation (CWT) of the force data.

From Figure 1 in the main text, the power spectrum shows that we expect two distinct frequencies which serve as indicators of bacterial motility. A CWT will look at the relative magnitude of various frequency components over time, where we can look for the activity of frequencies relating to body and flagella motion. It is evident from Figure S3 that the frequencies corresponding to flagella and body rotation are active for the majority of the time.
Fig. S1. (a) Visualisation of an optically trapped *E. coli*. Initially the cell is moving only under Brownian motion and is located in approximately the centre of the optical trap. The cell then starts swimming, through the application of a constant propulsive force. (b) The center of the *E. coli* is tracked, when the cell starts to swim, the centroid moves toward the edge of the optical trap, as seen in time-trace of the centroid position. (c) The instantaneous and averaged velocity is recorded throughout the simulation time. (d) These three force curves show the changes in the optical (blue), swimming (red) and drag (yellow) force. The time when the cell starts swimming is clearly shown as a deviation from zero force for all three curves.

**Supplementary Figure S3.** (A) Continuous wavelet transformation showing full frequency spectrum for the x spatial-dimension. Note the two light bands at ≈ 0.01kHz and 0.1kHz, frequency activity within these bands correspond to body roll and flagellum rotation respectively. (B) Low-frequency activity, highlighting body roll. (C) High-frequency activity, corresponding to flagellum rotation.

Fig. S2. (a) Unfiltered power spectrum for a motile *E. coli*. (b) Unfiltered time-series force data used to generate power spectrum.

data is being recorded, suggesting the larger histogram in Figure 4 of the main text corresponds to times where the cell is swimming. Furthermore, we can define a binary system to determine if the cell is swimming or tumbling by looking at the magnitude of the frequency band contributions in Figure S3. We can focus only on the magnitude of the flagella frequency band by comparing with frequency contributions for non-motile polystyrene beads. A 2 µm polystyrene bead is held in the optical trap and the CWT is recorded. We then isolate the flagella-related frequency band to determine the noise floor of the frequency contribution detectable in the CWT. If the magnitude of the flagella band is around this level, the cell is assigned a value of 0 corresponding to tumbling motion where the flagellum is inactive. Conversely, if the flagella band contributes a signal sufficiently higher than the noise floor, we say that the cell is swimming and assign a value of 1. This procedure has been carried out and presented in Figure S4.

**Supplementary Figure S4.** Determining if the cell is swimming or tumbling by looking at the flagella frequency contribution in the continuous wavelet transformation.

A. Selecting centroids at maximum displacements

When a motile cell is moving within an optical trap, we are looking for instances when the cell is close to the edge of the trap. Near this point will be when the restoring force is approximately equal to the swimming force. Since we take simultaneous position and force measurements, we determine the camera frames in which the cell is at a maximum displacement from the trap.
center. We then correlate these frames with force measurements taking within this time interval to determine the propulsive force. This process is shown in Supplementary Figure S5. The left side of this histogram extends out substantially further than the right side due to the direction of swimming.

**Supplementary Figure S5.** Histogram of centroid positions for an optically trapped motile *E. coli*. To determine the times when the cell is near the edge of the optical trap, and is therefore approximately stationary. Regions where the cell is at a maximum displacement from the center of the optical trap are isolated. These selected camera frames are then mapped to simultaneous force measurements to determine the propulsive force.

**REFERENCES**

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