Supporting Information

Direct upstream motility in *Escherichia coli*

Tolga Kaya[a] *and Hur Koser*[b]

[a]*School of Engineering & Technology, Central Michigan University, Mt. Pleasant, MI 48859, USA*

[b]*School of Engineering and Applied Science, Yale University, PO Box 208284, New Haven, Connecticut 06520, USA*

Corresponding author:

Hur Koser, Ph.D.

E-mail: hur.koser@yale.edu
Phone: (203) 432-9629
Fax: (203) 432-6420
Web: http://sites.google.com/site/koserlab

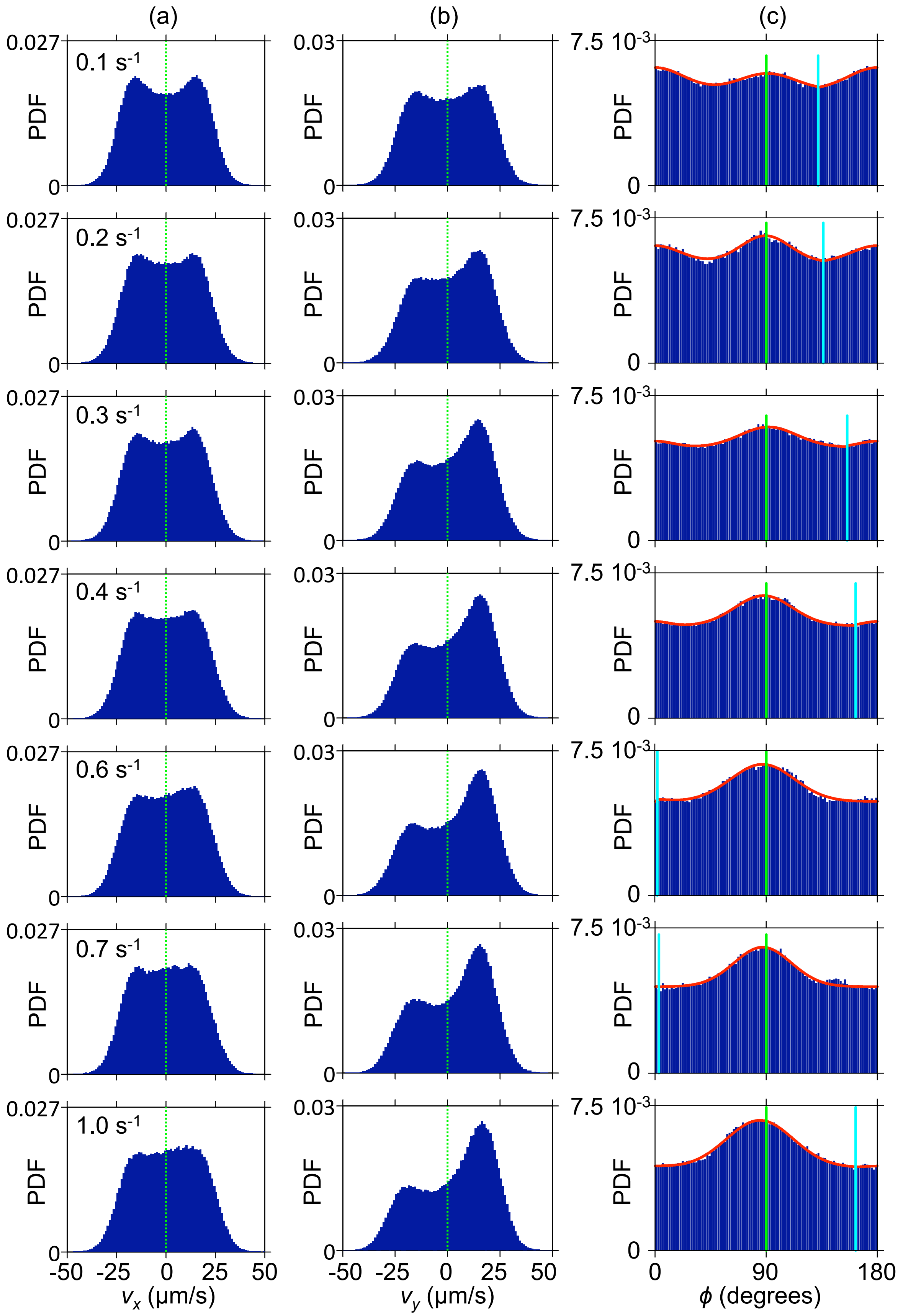
Mailing address: PO Box 208284, New Haven, CT 06520-8284
Shipping address: Becton Center, Room 507, New Haven, CT 06511

Relevant Fields: Physical Sciences, Microbiology, Applied Biophysics, Engineering, Microfluidics, Fluid Dynamics, Bacterial Motility and Pathogenesis, Healthcare

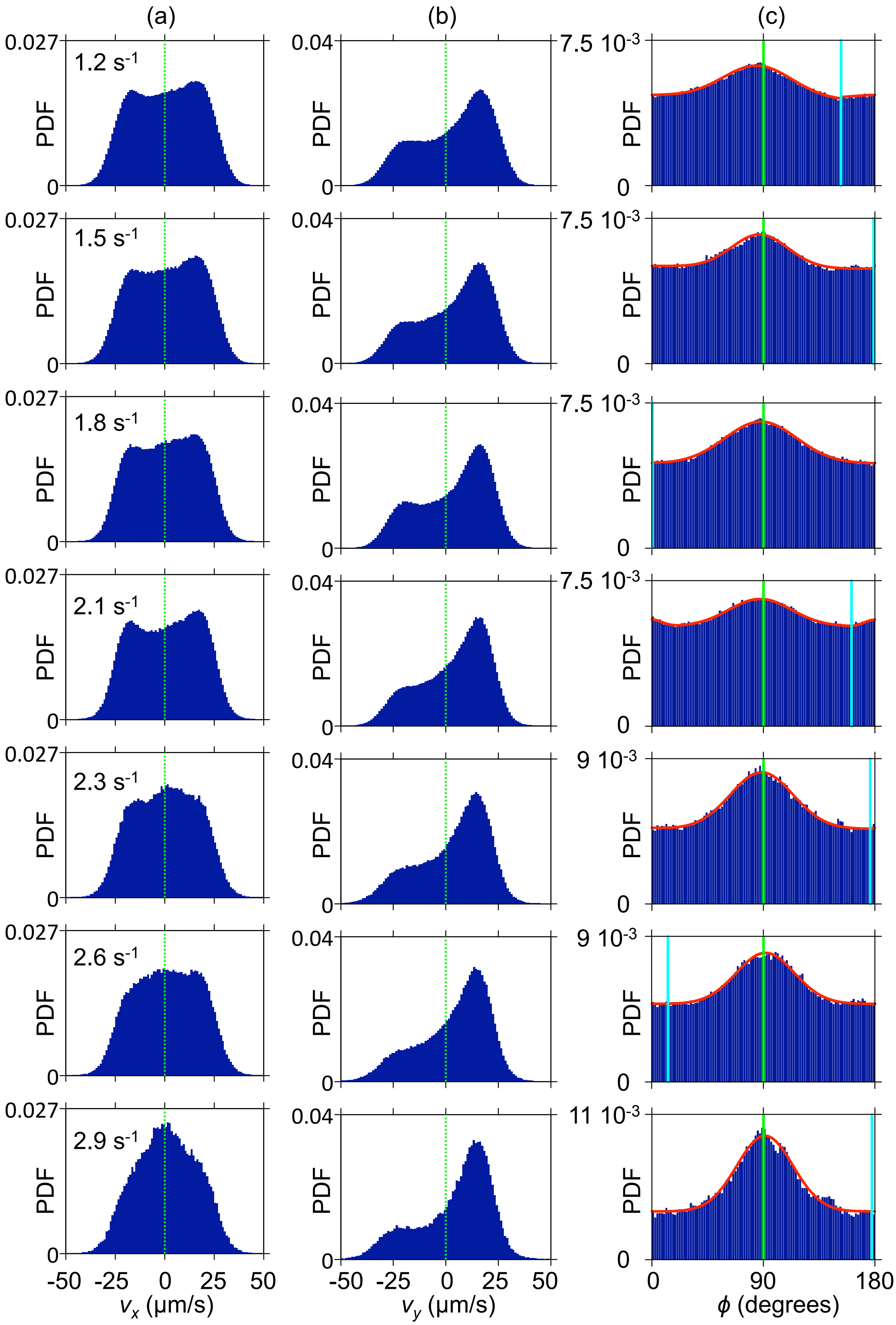
S.1. Complete data

Fig. S1 depicts a summary of v_x, v_y and ϕ data obtained from all experiments, covering a range of shear rates between 0.1 and 59 s^{-1} within the field of view of the imaging setup. As mentioned in the main text, the dominant orientation angle of approximately 90 degrees (i.e., facing upstream) appears gradually in the distribution of ϕ as the shear rate is increased. Correspondingly, more *Escherichia coli* (*E. coli*) engage in direct upstream motility (as can be seen from the asymmetry in v_y data). When the shear rate exceeds 6.4 s^{-1}, average v_y goes below 0. At faster shear rates, the bacteria begin to get dragged downstream on average, with the dominant orientation angle falling from 90 degrees towards 0. In this regime, most of the cells continuously swim sideways, eventually getting out of the high shear rate region and finding more optimal routes to swim upstream – either directly on the smooth surface (as explained in this work) or through using a sidewall (as described in [1]). At high flow rates, an increasing number of weak swimmers succumb to the tendency of the shear flow to roll cell bodies around the x-axis of the surface, leading to periodic Jeffery orbits with an average ϕ of 0 [2]. We capture the phenomena of random/circular swimming, flow-induced orientation and Jeffery orbits appearing at progressively higher shear rates by fitting a linear superposition of three random variables to the probability density function of ϕ. These fits involve a uniform distribution, a variable-mean Gaussian and a zero-mean Gaussian, respectively. This model explains the entire data set very well (see fits in Fig. S1c).

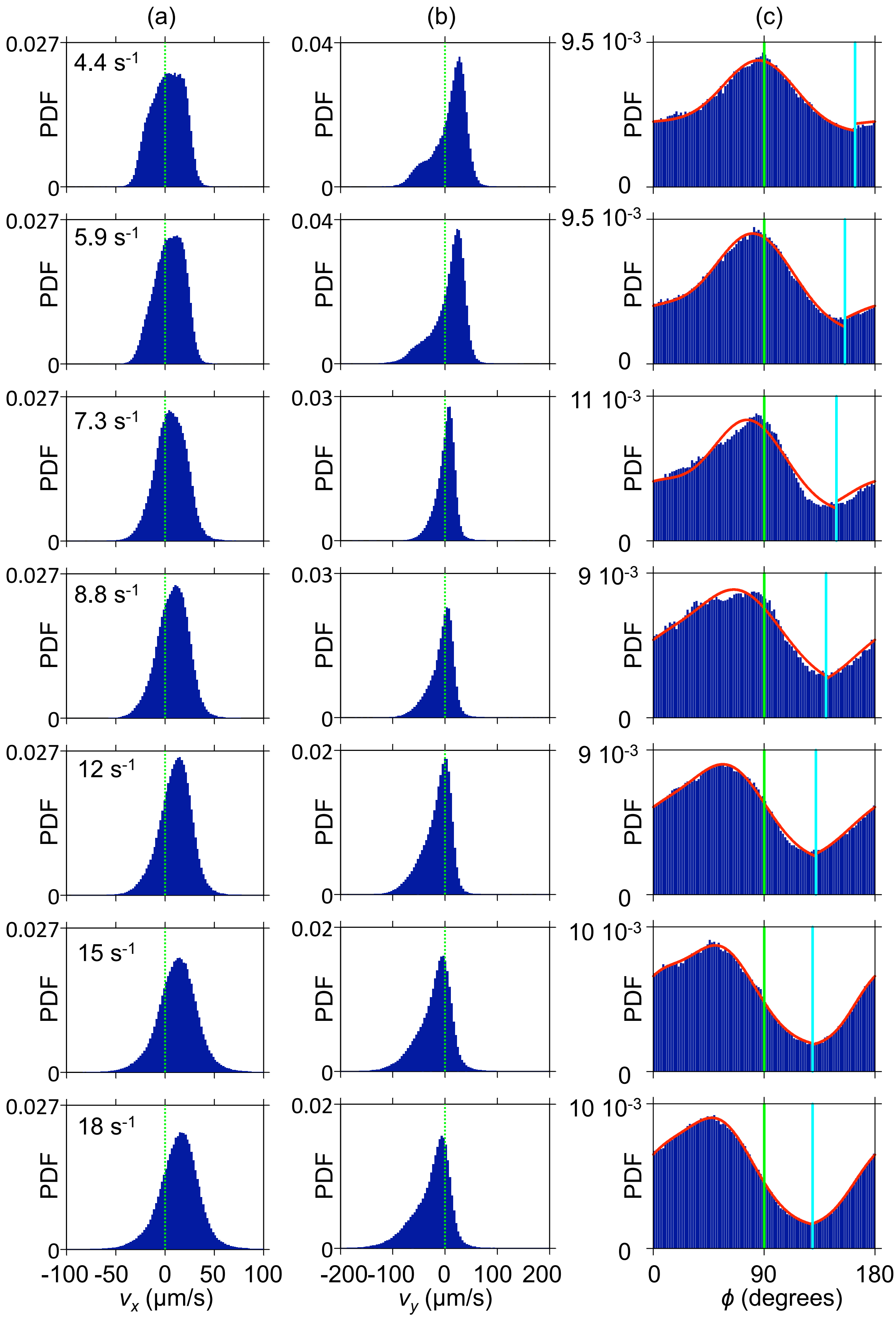
Figure S1. (Below) PDF's for (A) v_x, (B) v_y and (C) ϕ at all shear rates tested (0.1, 0.2, 0.3, 0.4, 0.6 0.7, 1.0, 1.2, 1.5, 1.8, 2.1, 2.3, 2.6, 2.9, 4.4, 5.9, 7.3, 8.8, 12, 15, 18, 23, 29, 35, 41, 47, 53, and 59 s^{-1}, respectively). For ease of interpretation, the center vertical lines in (C) denote 90° for 0.1-18 s^{-1} plots, and 0° for the highest shear rate data (23-59 s^{-1}). The off-center vertical lines in (C) depict the angle around which the fits (displayed as solid red curves) to ϕ distribution are periodic within 180°. Since Gaussians are not periodic, periodic troughs in the orientation PDF's were chosen as convenient end boundaries for these fits. The fits combine a linear superposition of uniform, variable-mean Gaussian and zero-mean Gaussian PDF's.



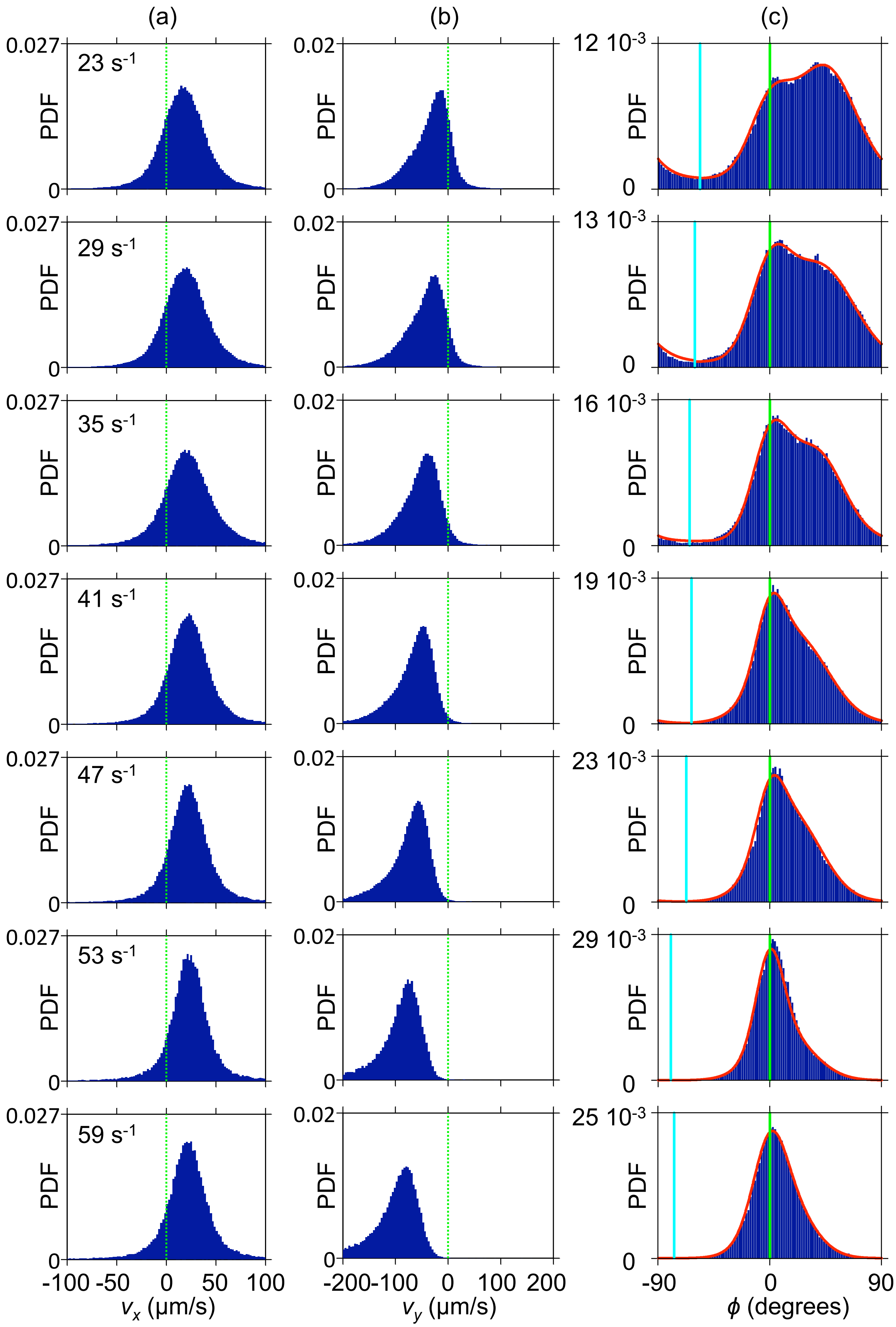
(a)
(b)
(c)
0.1 s-1
0.2 s-1
0.3 s-1
0.4 s-1
0.6 s-1
0.7 s-1
1.0 s-1
PDF
0.027
0.03
7.5 10-3
0
-50 -25 0 25 50
vx (μm/s)
vy (μm/s)
0 90 180
ϕ (degrees)



(a)
(b)
(c)
1.2 s-1
1.5 s-1
1.8 s-1
2.1 s-1
2.3 s-1
2.6 s-1
2.9 s-1
PDF
0.027
0.04
7.5 10-3
9 10-3
11 10-3
0
-50
-25
25
50
90
180
vx (µm/s)
vy (µm/s)
ϕ (degrees)



(a)
(b)
(c)
4.4 s-1
5.9 s-1
7.3 s-1
8.8 s-1
12 s-1
15 s-1
18 s-1
PDF
0.027
0.04
0.03
0.02
9.5 10-3
11 10-3
9 10-3
10 10-3
0
-100 -50 0 50 100
vx (μm/s)
-200 -100 0 100 200
vy (μm/s)
0 90 180
ϕ (degrees)


(a)
(b)
(c)
23 s-1
29 s-1
35 s-1
41 s-1
47 s-1
53 s-1
59 s-1
PDF
0.027
0.02
12 10-3
13 10-3
16 10-3
19 10-3
23 10-3
29 10-3
25 10-3
0
-100 -50 0 50 100
vx (μm/s)
-200-100 0 100 200
vy (μm/s)
-90 0 90
ϕ (degrees)

References

[1] J. E. Hill, O. Kalkanci, J. McMurry, and H. Koser, *Hydrodynamic Surface Interactions Enable Escherichia Coli to seek efficient routes to swim upstream*, Physical Review Letters, 98 (6), 68101 (2007).

[2] T. Kaya, and H. Koser, *Characterization of Hydrodynamic Surface Interactions of Escherichia coli Cell Bodies in Shear Flow*, Physical Review Letters, 103 (13), 138103 (2009).