Surface rheotaxis of three-sphere microrobots with cargo

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Upstream swimming governs bacterial contamination, but also the navigation of microrobots transporting cargo in complex flow environments. We demonstrate how such payloads can be exploited to enhance the motion against flows. Using fully resolved simulations, the hydrodynamic mechanisms are revealed that allow microrobots of different shapes to reorient upstream. Cargo pullers are the fastest at most flow strengths, but pushers feature a non-trivial optimum that can be tuned by their geometry. These results can be used to control navigation and prevent contamination from first principles.

INTRODUCTION

For unicellular microorganisms, motility is an essential feature of life [1]. To overcome or benefit from the fluid drag forces, these microbes have devised numerous swimming strategies [2]. Besides rich collective dynamics [3–5], even for isolated swimmers hydrodynamics can gravely affect microbial life [6, 7], through surface trapping [8], circular motion [9], boundary- [10] and shear-induced accumulation [11, 12] and swimming reorientation [13, 14]. Some microorganisms have also evolved to respond to flows, such as N. scintillans dinoflagellates who exhibit bioluminescence to reduce grazing by predators that generate flows [15] and S. ambiguum ciliates who perform hydrodynamic communication [16]. However, so far only circumstantial evidence exists concerning the behavioural response to flow [17]. It is therefore important to elucidate the inherent hydrodynamic mechanisms at play in microbiology.

In a bulk shear flow, one of the sources for the complex behaviour is the geometry of the cells. Classical Jeffery orbits [18] of elongated particles also apply swimmer dynamics [19], as seen in experiments with E. coli bacteria [20]. The chirality of their flagella was also shown to induce cross-streamline migration [21–23]. Interestingly, a rheotactic response leading to upstream swimming in bulk flows can also arise from viscoelasticity [24].

Conversely, surfaces are known to alter hydrodynamic interactions in their vicinity, thus affecting the shear response significantly even for rigid particles [25]. Surfaces may enhance rheotaxis by providing a strong environmental coupling in which swimmers react to an external shear flow by orienting upstream. In particular, shear has been argued to aid navigation in mammalian sperm cells [26–28], and govern the contamination dynamics of bacteria in channel flows [29–31]. The dominant mechanism behind this upstream reorientation, termed the ‘weathervane effect’, relies on the anisotropic and distance-dependent drag forces of the swimmer close to the surface. Far from walls this effect vanishes, which was also confirmed numerically [32, 33]. Even though this mechanism of surface rheotaxis is fairly understood, studies that couple this knowledge with other effects like confined Jeffery orbits, hydrodynamic wall attraction and chirality still lead to new discoveries like oscillatory rheotaxis [34] and long-tailed distributions of run–tumble dynamics that can cause ‘super-contamination’ [35].

Understanding the influence of flow on microorganism behaviour has opened the exploration of artificial rheotaxis, using synthetic nanoparticles and micro-robots. For these, upstream swimming in response to shear was also observed in a variety of contexts and for different propulsion mechanisms, including chemical and acoustic effects [36], photocatalytic autophoretic systems of colloidal rollers [37] and rod-shaped Janus particles [38, 39]. A generic swimming mechanism for natural swimmers involving elastohydrodynamic coupling is also strongly related to the dynamics of the environment and flow conditions [40].

In this contribution, we explore the transport of cargo by a simple model Najafi-Golestanian swimmer [41, 42] in an external shear flow close to a planar boundary, where one sphere is larger to hold the payload. Depending on the swimming mechanism (cargo pusher or puller), we observe different reorientation mechanisms that all lead to a positive rheotactic response. Hence, after reorienting upstream, the full three-dimensional dynamics reduce to a two-dimensional motion in the shear plane. This allows us to quantify the swimmer dynamics in a phase space spanned by the wall-separation distance and the head orientation. By analysing the fixed points in these phase diagrams we identify the rheotactic states, and their stability for the different swimmer geometries. Finally, we map out the upstream migration speed as a function of imposed shear rate, and find that pushers and pullers perform optimally in completely different external flow conditions.
Figure 1. **Surface rheotaxis in three dimensions.** (a). Diagram of a three-sphere swimmer in shear flow near a surface. Shown is a pusher, with the large sphere at the front. (b). Geometry of cargo pushers and pullers. (c,d). Swimming trajectories of (c) pullers and (d) pushers at various initial orientations $\phi_0$. The swimmers are initially released from $z_0 = 1$ and parallel to the surface, $\theta_0 = \pi/2$. (e,f). 3D trajectories at various shear rates. The swimmers are again released from $z_0 = 1$ with orientations $\phi_0 = \theta_0 = \pi/2$.

**MODEL**

We consider the dynamics of a Najafi-Golestanian swimmer [41, 43] near a planar no-slip boundary subject to an externally applied shear flow [Fig. 1a]. Throughout the paper, all quantities are non-dimensionalised by scaling lengths with the mean swimmer arm length, $L$, and velocities are scaled by the inverse of the free swimming speed in the absence of flow and boundaries, $V_0$. The total mean length of the swimmer is thus $2L$. The surface is located at $z = 0$ in Cartesian coordinates, and the flow is given by $\mathbf{u} = \hat{\gamma} z \hat{x}$ in terms of the shear rate $\hat{\gamma}$. So, for clarity, the dimensional shear rate is $\gamma^* = \hat{\gamma} V_0 / L$. The swimmer is neutrally buoyant, and is composed of three spheres joined by thin arms, all aligned along the swimming direction, $\hat{t}$. The arm lengths oscillate with frequency $\omega$, respectively, at an angle $\pi/2$ out of phase.

We consider both cargo-pushing swimmers with a larger sphere at the front, and pullers with a cargo at the back [Fig. 1b]. The hydrodynamic signature, the far-field flow generated by such a three-sphere cargo pusher (puller) corresponds to an extensile (contractile) Stokes dipole [44–46]. The radius of the two smaller spheres is $a = 0.1$ and the larger sphere has radius $a_+ = 0.12$.

The swimming dynamics are found by solving for the hydrodynamic interactions between the spheres and the wall, including the external shear flow [see Supporting Information (SI)]. We use the Rotne-Prager-Yamakawa approximation to account for the different-sized particles at low Reynolds numbers [47]. We also treat hydrodynamic interactions between the spheres and the wall [48], and the external flow, with the same level of accuracy using a shear disturbance tensor formalism. Hence, the generalised mobility tensor is constructed that relates the translational and rotational velocities of each sphere to the hydrodynamic forces and torques. By enforcing that the total external force and torque vanish, and by prescribing an oscillating distance between the three spheres as usual, the swimming motion is uniquely solved.

**UPSTREAM SWIMMING DYNAMICS**

The three-dimensional dynamics of these pullers and pushers are first described for different initial orientations $t_0$ parallel to the surface [Fig. 1c,d]. Indeed, we observe that all swimmers will eventually align with the shear plane, such that the component $\hat{t} \cdot \hat{y} \rightarrow 0$, for both swimmer types [also see Supplementary Videos S1, S2]. This alignment also occurs for different shear rates [Fig. 1e,f]. As expected, stronger flows will reorient the swimmers more quickly. Of course, at very strong shear the swimming speed no longer exceeds the local flow strength, leading to downstream advection [Videos S3, S4], but the swimmers can still be oriented upstream.

As a result of this alignment with the shear plane, the 3D trajectories reduce to two dimensions over time. This is true in all tested cases, regardless of initial conditions, shear rate or swimmer type, as long as the swimmers come close enough to interact hydrodynamically with the surface. Then, the orientation of the swimmer in the shear plane is given by the pitch angle, $\theta \in (-\pi, \pi]$, where negative (positive) values indicate upstream (downstream) orientations. Still, the mechanism of rheotaxis is not trivial. Both pullers and pushers tend to swim upstream at weak flows, but they do so in a completely different fashion.

On the one hand, we describe the rheotaxis of pullers at low shear, as shown in the Videos S5–S6 in the laboratory frame and the co-moving frame, respectively. The three-sphere pullers tend to swim almost parallel to the surface, $\theta \lesssim -\pi/2$, with the director $\hat{t}$ slightly pointing towards the surface. Hence, the back sphere with the larger radius tends to stick out into the liquid where the flow gets stronger for larger $z$ values, so the puller can rotate against the flow. This reorientation is referred to as the ‘weathervane effect’, as described for example in Refs. [29, 34]. The pullers tend to align with the shear plane rather slowly, taking tens to hundreds of oscillation periods.
Figure 2. **Phase-space diagrams of upstream swimming**, showing the dynamics in \((\theta, z)\) space for various flow strengths. Grey lines are streamlines in this phase space, coloured lines show example trajectories, and the background colours indicate the final state for each initial condition. Insets illustrate the corresponding final-state behaviours, as observed in real space, where blue arrows on the axis of the swimmer indicate its orientation \(\hat{t}\) and the black arrows above show the overall (lab frame) direction of motion, the sum of advection and self-propulsion. (a). Pullers at \(\dot{\gamma} = 1/3\). Red indicates that the swimmer ends up swimming upstream, parallel to the surface. Blue is moving downstream, parallel to the surface. (b). Pullers at \(\dot{\gamma} = 2\). Green indicates that the final state is moving downstream, but oriented upstream and parallel to the surface. Blue as before. (c). Pushers at \(\dot{\gamma} = 1/3\). Brown shows that all swimmers move upstream, oriented almost perpendicular to the surface. The orange star indicates the final fixed point. (d). Pushers at \(\dot{\gamma} = 1\). Cyan shows that all swimmers are advected downstream, following an indefinite toppling motion detached from the surface. The white arc-like regions are inaccessible due to the swimmer shape.

On the other hand, we describe the pusher dynamics at low shear, as shown in the Videos S7-S8. The three-sphere pushers tend to swim almost perpendicular to the surface, \(\theta \gtrsim -\pi\), with the director \(\hat{t}\) slightly pointing upstream. While the front sphere almost touches the surface, the back sphere sticks out into the flow so it gets advected downstream, leading to an upstream orientation. Because the tail of the perpendicular pusher sticks out much further than the parallel puller, the ‘weather-vane effect’ is stronger, so the pushers have a much faster reorientation rate and only require a few three-sphere oscillations to turn upstream. Rather than a burden, the cargo can therefore also be exploited to enhance rheotaxis. This fundamental difference in the steady-state orientation also affects the velocity at which the two swimmer types can move against the flow. This is described in detail below, when we discuss the fixed point analysis.

**SWIMMING STATE DIAGRAMS**

Until now we have described the upstream motion at low shear, which is already fairly complex, but more intricate dynamics emerge at stronger flows. We aim to quantify this systematically for different shear rates and initial conditions. Because the 3D dynamics reduce to 2D over time, we can cast them into a dynamical system where the relevant variables are the pitch angle, \(\theta\), and the position of the central sphere, \(z\). Figure 2 shows the evolution of these dynamics in \((\theta, z)\) phase-space diagrams, where the top row shows the behaviours for pullers and the bottom row for pushers. The steady-state swimming behaviours correspond to stable fixed points in these phase portraits, which change for different flow rates.

At weak flows, at \(\dot{\gamma} = 1/3\), [Fig. 2(a)], the pullers mostly tend to swim upstream parallel to the surface (red), a stable fixed point around \((-7/6, 1/2)\), in agreement with the observations in Fig. 1. A small fraction of initial conditions also leads to downstream swimming parallel to the surface (blue), a stable fixed point around \((5/6, 1/2)\). The phase portraits corresponding to \(\dot{\gamma} = 2/3\) and \(\dot{\gamma} = 1\) are essentially the same as panel (a). At strong flows, at \(\dot{\gamma} = 2\), [Fig. 2(b)], almost all pullers are first advected downstream during a transient ‘toppling’ motion. However, over time they will end up in a stable state on the surface, oriented upstream. If the external flow is stronger than the self-propulsion, this leads to downstream advection in the upstream orientation (green). The transition of the final state from moving upstream (red) to downstream (green) occurs at \(\dot{\gamma} \approx 1.33\), as discussed below.

The pushers show very different dynamics, because the two fixed points around \((\pm \pi/2, 1/2)\), of orientations parallel to the surface, are both unstable. Instead, at \(\dot{\gamma} = 1/3\), [Fig. 2(c)], the pushers tend to orient themselves almost normal to the wall (brown), but still a little directed upstream. This corresponds to a fixed point...
Figure 3. Rheotactic performance. We compare (a) pullers and (b) pushers, as a function of applied shear rate. Shown are the swimmer velocity $V_x(\dot{\gamma})$ in blue squares, where negative values indicate upstream swimming, the pitch angle $\theta(\dot{\gamma})$ in green open circles, and the position of the central sphere $z(\dot{\gamma})$ in green filled circles. Note the different axes.

around $(-0.8\pi, 0.9)$, which is marked with an orange star. Regardless of the initial conditions, all pushers end in this state, for all cases tested. As the flow strength grows, the phase portraits corresponding to $\dot{\gamma} = 0.4$ and $\dot{\gamma} = 0.5$ remain essentially the same as panel (c). At even larger shear rates, however, at $\dot{\gamma} = 1$, [Fig. 2(d)], the orange star fixed point also becomes unstable, so the pushers tend to detach from the wall and topple downstream indefinitely (cyan). These are the arc-like trajectories depicted in Fig. 1(f).

FIXED POINT ANALYSIS

Having identified the stable fixed points of the phase diagrams, we can determine the properties of these steady-state swimming modes as a function of shear rate. In particular, we compute the velocity component $V_x(\dot{\gamma})$, which is negative for upstream swimming, the pitch angle $\theta(\dot{\gamma})$, and the vertical position $z(\dot{\gamma})$. These quantities evolve very differently for pushers and pullers.

Pullers in weak flows can move upstream very fast, $V_x \approx -V_0$, almost their free swimming speed [Fig. 3(a)]. As the shear rate increases, $V_x$ increases linearly [blue line]. This trend is also enhanced because the vertical position gradually increases [green line], exposing the swimmer to more flow. Therefore, the upstream swimming velocity tends to zero around $\dot{\gamma}_0 \approx 1.35$. At higher shear the pullers are still oriented upstream, but they are advected downstream.

Surprisingly, the pushers show the opposite behaviour [Fig. 3(b)]. Their vertical position decreases with shear rate [filled circles], and the pitch angle changes from swimming perpendicular to parallel to the surface [open circles], so the swimmer is less exposed. As a result, $V_x$ is almost zero in weak flows, but it decreases with shear rate, leading to faster upstream motion. Moreover, around $\dot{\gamma}_c \approx 0.38$ there is a sharp transition. The vertical position suddenly drops even further, so the upstream swimming speed also jumps up to $-V_x/V_0 \approx 0.8$. At higher shear it stays relatively constant, until the pushers detach due to the toppling instability. The critical shear rate at which this occurs is $\dot{\gamma}_t \approx 0.56$.

DISCUSSION

In summary, the rheotactic performance can be enhanced by exploiting the cargo, by tuning the swimmer geometry for a given shear rate. Indeed, both cargo pushers and pullers tend to swim upstream near surfaces, but in a very different manner. Pullers move almost parallel to the wall, so they are less susceptible to flow. As a result, they take longer to reorient against the flow, but their upstream swimming speed is generally large. This speed decreases in strong currents, but even when detached they tend to return to the surface and move upstream. Pushers, however, move almost perpendicular to the wall, so they are more susceptible to currents. Consequently, they can reorient against the flow much faster, but their upstream swimming speed is poor at low shear. Interestingly, this speed dramatically improves at intermediate shear, to an extend that the pushers will actually outperform the pullers. But in even stronger flows the pushers will detach from the wall and are washed downstream. Thus, each cargo configuration has its own advantages, which may be optimised for different applications. For example, if the swimmer were to be used to transport cargo [49] upstream in fluctuating flow environments, it may be beneficial to use a puller for its robustness, while in strong but stable flows a pusher can be more expedient.

When comparing our work with related literature, some important insights are revealed. For autophoretic Janus (Au/Pt) nanorods, the pullers assume a larger tilt angle compared to pushers and they reorient faster against the flow [38], while we see that the opposite is true for three-sphere swimmers. Therefore, the far-field hydrodynamic signature (dipole moment) is not a good classifier of surface rheotaxis, and near-field flows must be considered. For spherical squirmers [32], the pullers ($B_2/B_1 > 0$) also feature two stable fixed points facing upstream and downstream, both almost parallel to the surface, but unlike three-sphere swimmers the majority of initial conditions leads to escape from the surface or downstream motion. Also spherical catalytic Janus particles can move upstream near surfaces [37], where high coverage by catalyst results in orientations almost perpendicular to the wall and a half catalyst coverage results in motion almost parallel to the wall [32]. These pitch angles may be observed in holography experiments [50].

A natural extension of our work would be to include effects of chirality, as observed in the dynamics of spermatozoa [26, 27] or bacterial flagella [27]. This chirality induces an additional torque that leads to circular mo-
tion in the absence of flow [9], but in flows it can lead to different dynamical regimes separated by critical shear rates [34]. The universality of these predictions could be tested with three-sphere swimmers by introducing a counter-rotation to the head and tail spheres. Moreover, navigation strategies for complex flow environments may be designed by tuning the swimmer shape and stroke.

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