Shear-Induced Oscillations and Hydrodynamic Buffering Stabilize Sperm Surface Navigation

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Extended Abstract

Motivation. Navigation in dynamic fluid environments is central to active matter physics and reproductive biology. For mammalian sperm, rheotaxis is a primary guidance cue, as chemical and thermal gradients are often unstable in vivo. However, existing models largely overlook physiologically relevant high-shear conditions found in the female reproductive tract[1]. This study addresses a critical question: how do sperm maintain proximity to fertilization sites without being washed away by strong flows? Answering this is vital for deciphering the physical mechanisms of fertility and designing artificial microswimmers.

Approach and Methodology. To explore this dynamism, we combined high-resolution microscopy with microfluidics to mimic physiological shear. Tracking bovine sperm near boundaries and the distribution along y-axis across flow rates(Figure 1), we complemented experiments with a first-principles model. This framework integrates: (1) dipolar hydrodynamics, (2) shear-induced rotation (Jeffery orbits), and (3) steric repulsion[2]. Notably, sperm-wall collisions used a phenomenological parameter, calibrated to reflect the effective mechanical response. Simulations recapitulated surface retention, demonstrating that hydrodynamic, steric, and fluidic interactions collectively explain the phenomenon, independent of complex biochemical signaling.

Results. Our key finding is the identification of Near-Surface Oscillation (NSO), a distinct dynamical mode bridging stable rheotaxis and bulk tumbling. This phenomenon is robustly observed in experiments (Figure 1). Unlike bacteria or active colloids dispersed by strong flows, sperm maintain wall proximity even at high shear rates. We observed a nonmonotonic alignment response to flow intensity; alignment improves with shear but yields to oscillatory instabilities beyond a critical threshold. Our simulations elucidate this transition pathway, revealing six distinct dynamical states (Figure 2a,b), which arise with a hydrodynamic buffer zone where Jeffery orbit destabilization is counterbalanced by steric collisions and dipolar attraction, effectively preventing washout(Figure 2c,d).

Conclusions and Outlook. We conclude that sperm navigation in high-shear environments is mechanically robust, relying on a physical "buffer zone" rather than explicit sensory feedback to avoid washout. This mechanism ensures sperm remain within the boundary layer where flow velocities are lower and surface guidance cues are available, thereby maximizing fertilization probability. By the time of the conference, we plan to complete in-depth studies on individual sperm motility and collective dynamics under precisely controlled flow field conditions. Additionally, we intend to extend this research framework to investigate the mechanisms of collective motion regulation in dense sperm suspensions.

References

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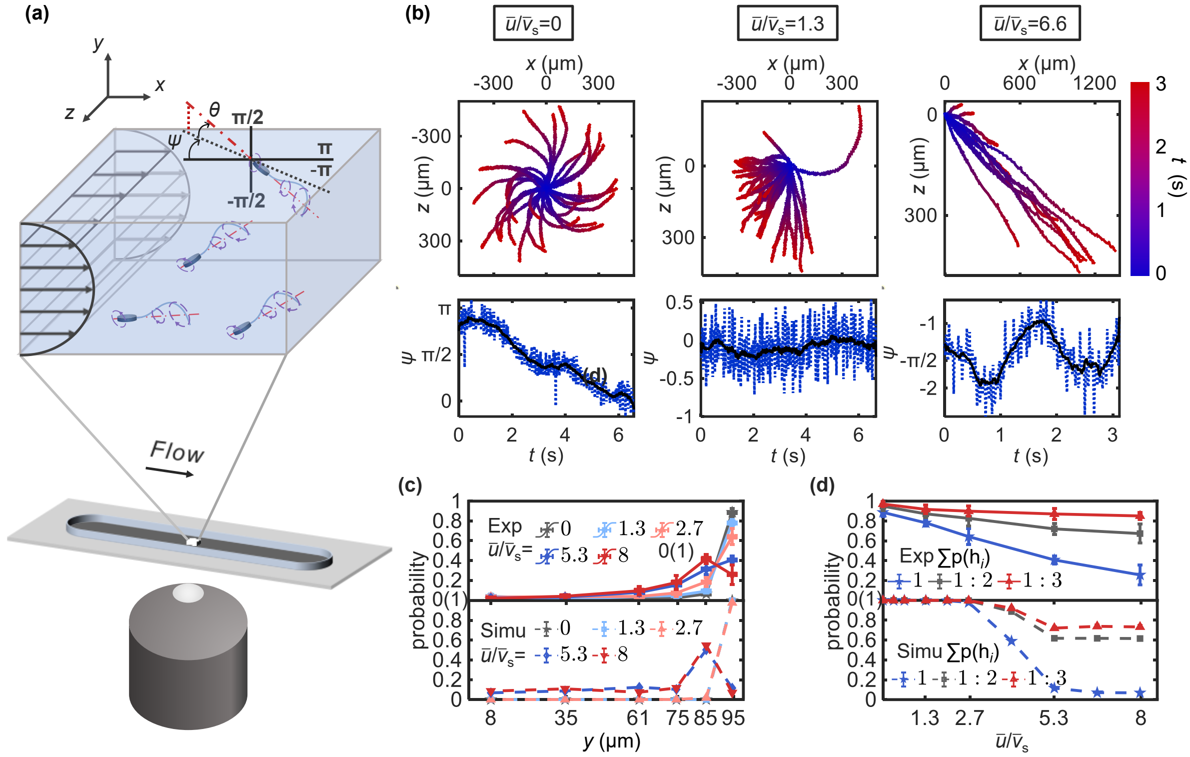

Figure 1. Flow-dependent motility and distributions. (a) Coordinate system and motion parameters. (b) Typical trajectories at three flow intensities. (c) Normalized sperm distribution at six wall-normal positions. (d) Cumulative near-surface probability vs. flow intensity (errors: SEM).

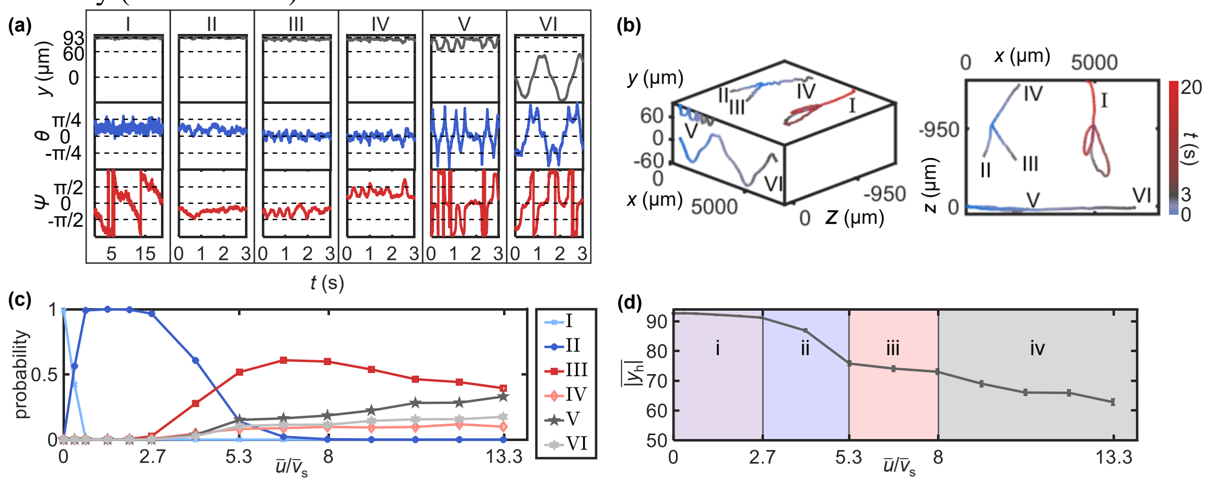

Fig. 2. Classification and statistics of simulated sperm motility modes. (a)Six patterns: (I) Circular swimming (CSS, no flow); (II) Rheotaxis (RS, low flow); (III, IV) Near-surface oscillations (LNSO/RNSO, high flow); (V, VI) Bulk flow oscillations (OC-BFO/CC-BFO, very high flow). (b) 3D trajectories and x–z projections. (c) Mode probability vs. flow. (d) Mean absolute y-coordinate ($\overline{|y_h|}$) vs. flow.