

Bacterial strategies for navigating surface constraints

Keywords: E. coli, tumble bias, motion behaviors, surface residence, transport

Extended Abstract

Motivation. In natural environments, solid surfaces present both opportunities and challenges for bacteria. On one hand, they serve as platforms for biofilm formation, crucial for bacterial colonization and resilience in harsh conditions [1]. On the other hand, surfaces can entrap self-propelled bacteria for extended periods and force them to swim along circular trajectories, constraining their environmental exploration compared to the freedom they experience in the bulk liquid [2]. This raises the question of how self-propelled bacteria modulate motion behaviors to balance the opportunities and challenges of surfaces during their evolution. Answering this scientific question will help reveal the adaptive survival strategies and evolutionary directions of microorganisms, providing deeper insights into understanding the interactions between life and the environment.

Approach and Methodology. We quantified the run-and-tumble behaviors and the duration *E. coli* cells spend on surfaces (surface residence time) using dual-optical trapping (Figure 1) combined with a novel 3D tracking technique. These key experimental techniques enable high-precision measurement of bacterial motion behaviors near solid surfaces at the single-cell level.

Results. Through systematic single-cell behavioral measurements, phenomenological modeling, and theoretical analysis, we revealed how *E. coli* strategically navigate surface constraints. It is observed that bacterial surface residence time decreases sharply with increasing tumble bias from zero, transitioning to a plateau at the mean tumble bias of wild-type *E. coli*. Furthermore, it is found that bacterial surface diffusivity peaks near this mean tumble bias (Figure 2). Considering the phenotypic variation in bacterial tumble bias, which is primarily induced by noise in gene expression, this reflects a strategy for bacterial offspring persistence: In the absence of stimulus cues, some bacteria swiftly escape from the nearby surface in case it lacks nutrients, while others, with longer surface residence times, explore this 2D environment most efficiently to find potential livable sites. These findings answer the question of how *E. coli* modulates motion behaviors to navigate surface constraints, thereby maximizing its offspring persistence in uniform environments.

Conclusions and Outlook. In conclusion, we reveal the significance of bacterial adjustment of tumble bias in uniform environments—to balance their surface residence and escape, and optimize 2D transport. Bacteria employ diverse motion patterns in response to their interactions with surfaces, suggesting that many survival mechanisms likely remain to be discovered in future studies.

References

- [1] Reference 1 Sauer, K. et al. The biofilm life cycle: expanding the conceptual model of biofilm formation. (2022), Nat. Rev. Microbiol. 20, pp. 608–620.

[2] Reference 2 Lauga, E. Bacterial hydrodynamics. (2016) Annu. Rev. Fluid Mech. 48, pp. 105–130.

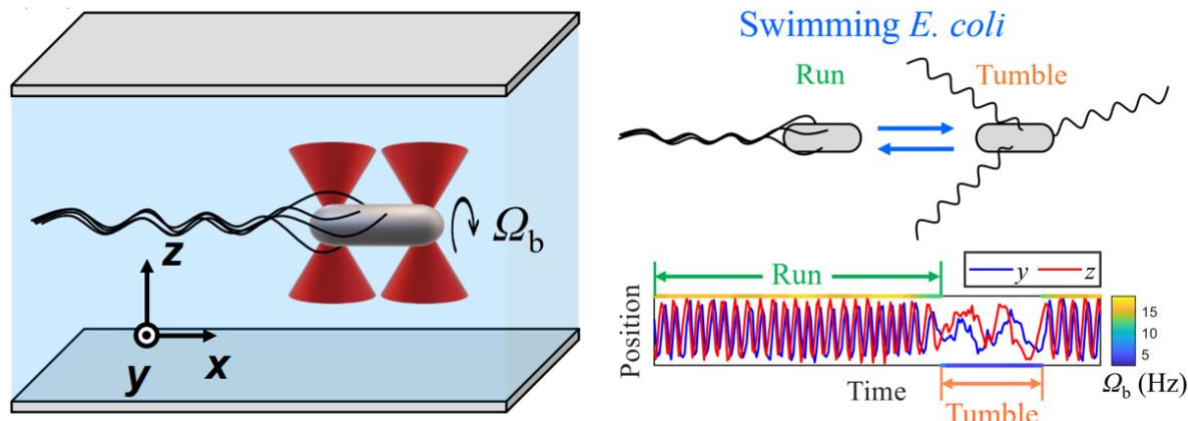


Figure 1. **Illustration of run-and-tumble determination using optical trap signals.** The motion of trapped cell poles is recorded as position signals. The cell body's wobble (or rotating) frequency Ω_b (color bar) is derived from the signals and used to differentiate between runs (oscillatory, high frequency) and tumbles (erratic, low frequency).

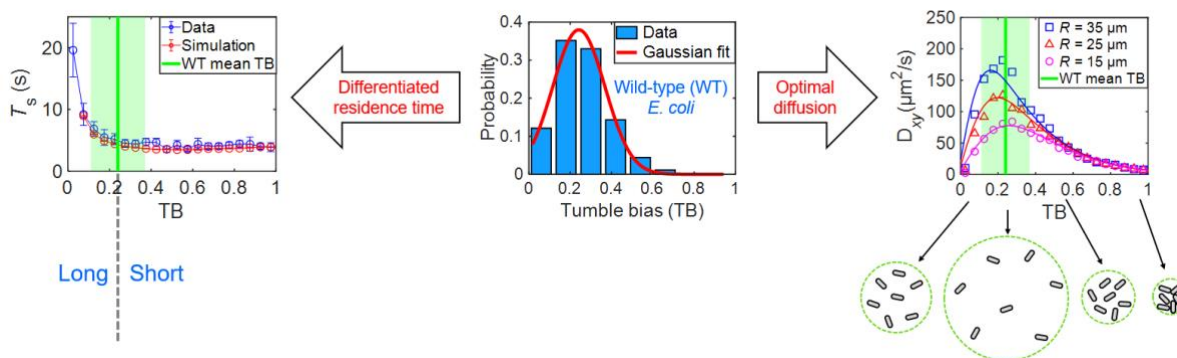


Figure 2. **Significance of bacterial tumble bias in uniform environments.** Without stimulus cues, bacteria cannot determine whether solid surfaces contain livable sites. Under these conditions, some bacteria (with large TB) can swiftly escape from nearby surfaces to regain greater freedom of movement in bulk liquid if the surface lacks nutrients. Meanwhile, for those that spend more time on the surface (with smaller TB), they perform the most efficient 2D exploration, which increases the chances of finding randomly distributed food patches. For the right panel, scattered markers denote values from simulation, and solid curves represent the theoretical relationships.

Note: This study has been published. <https://doi.org/10.1002/advs.202502063>. I would be honored to have the opportunity to present my findings and engage in academic discussions with fellow researchers in this high-level academic conference.