5 Broader impacts

The long-term broader impacts of this work are that a better understanding of swimming microorganisms in liquid-crystals will lead to a deeper understanding of swimmers in more realistic environments, and also possibly lead to novel means of manipulating small particles. The immediate broader impacts of this program will be the training of graduate students and participation in outreach and recruitment activities. Other broader impacts will be the dissemination of the results of this work to the broader scientific community through papers, conferences, workshops, and summer schools. Examples of my leadership in this area are discussed in section 6.2.

At Brown, I will participate in the *Research Experiences for Teachers* program which invites K-12 teachers from local schools to the Brown campus to participate in laboratory research and course development projects during the summer. I will also participate in the *Brown University Summer High School program*, giving presentations, demonstrations and leading discussions on the physics of locomotion and liquid crystals. I has previously participated in both of these programs. In a new effort, I will also contribute lectures and lead discussions with students in the *Providence After School Alliance (PASA)*—a local organization that provides expanded learning opportunities to high-school students through science-oriented programs.

The topics of this proposal will also be woven into a wide variety of educational material taught at both Brown. For example, at Brown, in ENGN 0040, "Introduction to Dynamics and Vibrations", 170 freshman engineering students are introduced to the strange inertia-less world of swimming microorganisms via Taylor's classic demonstration of the kinematic reversibility of highly viscous flow. I have also introduced new graduate/undergraduate courses at Brown University related to the topics of this proposal, such as PHYS 2610E "Selected topics in physics of locomotion" and ENGN 2912F "Soft Matter."

6 Summary of prior NSF support

I was the PI of a recently completed collaborative NSF award with co-PI's K. Breuer (Brown University) and A. Kudrolli (Clark University): CBET-0853942 "Collaborative Research: Fundamental Principles of Swimming in Viscoelastic Media," 09/1/09–08/31/2013, $525,000. This award is the one most closely related to the current proposal, and is reported on below. I was also recently supported by award NSF-CBET grant No. 0966000 ["Collaborative Research: Chiral Objects in Microfluidic Shear Flows: Chiral Separation and Microbial Locomotion," $21,617 10/1/10–9/30/13, PI R. Stocker (MIT) and co-PI H. Fu (University of Nevada, Reno)], an effort that deals in part with swimming microorganisms, but focuses on shear flow and trajectories of swimming bacteria in water, themes which bear on the the current proposed work [103, 104], but do not involve liquid crystals. I have also received prior support (DMS grant No. 0615919, "Mathematical models for swimming in a viscoelastic fluid," $314,104, Powers, 9/1/06–8/31/09) . This support led to multiple publications [15,53,54,105–108] related to important advances in the treatment and understanding of the hydrodynamics of swimming microorganism. The PI's work on two-dimensional liquid crystals on curved surfaces is also of note for this proposal [109].

6.1 Intellectual Merit for CBET-0853942

This award supported a concerted theoretical, experimental, and computational investigation of swimming in viscoelastic media. An important result of the prior NSF result is a review article on the hydrodynamics of swimming microorganisms [1]. The award also supported theoretical work on swimming in gels [110] which showed how viscous and elastic stresses affect swimming speed in the presence of a cross-linked polymer network. A key advance from this award was the elucidation of the effects of a polymeric solution on swimming speed.

Theoretical calculations with small-amplitude sinusoidal or helical waves showed that the viscoelasticity of a polymer solution slows a swimmer [52–54], whereas numerical calculations showed that viscoelasticity can make a finite-length swimmer with large-amplitude deformations go faster [58]. We measured the swimming speed of a rotating helix in a polymer solution and found for the geometries we tested that viscoelasticity can enhance swimming speed [61]. A by-product of this work was the development of a novel boundary-element code based on helical symmetry that we used to validate our experiment in the Newtonian (viscous) regime [111]. We also developed numerical calculations to show that that the whether or not viscoelastic effects enhanced swimming speed depends on the amplitude of the helix [59], thereby showing that the theoretical and numerical results were not in contradiction (Fig. 6).

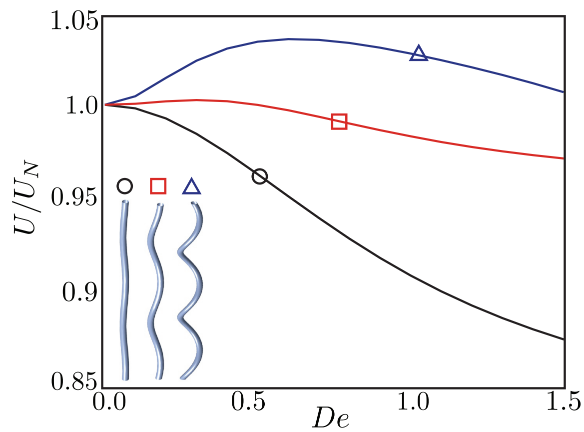

Figure 6: *Results of numerical calculations for the ratio of swimming speed in a polymeric liquid to swimming speed in a Newtonian liquid verse Deborah number. The Deborah number De is the product of the rotation frequency and the relaxation time of the polymer. Swimming speed decreases with De for small-amplitude helices (open circle), but can have a peak when the rotation period is comparable to the relaxation time (triangle). Figure from reference [59].*

6.2 Broader impacts for CBET-0853942

The support of the NSF in these studies has lead to multiple publications many of which have had significant impact on the research community. Of particular relevance to this proposal is the PI's review article with Eric Lauga entitled "The hydrodynamics of swimming microorganisms" [1], which was solicited by *Reports on Progress in Physics* and has had a significant impact, being cited over 400 times in the four years since its publication, according to *Google Scholar*. The PI has led scientific outreach in this research field. The PI was a co-organizer for a minisymposium entitled "Complex material properties in biological locomotion," at the SIAM Conference on Mathematical Aspects of Materials Science, held in Philadelphia in 2010, was co-organizer for the 2011 Aspen Center for Physics Winter Conference, "Physical micro-environments modulating biological interactions in the ocean," and was co-organizer for the minisymposium, "Hydrodynamics and microstructure: from single self-propelled particles to active soft matter" at the 2012 APS March Meeting in Boston.

The extended NSF support to the PI has also resulted in the training of multiple scholars at every level, ranging from undergraduate students who have gone onto graduate study (e.g. Jacy Bird, currently an Assistant Professor of Mechanical Engineering at Boston University; David Gagnon, currently a graduate student in Mechanical Engineering at the University of Pennsylvania), to graduate students (e.g. Hongyuang Jiang, Professor in the Department of Modern Mechanics at UST in Hefei, Anhui) and postdoctoral scholars (e.g. Henry Fu, Assistant Professor of Mechanical Engineering at the University of Nevada, Saverio Spagnolie, Assistant Professor of Mathematics at University of Wisconsin, T. Kuriabova, Lecturer in Physics at California Polytechnic State University at San Luis Obispo). Finally, the PI has participated in outreach to K-12 teachers and students through the programs described in Section 5.