Numerical Study of Millimeter-Scale Magnetorheological Elastomer Robot for Undulatory Swimming

C. Wu[1], X. Fan[1], Y. Song[1]* & Q. Zheng[1]*

1. Department of Polymer Science and Engineering, Zhejiang University, Hangzhou 310027, China

INTRODUCTION: Untethered small-scale robots inspired by microorganisms evolved have greatly attracted attention from scientists and engineers to non-invasively access and navigate in limited accessible environments to perform therapeutic and diagnostic operations.[1-3] However, these soft robots actuated by distributed torques cannot be simulated in many commercial finite-element software.[4,5]

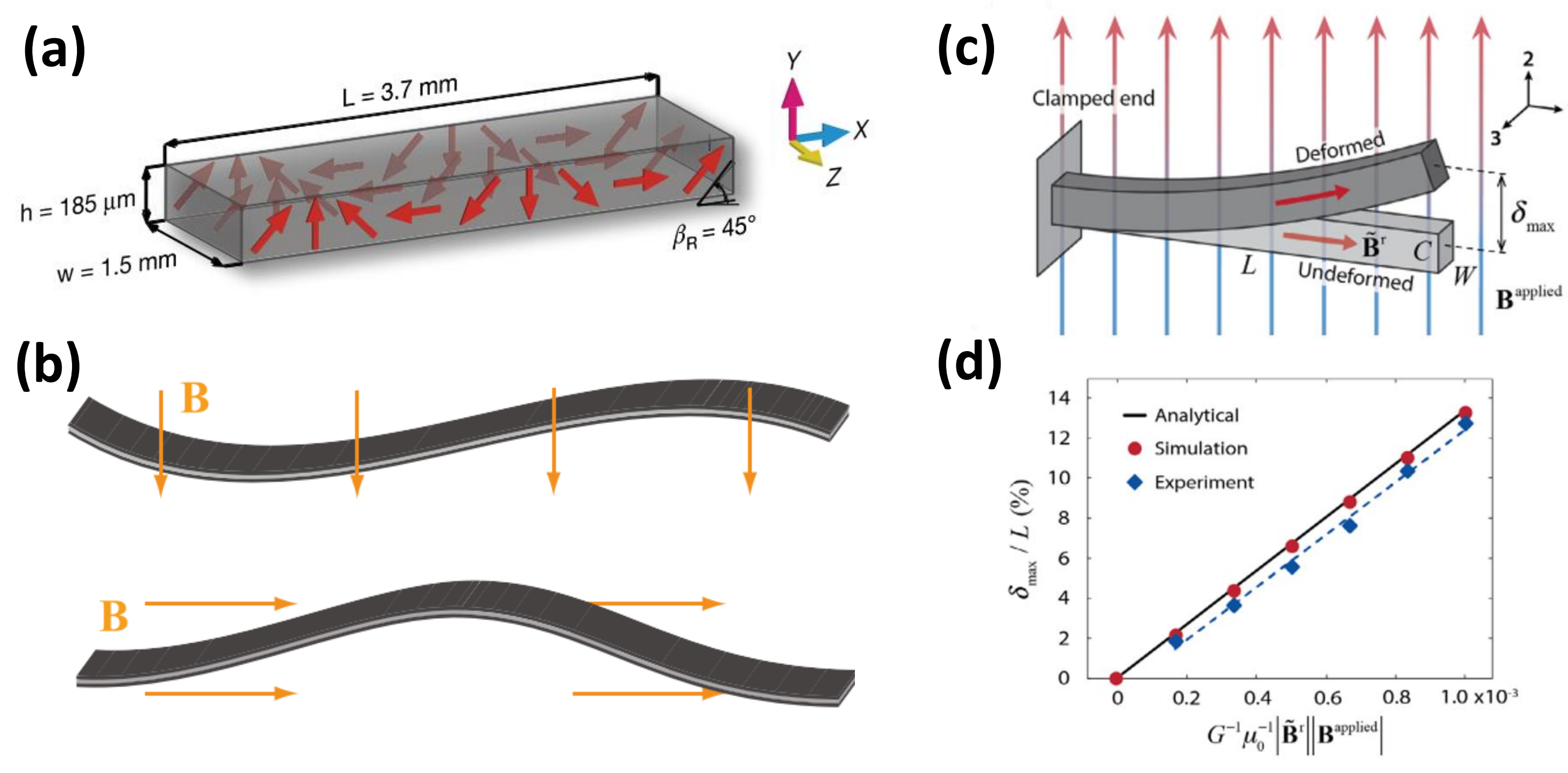

Figure 1. Magnetization of soft robot (a). Deformation of soft robot under a magnetic field (b). Deflection of magnetic soft beam (c). Comparison of simulated, analytical, and experimental results (d).

COMPUTATIONAL METHODS: The robot is divided into several equivalent elements whereby the distributed magnetic body torques are replaced by a summing magnetic torque realized by two opposite and tangential surface forces (Unit: N/m^2) with respect to boundary frame, as shown in Fig. 2. Tangential surface force magnitude in a certain element (F_i) is expressed as

$$F_i = M_x^i B_y - M_y^i B_x$$

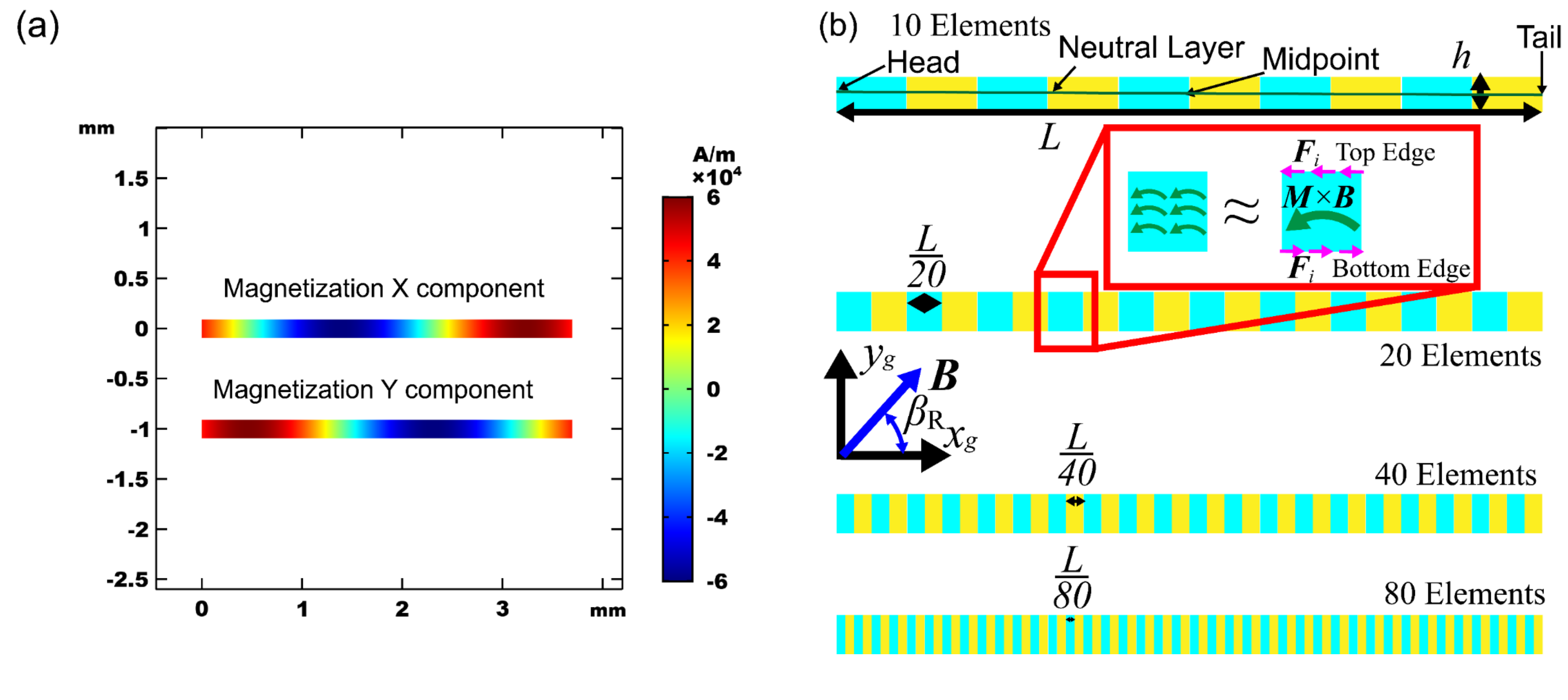

Figure 2. Magnetization profile of small-scale robots (a). The Y component profile is shifted by -1 unit for clear display. Millimeter-scale robots composed of equivalent ten, twenty, forty, and eighty elements where magnetic body torques are taken the place by a summing magnetic torque realized by two equivalent opposite tangential surface forces (b).

RESULTS: For the robot with 3.7 mm in length, approximate discrepancies of 30% are observed between simulated swimming speed (V_{swim}) and that predicted by Taylor's model under varied field strength, as illustrated in Fig 3(a). At the length of 1.85 mm, the simulated V_{swim} even reduces to approximately one-third of V_{swim} predicted by Taylor's model, as shown in Fig 3(b). The prediction of the theoretical swimming gait function shows great consistency with simulated results, However, Taylor's model is nearly invalid to describe the swimming gaits of the robot, as shown in Fig. 4.

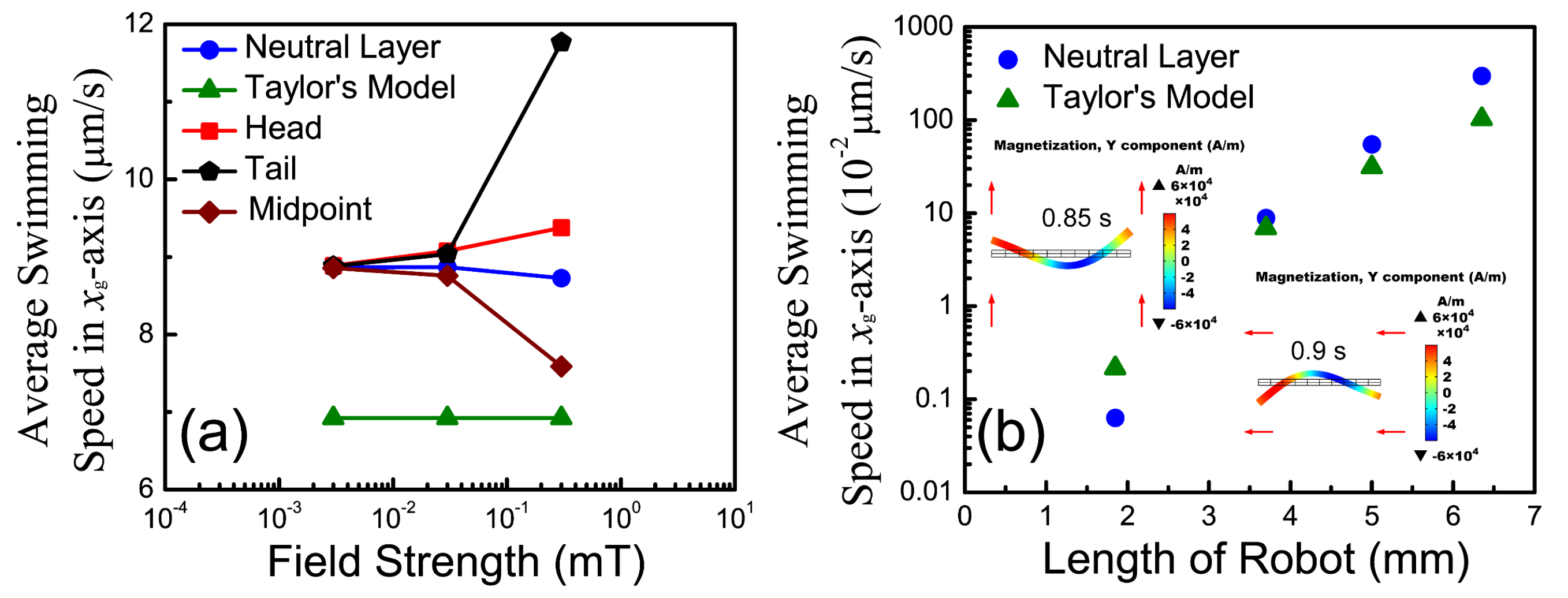

Figure 3. Average swimming speed of the ten-element robot of L = 3.7 mm under varied magnetic field strength (a) and at B = 0.03 mT with various lengths (b). The rotating frequency is 5 Hz. The results obtained from 0.003 mT and 0.03 mT times 10000 and 100, respectively, for clear display. The illustrations show the deformation and Y magnetization of the robot, and the background magnetic field at 0.85 s and 0.9 s.

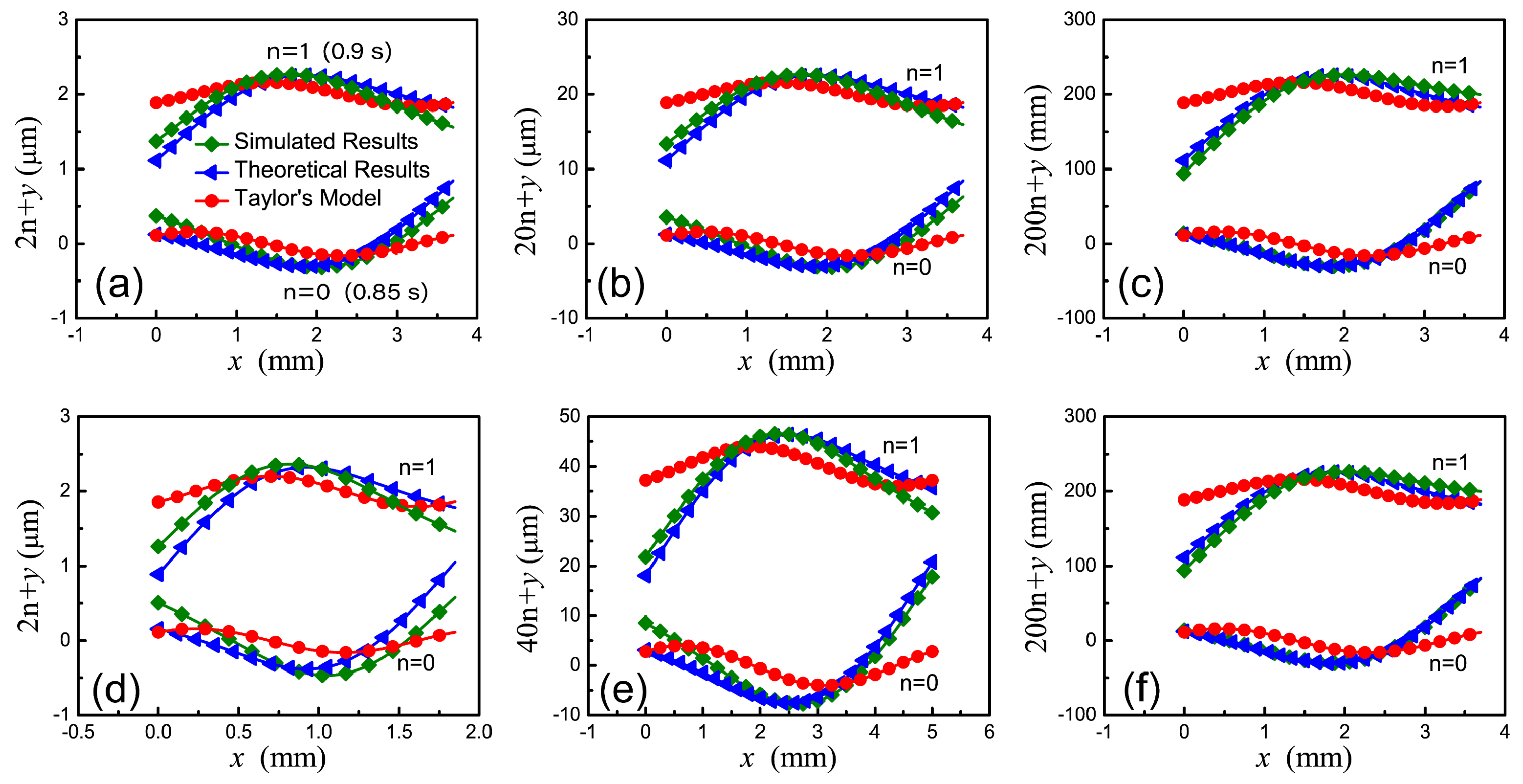

Figure 4. Swimming gaits of the robot of 3.7 mm (a, b, c), 1.85 mm (d), 5 mm (e), and 6.35 mm (f) in length at 0.85 s (n=0) and 0.90 s (n=1) under the field strength of 0.003 mT (a), 0.03 mT (b,d,e,f), and 0.3 mT (c) with a rotating frequency of 5 Hz. The results at 0.90 s are shifted along the vertical axis for clear display.

CONCLUSIONS: The undulating swimming gaits of the robot in low-Re conditions is simulated and commendably characterized by the proposed theoretical model extensively different from Taylor's model, which provides a general scheme for the study of soft-bodied locomotion

REFERENCES:

1. Hu, Wenqi, et al. "Small-scale soft-bodied robot with multimodal locomotion." ***Nature*** 554 81 (2018).
2. Diller, Eric, et al. "Continuously distributed magnetization profile for millimeter-scale elastomeric undulatory swimming." ***Applied Physics Letters*** 104 174101 (2014).
3. Sitti, Metin. "Miniature soft robots—road to the clinic." ***Nature Reviews Materials*** 3 74 (2018).
4. Kim, Yoonho, et al. "Printing ferromagnetic domains for untethered fast-transforming soft materials." ***Nature*** 558 274 (2018).
5. Zhao, Ruike, et al. "Mechanics of hard-magnetic soft materials." ***Journal of the Mechanics and Physics of Solids*** 124 244 (2019).

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