

## APPENDIX: CFD SIMULATION METHODS

A commercially available, finite-volume code, FLUENT<sup>TM</sup> (version 4.5) is used in the CFD simulations of the present study. FLUENT<sup>TM</sup> (version 4.5) has been well tested for simulating low-Reynolds number flows such as those created by copepods (Jiang *et al.* 1999 & 2002). A CFD simulation allows for 1) considering realistic copepod body morphology, 2) including the effect due to a finite Reynolds number, and 3) calculating the power input for generating the flow, which can not be calculated from the Stokes flow model because of the flow-velocity singularity at the application point of the point force.

A  $46.2L \times 46.2L \times 46.2L$  cubic box is chosen as the computational domain with the model copepod of a prosome length,  $L$ , located at the center of the box. The center of the copepod's ventral-side surface is chosen as the origin of the FLUENT<sup>TM</sup> coordinate system. The direction from dorsal-side to ventral-side is set to be the positive  $x$ -direction, the positive  $z$ -direction is from posterior to anterior, and the positive  $y$ -direction is chosen according to the right hand convention. The entire domain is discretized into small control volumes/cells with an overall number of  $81 \times 80 \times 81$  cells. A curvilinear body-fitted coordinate system is used, so that the body shape is represented smoothly. The main body of the model copepod occupies  $7 \times 10 \times 14$  cells, with indices in the range  $(I, J, K) = (34-40, 36-45, 34-47)$ . The grid lines are concentrated in the region around the main body of the model copepod.

Since the beating movement of the cephalic appendages plays a key role in shaping the geometry of the flow field in the vicinity of the appendages, it is crucial to include the effect of the beating movement into the numerical simulation. However, it is difficult to use the curvilinear body-fitted coordinates to depict the morphology and time-dependent positions of these appendages in detail. As in the previous works (e.g. Jiang *et al.* 1999 & 2002), the effect

of the beating movement can be represented by applying a distributed force field to the finite volume cells ventrally adjacent to the copepod's main body. Malkiel *et al.* (2003) developed a method of using digital holographic cinematography to measure 3-D instantaneous velocity field around a free-swimming copepod, *Diaptomus minutus*. From the measured flow field and with the aid of a Stokeslet model, they were able to estimate that the propulsive force the copepod exerts on the water is  $\sim 1.8 \times 10^{-8}$  N, and that the excess weight of the copepod is  $\sim 7.2 \times 10^{-9}$  N. They also show that the copepod of a prosome length of 1.135 mm performs the partial sinking behavior at a sinking speed of  $0.29 \text{ mm s}^{-1}$ , and that the maximum tip velocity of the appendages is  $\sim 3.6 \text{ mm s}^{-1}$ . With all these data and with the typical distribution of copepod cephalic appendages taken into account, we have designed a distributed force field (figure A1). Ventral to the model copepod, 30 cells with (I, J, K) = (41-41, 38-43, 42-46) receive for each cell a propulsive force of  $-3.850 \times 10^{-10}$  N (level a in figure A1); 20 cells with (I, J, K) = (42-42, 38-39, 43-45), (42-42, 42-43, 43-45), (43-43, 37-38, 44-45) and (43-43, 43-44, 44-45) receive a propulsive force of  $-8.610 \times 10^{-11}$  N for each cell (level b in figure A1); 2 cells with (I, J, K) = (44-44, 36-36, 45-45) and (44-44, 45-45, 45-45) receive a propulsive force of  $-2.364 \times 10^{-9}$  N for each cell (level c in figure A1). The '-' sign of the forces indicates the forces are applied along the negative *z*-direction. The total propulsive force applied is  $-1.8 \times 10^{-8}$  N. With this distribution of force field and a velocity inlet boundary condition modeling the sinking speed of  $0.29 \text{ mm s}^{-1}$ , a flow velocity vector field is simulated around the model copepod (figure A2) which is comparable to the observation by Malkiel *et al.* (2003). A maximum velocity of  $3.61 \text{ mm s}^{-1}$  is reached at the regions where the tips of copepod cephalic appendages would locate. From our simulation, the excess weight of the model copepod is calculated to be  $7.12 \times 10^{-9}$  N (less than 1% of difference compared to the estimation from the observation).

The above-described distribution of force field is then taken as the baseline distribution for simulating the flow field created by a *Euchaeta rimana* female performing the partial sinking behavior with different sinking speeds. The *Euchaeta rimana* female has a prosome length of 2.5 mm and an excess weight of  $1.7438 \times 10^{-7}$  N, the same as that of the spherical model copepod shown in figure 9 of the main text of this paper. To do so, the ratio between the magnitudes of forces (level a : level b : level c, figure A1) is kept constant, and the total propulsive force is determined for each sinking speed. For each case, the force balance among thrust, body drag and excess weight is achieved by using a trial-and-error method. We impose for each case the error of the force balance to be less than 0.5% of copepod excess weight.

#### **REFERENCES:**

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- Jiang, H., Meneveau, C. & Osborn, T. R. 2002 The flow field around a freely swimming copepod in steady motion: Part II numerical simulation. *J. Plankton Res.* **24**, 191-213.
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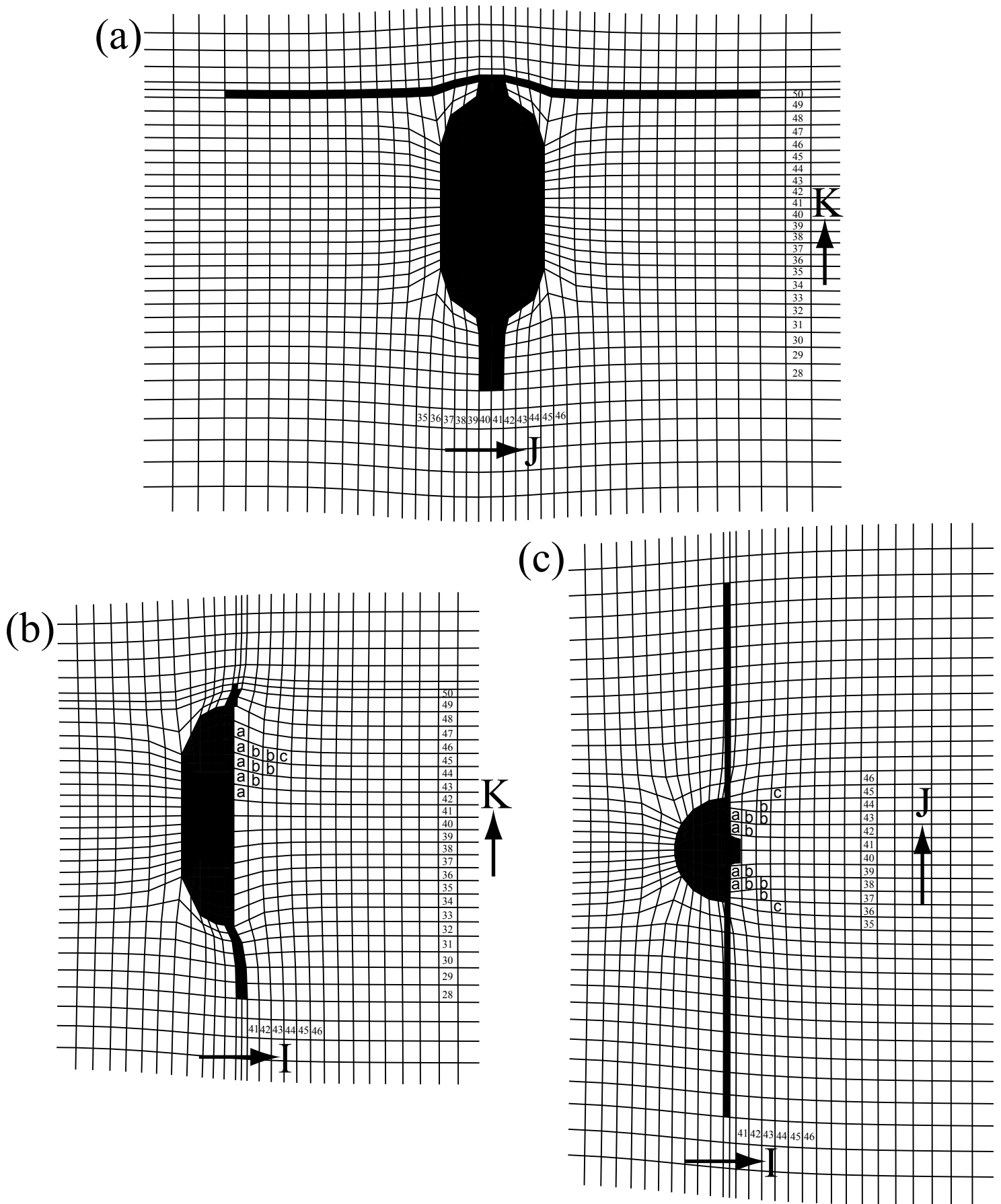


Figure A1. The distribution of forces representing the effect of the beating movement of the cephalic appendages of the model copepod used in the CFD simulations. See text for detailed explanation.

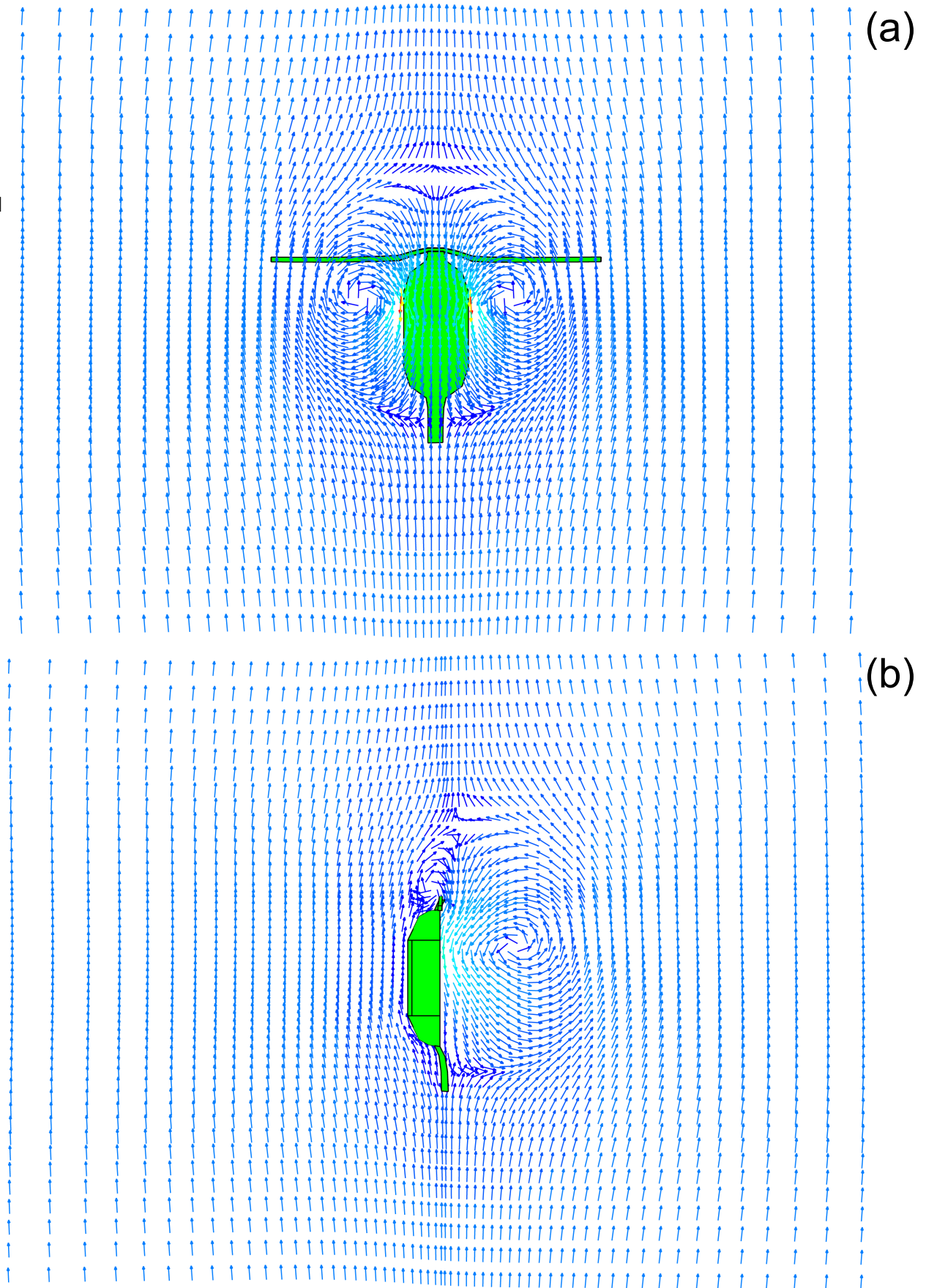
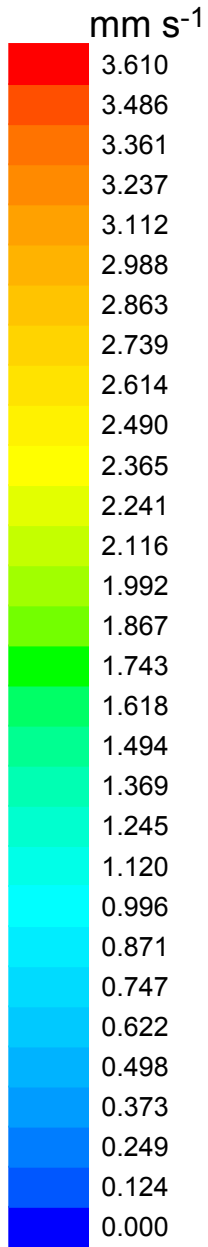


Figure A2. CFD simulation of the flow field around a model copepod sinking partially at  $0.29 \text{ mm s}^{-1}$ . The prosome length of the model copepod is  $1.135 \text{ mm}$ . Velocity vector plots (a) along a plane  $0.23 \text{ mm}$  ventral to the copepod body surface, and (b) along the median plane of the model copepod. This simulated flow field is similar to the observed flow field by Malkiel *et al.* (2003). A frame of reference fixed on the copepod's body is used. Uniform length vectors are drawn with colors representing the magnitudes of the velocity vectors. See text for detailed explanation.