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A physical model for galvanotaxis of *Paramecium* cell

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Abstract

We propose a qualitative physical model of galvanotaxis of *Paramecium* cells using a bottom-up approach to link the microscopic ciliary motion and the macroscopic behavior of the cells. From the characteristic pattern of ciliary motion called the Ludloff phenomenon, the torque that orients the cell toward the cathode is derived mathematically. Dynamical equations of motion are derived and their stability is discussed. In numerical simulations using our model, cells exhibit realistic behavior, such as U-turns, like real cells.

Keywords: *Paramecium*; Galvanotaxis; Physical model; Ludloff phenomenon

1. Introduction

Galvanotaxis is an intrinsic locomotor response to an electrical stimulus, universally observed in diverse types of cells (Robinson, 1985), such as bacteria (Shi et al., 1996), amoebae and slime molds (Korohoda et al., 2000; Anderson, 1951), protozoa (Ludloff, 1895), and vertebrate cells including human tissue cells (Erickson and Nuccitelli, 1984; Orida and Feldman, 1982; Zhang et al., 2000; Fukushima et al., 1953; Gruler and Nuccitelli, 2000; Djamgoz et al., 2001). Recent studies have indicated that galvanotaxis may be involved in a number of biological phenomena (McCaig et al., 2005), such as embryo development (Erickson and Nuccitelli, 1984; Levin, 2003) and wound healing (Robinson, 1985; Chiang et al., 1992).

Ciliates, especially *Paramecium* cells, exhibit quite strong negative galvanotaxis (Machemer and de Peyer, 1977). That is to say, viewed macroscopically, the cell is forced to swim toward the cathode in a DC electric field. Since the first reports on galvanotaxis by Verworn (1889, 1896), pioneers in microbiology have eagerly investigated galvanotaxis of ciliates (Ludloff, 1895; Jennings, 1923; Kamada, 1929, 1931a,b; Kinosita, 1939). They found that galvanotactic movement is caused by a change in direction of the ciliary beating, in contrast to general cells, which move by elongation of actin filaments followed by rearrangement of the cytoskeleton (Mycielska and Djamgoz, 2004). This characteristic pattern of ciliary beating in *Paramecium* galvanotaxis is called the Ludloff phenomenon, explained qualitatively by Ludloff (1895). Since his original work, however, there has been almost no quantitative discussion of the physical relationship between the microscopic ciliary beating pattern and the macroscopic behavior of a cell. The purpose of this paper, therefore, is to propose a novel physical scheme for *Paramecium* galvanotaxis to provide a quantitative explanation for the Ludloff phenomenon, using a bottom–up approach based on systems theory.

Although several properties of *Paramecium* cells have been modeled, conventional models have mainly been physiological and biochemical ones that have focused on the membrane potential or signal transduction, ignoring the physical properties (Jahn, 1961; Cooper and Schliwa, 1985). Moreover, the few physical models that have been presented have tended to disregard galvanotaxis. For example, a physical model of the swimming behavior proposed by Naitoh and Sugino (1984) considered only the

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behavior in the absence of an electrical stimulus. Though there are some physical *Paramecium* models based on gravitaxis or geotaxis (Fukui and Asai, 1980; Mogami et al., 2001; Hemmersbach et al., 2005), chemotaxis or chemokinesis (Houten and Houten, 1982; Sakane et al., 2001; Hirano et al., 2005), avoiding reaction (Sakane et al., 2001), calcium regulation (Laurent and Fleury, 1995), and thermotaxis (Oosawa and Nakaoka, 1977), they are not applicable to galvanotaxis, which is a side-effect of the electrophysiological properties of the membrane, a fundamentally different mechanism from other taxis or reactions. Fearing (1991) and Itoh (2000) independently performed pioneering experiments on controlling protozoa motion using galvanotaxis, but their approach was based on empirical rules. Some models on general taxis, that is, not limited to galvanotaxis in paramecia, are based on top–down qualitative mathematical assumptions rather than firm physical grounds (Schienbein and Gruler, 1993; Ohtake et al., 1997; Gruler and Nuccitelli, 2000; Ionides et al., 2003). One rare physical model of galvanotaxis is that constructed by Roberts (1970); however, its validity is uncertain because his assumptions were rough, and the accuracy of his model was not fully verified by comparing it with experimental data. This paper is the first attempt to construct a physical model of *Paramecium* galvanotaxis based on mechanics using a bottom–up approach, accompanied with experimental validation.

Our original motivation for this work stemmed from an engineering viewpoint; we have studied microrobotic applications of *Paramecium* cells, and have utilized galvanotaxis as a means of actuation of cells (Ogawa et al., 2005). The model that we propose in this paper was originally constructed in order to introduce the methodologies of robotics and systems theory based on physics for controlling cells, and it was found to be quite useful in controlling cells and trajectory planning. We believe that our model also has sufficient significance and novelty from a biological point of view.

2. Model of galvanotaxis

2.1. *Paramecium and its galvanotaxis*

2.1.1. *Biological background*

In this paper, we consider *Paramecium caudatum* because it has been extensively studied and its behavior is well known. *P. caudatum* is a unicellular protozoan with an ellipsoidal shape, inhabiting freshwater. It swims by waving cilia on its body; thousands of cilia beat the water backward to yield a forward reaction force (Naitoh and Sugino, 1984). The ciliary motion is controlled by shifts in the membrane potential and the accompanying changes in ion concentration in the cell.

When an external electrical stimulus is applied, it modifies the membrane potential and alters the ciliary movements, thus affecting the cell motion. Viewed macroscopically, the cell is made to swim toward the cathode. This phenomenon is called negative galvanotaxis. Note that galvanotaxis is simply a side-effect of the electrophysiological nature of the cell, unlike chemotaxis and phototaxis, which are behaviors conferring a survival advantage.

A *Paramecium* cell in an electric field shows a characteristic ciliary movement pattern. Assume an imaginary plane that is perpendicular to the electric field and located near the center of the cell, slightly closer to the cathodal end, dividing the cell into two parts, as illustrated in Fig. 1. The electric field causes cilia on the anodal end to beat more frequently (ciliary augmentation) (Kamada,

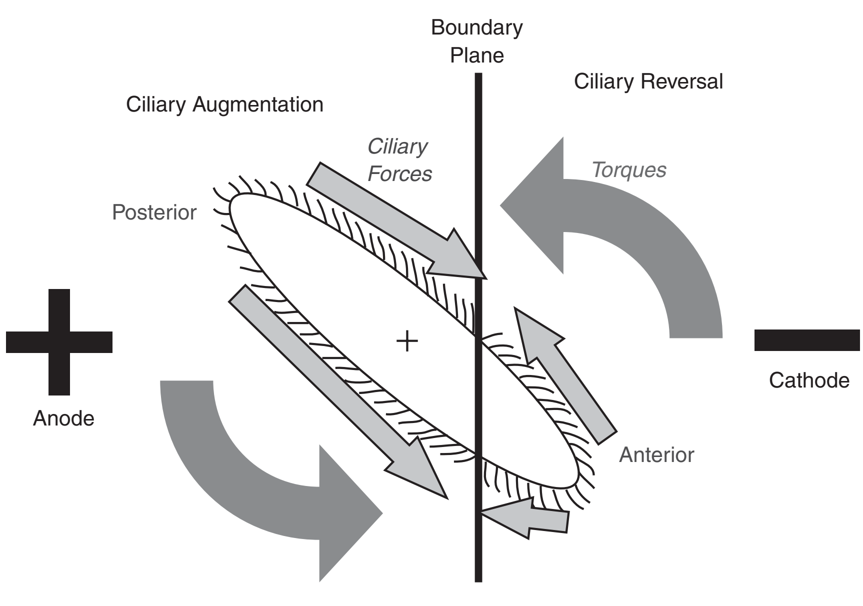

Fig. 1. Qualitative explanation for galvanotaxis. By applying an electric field, cilia on the anodal end begin to beat more frequently (ciliary augmentation) (Kamada, 1929), and cilia on the cathodal end beat more frequently but in the opposite direction (ciliary reversal) (Ludloff, 1895). The asymmetry in the ciliary beatings generates a rotational force and orients the cell toward the cathode.