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Energetic effects of molecular motor–cargo linkage

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Abstract

A Brownian motor needs a motor–cargo link to carry a cargo. The property of the link can affect the energetic efficiency of the motor. Consequently, inferring motor mechanisms from single-molecule experiments in terms of, e.g., the so-called Stokes efficiency can sometimes be misleading. Also, it was found that in some cases there is an optimal link stiffness for motor energy efficiency.

Keywords: Biomolecular motors; Motor–cargo link flexibility; Fluctuating ratchet; Energetics; Stokes efficiency

1. Introduction

Active transport of macromolecule complexes and organelles are required inside eukaryotic cells. Motor proteins such as kinesins serve as the tiny engines for this intracellular transport carrying cargo that are often much larger than themselves along particular tracks [1]. The motor and cargo are connected by a flexible link (e.g., the measured stiffness of the link for

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kinesin is ~0.1 pN/nm [2]). It is expected that the stiffness of the link, the thermal fluctuation, and the size of the cargo affect the motor fluctuation and the effective potential felt by the motor. This in turn alters the motor velocity and energetics. In the present paper, the effect of link on the energetics of ratchet motors is studied quantitatively.

The study of the effect of the motor–cargo link has direct relevance to interpreting the optical trap experiments data often used to study the motility and force generation of molecular motors [3]. In these experiments, the motion of an optically trapped bead elastically attached to the motor is analyzed to obtain information about the motor motion. The motor can be made to move against a force applied to the bead and the kinetic features of the bead motion are interpreted in terms of motor properties (e.g., Ref. [4]). In such studies the effect of the link stiffness and the bead diffusion constants are absorbed into effective kinetic rates for motor transition between different states and are obtained by fitting to the experimental data. Another example is the experimental studies of F_1-ATPase motor [5] in which motion of an actin filament elastically connected to the motor is observed to infer motor mechanism. Here, it is found that to have a high motor efficiency (Stokes efficiency of Ref. [6]) the force experienced by the actin filament should be a constant. Thus, it is suggested that the motor itself produces a constant force output. As we show below, the Stokes efficiency is dependent on the link stiffness, so such a conclusion about the motor itself must be taken with caution.

A previous study in this direction [7,8] considered the variation of motor velocity with the stiffness of the link when the motor is modeled as a Brownian ratchet or as a fluctuating ratchet. Detailed analytic results were given for the asymptotic regions of large and small link stiffness and cargo diffusion constant. The focus of the present paper is the effect of the link on the efficiency of the motor–cargo system. An approximate analytic description of velocity is given for non-asymptotic stiffness regions as well.

In Section 2, a simple ratchet model for the motor–cargo system used in this paper is described. In Section 3, variation of motor velocity with the stiffness of the link is studied by numerically solving the Fokker–Planck equations. An analytically solvable limit of the system is analyzed for various link stiffness cases. In Section 4, the dependence of Stokes efficiency on the link stiffness is studied. The result indicates that interpretation of the Stokes efficiency is not straightforward.

2. Motor–cargo system

There are many possible physical realizations of the ratchet [9]. We adopt the simplest scheme proposed in Ref. [10,11]. The motor is modeled as a strongly damped particle moving in a (spatially asymmetric) ratchet potential that fluctuates between two different states 1 and 2 with potential Φ_1 and Φ_2, respectively. Fig. 1