



Crawling on directional surfaces

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ABSTRACT

In this paper we study crawling locomotion based on directional frictional interactions, namely, frictional forces that are sensitive to the sign of the sliding velocity. Surface interactions of this type are common in biology, where they arise from the presence of inclined hairs or scales at the crawler/substrate interface, leading to low resistance when sliding ‘along the grain’, and high resistance when sliding ‘against the grain’. This asymmetry can be exploited for locomotion, in a way analogous to what is done in cross-country skiing (classic style, diagonal stride).

We focus on a model system, namely, a continuous one-dimensional crawler and provide a detailed study of the motion resulting from several strategies of shape change. In particular, we provide explicit formulae for the displacements attainable with reciprocal extensions and contractions (breathing), or through the propagation of extension or contraction waves. We believe that our results will prove particularly helpful for the study of biological crawling motility and for the design of bio-mimetic crawling robots.

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1. Introduction

The study of locomotion of biological organisms and bio-mimetic engineered replicas is receiving considerable and increasing attention in the recent literature [1,3,6,7,13,17–19,22,27,34]. In several cases, such as motility at the micron scale accomplished by unicellular organisms, or such as the ability to navigate on rough terrains exhibited by insects, worms, snakes, etc. Nature has elaborated strategies that surpass those achievable through current engineering design. The combination of quantitative observations, theoretical and computational modelling, design and optimization of bio-inspired artefacts is however leading to fast progress both in the understanding of the options Nature has selected and optimized through evolution, and on the possibility of replicating them (or even improving upon them) in man-made devices.

For example, the swimming strategies of unicellular organisms can be understood, starting from videos of their motion captured with a microscope and processed with machine-learning techniques [6], by using tools from geometric control theory [2,4]. In fact, self-propulsion at low Reynolds numbers [31] arises from non-reciprocal looping in the space of shape parameters [2,6], it can be replicated by using actuation strategies that can induce non-reciprocal shape changes [5,19], and optimized by solving optimal control problems [2,4]. This

has also been observed, e.g., in [10], where techniques originally proposed in [11] for the study of control problems for the ski and the swing have been extended to the problem of locomotion in fluids.

Crawling motility on solid substrates of some model organisms (snails, earthworms, etc.) can be understood using similar techniques. In the case of crawlers exploiting dry friction, or lubricating fluid layers with complex rheology (such as the mucus secreted by snails [13,15]), resistance forces are non-linear functions of the sliding velocity and locomotion is typically accomplished through stick-and-slip. Even when resistance forces are linear in the sliding velocity, if they also depend on the size of the contact region, then locomotion is still possible, provided that more elaborate strategies are employed [17,18,29]. These are very similar to those that are effective in low Reynolds number swimming, and show that the transition between crawling and swimming motility is much more blurred than what was previously thought.

The results above may provide a useful theoretical framework on the way of a more detailed understanding of crawling motility of metastatic tumor cells, neuronal growth cones etc., see, e.g., [12,22]. In addition, they may provide valuable new concepts in applications, by helping the practical design of a new generation of soft bio-inspired robots ranging from crawlers able to advance on rough terrains to microscopic devices that may navigate inside the human body for diagnostic or therapeutic purposes [7,19,24,36].

Much of the physics of the problem is contained in the question of which are the minimal mechanisms needed to make (efficient) self-propulsion possible. Here we concentrate on the question on how is it possible to extract positional change (i.e., a non-periodic

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history of positions) from reciprocal shape changes (i.e., a very restrictive class of periodic histories of shape change, obtained by tracing backward and forward an open curve in shape space). The famous ‘scallop theorem’ is precisely the statement that this is impossible for low Reynolds number swimming, see [31]. In addition, we study the motion produced by the propagation of travelling waves of contraction or extension, which is a typical strategy for self-propulsion in biology.

The interest for reciprocal shape changes arises from the fact that they can be easily accomplished by natural or artificial actuation: the breathing motion of a balloon (or of a bio-membrane) inflated and deflated by cyclic variations of (osmotic) pressure, or the motion of a specimen of a stimulus-responsive material (e.g., a shape-memory alloy) under cyclic actuation (e.g., temperature change) are all relevant examples. The conditions under which such oscillatory motions can be rectified to produce non-zero net displacements has been the object of several studies, see, e.g., [14,17,23,28]. In this paper, we analyse quasi-static crawling in the presence of ‘directional’ interactions with the environment and study in detail a model of continuous one-dimensional crawlers on directional surfaces. By this, we mean a situation in which the resistance force is not odd in the velocity: this may arise, for instance, when the substrate is hairy or it is shaped as a ratchet, or else when the interaction with the substrate is mediated by oblique flexible filaments or bristles (so that, if one reverses the sign of the velocity and moves against the grain, then the resistance force does not only change in sign, but may also change in magnitude). Concrete examples of such biological or bio-inspired directional surfaces are reviewed, e.g., in [26]. Prototypes of micro-robots exploring this motility strategy are presently being manufactured and tested, and will be described in a forthcoming paper [30].

2. Formulation of the problem

In this study we generalize the approach to quasi-static crawling introduced in [17,18,29] to the case of directional substrates, namely, substrates on which the resistance to motion is sensitive to the sign of the sliding velocity. More precisely, we consider cases in which the mechanical interactions between the crawler and the substrate on which it moves are described by a force per unit (current) length denoted by $f(x, t)$, which we call ‘friction force’. By *directional substrate* we mean a surface such that the friction exerted on the crawler at one point depends (only) on the velocity at that point according to a force-velocity law that is not odd in the velocity. A relevant example is the following one-dimensional force-velocity law of *Bingham-type*:

$$f(x, t) = \begin{cases} \tau_- - \mu_- v(x, t) & \text{if } v(x, t) < 0, \\ \tau \in [-\tau_+, \tau_-] & \text{if } v(x, t) = 0, \\ -\tau_+ - \mu_+ v(x, t) & \text{if } v(x, t) > 0, \end{cases} \quad (2.1)$$

where $\tau_-, \tau_+, \mu_-, \mu_+$ are all non-negative material parameters,¹ see Fig. 1.

There are two interesting special cases of (2.1), obtained by setting either $\mu_+ = \mu_- = 0$ or $\tau_+ = \tau_- = 0$. We refer to them as the *dry friction* and the *Newtonian friction* case, respectively, because they are reminiscent of the tangential forces arising either from dry friction or from the drag due to a Newtonian viscous fluid, see Fig. 2. In the case of dry friction, the force depends only on the sign of the velocity ($\mu_+ = \mu_- = 0$), whereas in the Newtonian case there are no yield forces ($\tau_+ = \tau_- = 0$), so that friction depends linearly on speed through a coefficient determined by the direction of motion.

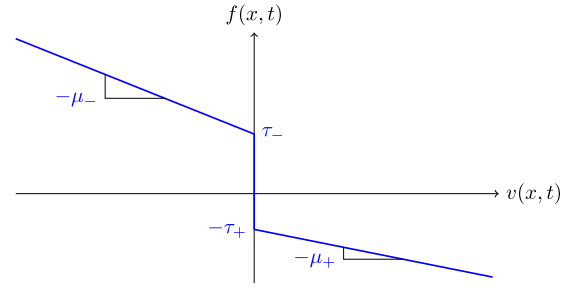


Fig. 1. The general force-velocity law (2.1) for friction used in this study.

We study a straight, one-dimensional crawler moving along a straight line. Let the coordinate X describe the crawler's body in the reference configuration. The left end of the body is denoted with $X_1 = 0$, while the right end with $X_2 = L$, where L is the reference length. The motion of the crawler is described by the function

$$x(X, t) = x_1(t) + s(X, t), \quad (2.2)$$

where $x_1(t) = x(X_1, t)$ is the current position of the left end of the crawler (similarly, we define $x_2(t) = x(X_2, t)$ as the current position of the right end), while the arc-length $s(X, t)$, which is the current distance of point X from the left end, describes its shape in the deformed configuration. By definition we have $s(0, t) = 0$, while, denoting with a prime the derivative with respect to X , we guarantee that the deformation described by (2.2) is one-to-one for every t by assuming that

$$s'(X, t) > 0. \quad (2.3)$$

The length $l(t)$ of the crawler at time t is given by

$$l(t) = \int_0^L s'(X, t) dX, \quad (2.4)$$

and the Eulerian velocity $v(x, t)$ at position x of the crawler and time t reads

$$v(x, t) = \dot{x}(X_x, t) = \dot{x}_1(t) + \dot{s}(X_x, t), \quad (2.5)$$

where $X_x = s^{-1}(x - x_1(t), t)$.

We assume that the crawler is able to control its shape, namely, to freely prescribe $s(X, t)$ subject only to the constraint (2.3). Moreover, we neglect inertia and make use of the force balance

$$F(t) = \int_0^{l(t)} f(x_1(t) + s, t) ds = 0 \quad (2.6)$$

to obtain the velocity $\dot{x}_1(t)$ at the left hand side of the crawler.

3. Crawling with two shape parameters

In this section, we restrict our study to the case of a model crawler composed of two segments, namely, $\overline{X_1 X^*}$ and $\overline{X^* X_2}$, each of which is allowed to deform only affinely. Therefore, the shape of the crawler can be described by just two parameters, such as the current lengths of the two segments $l_1(t) = x^*(t) - x_1(t)$ and $l_2(t) = x_2(t) - x^*(t)$, where $x^*(t) = x(X^*, t)$. We shall consider in the following two special cases of these systems, particularly relevant to crawling on directional surfaces.

3.1. Crawling with only one shape parameter: breathers

We start by considering a simpler crawler made of a single segment that can only deform affinely, so that $s(X, t)$ can be expressed as a function of the current length $l(t)$ in the following way:

$$s(X, t) = \frac{X}{L} l(t). \quad (3.1)$$

¹ We exclude the trivial case when all the parameters vanish ($\mu_+ = \mu_- = \tau_+ = \tau_- = 0$) and therefore no frictional interaction with the substrate occurs.

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