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Biomimetic study of rolling transport through smooth muscle contraction

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ABSTRACT

Inspired by the rolling behavior of oosperm through smooth muscle contraction of fallopian tube, a simple biomimetic experiment is devised in order to disclose the possibly mechanical transport mechanism. An interesting experimental observation demonstrates that an elastic strain gradient can be utilized to transport a soft latex bubble on a stretchable substrate by rolling. A corresponding theoretical model is established, in which an elastically three-dimensional bubble contacts adhesively on an elastic substrate subject to strain gradient. The initiation and steady-state energy release rates for such a rolling motion are achieved and analyzed. The influencing factors of rolling are found. The finding may have general implications on designing active transport systems with strain gradient.

1. Introduction

Biological transport via tissue contraction is a ubiquitous phenomenon in living systems. A prominent example is the transport of oosperm from ovary to uterus through the fallopian tube during pregnancy. While it is clear that the transport of oosperm involves smooth muscle contraction [1,2], the detailed mechanism still remains elusive [1–7], due in part to the complexity of cell-substrate interactions via receptor-ligand binding as well as various physical forces inside and outside of the cytoskeleton [8–12]. Cells are known to respond to mechanical forces exerted through surrounding fluid, adhering beads or substrates [9,12–14], and they could detach, slip or roll on a substrate in response to these forces [15–22]. For example, cells on a cyclically stretched substrate tend to reorient themselves away from the stretching direction [23–27], and cells migrate along a substrate with rigidity gradient (durotaxis) [18]. Blood cells are found to undergo a transition from rolling to translational motion on a blood vessel wall under increasing hydrodynamic shear forces [19], exemplifying a general fact that it takes less effort for a round object to roll than to slip on a substrate [28,29].

Could muscle contraction actually provide a driving force for the transport of an object? If so, what determines the direction of transport? While a symmetric contraction cannot provide a direction of motion, a strain gradient generated by a spatially non-uniform contraction could. Here we examine the hypothesis that an elastic strain gradient along a non-uniformly deforming substrate could induce the rolling of a particle in the direction of strain gradient.

In this paper, a biomimetic experiment is conducted first in order to verify our hypothesis. Then, a corresponding contact model of an elastic bubble adhering on an elastic substrate subject to strain gradient is established, in which influencing factors of the initial and steady-state rolling are analyzed. Conclusions are made finally.

2. Biomimetic experiment of adhesive rolling

To demonstrate the basic phenomenon, we devised a simple experiment in which a soft elastic latex bubble is placed in adhesive contact with a sticky and non-uniformly deforming substrate. In the experimental set-up shown in Fig. 1(a), a sticky elastic layer made of thermal plastic rubber is put on a rigid epoxy resin substrate. To create a strain gradient on the surface of the elastic layer, an interfacial crack is introduced near the edge of the interface and a horizontal displacement is imposed at the detached end of the elastic layer. As the layer is stretched beyond a critical strain, the interfacial crack starts to propagate, inducing an elastic strain gradient in the layer that moves with the crack tip.

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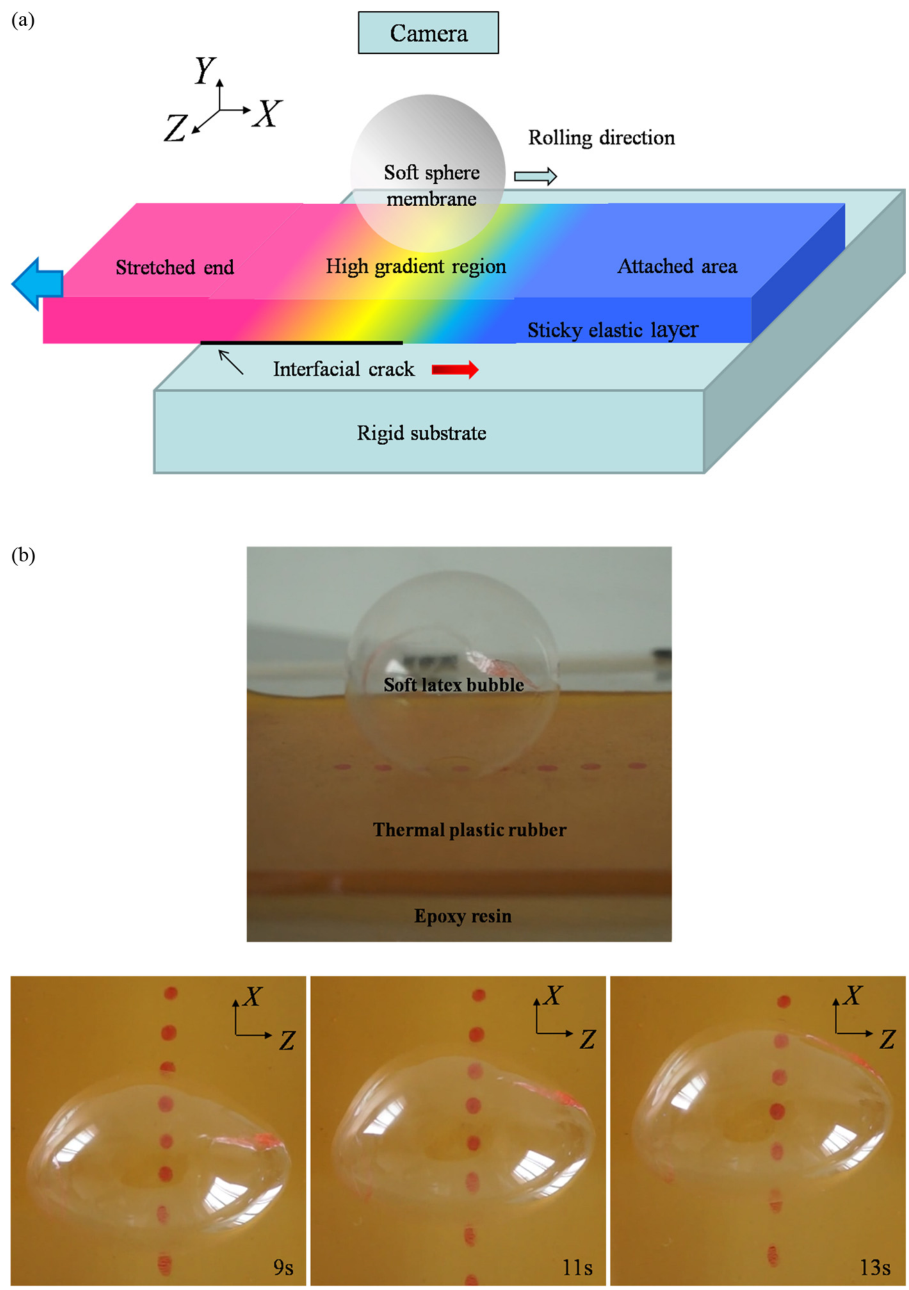

Fig. 1. The experimental set-up. (a) Schematic of a soft latex bubble placed on the surface of a sticky thermal plastic rubber layer adhering to a relative rigid epoxy resin substrate. A sharp strain gradient is created near the tip region of an interfacial crack between the rubber layer and rigid substrate, which moves the bubble along the surface through rolling; (b) The soft bubble on the stretched strip moves in the propagating direction of the interface crack.

The latex bubble is then placed on the surface of the elastic layer ahead of the interfacial crack tip, where the layer is well bonded to the rigid epoxy resin substrate. As the elastic layer is stretched but before the crack tip reaches the bubble, the surface strain is nearly zero due to the constraint from the rigid substrate. As the moving crack tip reaches where the bubble adheres and brings with it an elastic strain gradient across the crack tip, the elastic bubble begins to roll along the surface, as shown in Fig. 1(b).

It is easy to show that the observed bubble motion is not caused by gravity by simply repeating the experiment with the whole device tilt at a small angle while observing the bubble to continue to roll along the strain gradient against gravity, as shown in Fig. S1 in the Supplementary Material.

Supplementary Fig. S1 related to this article can be found, in the online version, at http://dx.doi.org/10.1016/j.colsurfb.2014.08.014.

If the propagating velocity of the interface crack is increased, the bubble is observed to roll faster with the crack tip. If the interface crack is stopped, the bubble stops too at a small distance ahead of the crack tip. When the interface crack propagates slowly, the bubble rolls with nearly the same velocity as that of the crack tip. The phenomenon is somewhat analogous to a boat traveling with a moving tide. If the bubble is initially placed far away from the interface crack, rolling does not occur until the crack tip moves near the bubble. If the bubble is placed behind the interface crack tip, it hardly moves at all as the crack propagates away. Only when the bubble lies within the strain gradient region near the tip of a moving interface crack does it roll along with the crack. No external force is applied on the bubble during the experiment.

Previous researches have shown, both theoretically and experimentally, that a uniform elastic strain imposed on a substrate tends