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Snakes move their scales to increase friction

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ABSTRACT

Snakes can climb a range of surfaces, from tree trunks to brick walls, using a hitherto poorly understood mechanism. The bellies of snakes are covered in a series of flexible scales that can be activated by the snake to prevent sliding. It is previously shown that conscious snakes can use this ability to double their friction coefficient relative to unconscious snakes. In this combined experimental and theoretical study, we give further evidence that snakes actuate their belly scales. We perform experiments where we slide snakes backwards atop an array of pillars. Our theoretical model suggests that snakes that do not apply an opening moment to their scales should have quite short contact with these pillars. In our experiments, snakes slide their ventral scales down the pillars, prolonging contact. Our modeling suggests that this phenomenon can only occur if snakes apply a moment at the scale base. We hope this result encourages further research in actively-generated friction.

1. Introduction

Snakes are one of the few organisms that propel themselves by sliding their bodies against the ground. Compared to limbed organisms, this mode seems like a poor locomotory choice. However, snakes are able to move their limbless bodies across a range of terrain, including rock, sand, mud, and leaf litter. Moreover, they can propel themselves both across flat ground and straight up trees and brick walls. Clearly, such versatility suggests that they have adaptations to both reduce and increase friction as they move. However, most studies of friction cannot be directly applied to understand snake movement. Most friction studies rely on flat or gently rounded surfaces in contact, such as tires and ball bearings. In contrast, biological surfaces such as snakeskin can be scaly, involving consideration of soft flexible components jamming or in stick–slip. Little work has been done on understanding the frictional properties of such surfaces and how they are adapted for increasing friction. The goal of this study is to understand how snakes can resist sliding backwards.

Snakeskin has attracted a great deal of attention for its unique frictional properties [1,2,3,4,5]. Their ventral scales in particular have attracted many attempts to characterize their frictional properties. Most studies involve deceased or unconscious snakes [1,2,3,4,5,6,7]. Classical studies of snake locomotion by Gray involve measurement of the frictional properties of snakes sliding on different substrates such as wood and metal [6,8]. Gray was the first to observe the frictional anisotropy of the snakeskin, the variation in friction coefficient μ according to sliding direction. Friction coefficient μ is the ratio between sliding friction force and normal force. As shown in later experiments by Hu et al., snakes have the lowest friction coefficient if sliding in the forward direction, twice the friction in the lateral direction and four times the friction in the rearward direction [9]. This anisotropy is due in part to the macro-scale structure of the snake's ventral scales, which resemble overlapping shingles.

One source of frictional anisotropy is microscopic features on the ventral scales. Hazel et al. discover pawl-like microscopic features on boa scales [2]. Using atomic force microscopy, they report that tail-to-head friction coefficient of a single scale is 3–4 times that of the opposite direction [2]. Gorb et al. study the micro-ornamentation and frictional properties of various parts of the snakes, including dorsal, lateral, and ventral regions [4]. They report that ventral scales have the highest frictional anisotropy of 26%, compared to only about 4–5% for both lateral and dorsal. These characteristics provide further evidence of a unique specialization of the ventral scales toward friction enhancement in locomotion. Frictional properties of snakeskin are also studied by Abdel-Aal et al. [7]. Studying the shed skin of a *Python regius*, the research maps out coefficients of friction for scales on all parts of the body: lateral, dorsal, and ventral. They find that frictional anisotropy is more significant in the ventral scales than any other part of the body [7].

Marvi et al. report that the friction coefficients of conscious corn snakes are almost twice as those of unconscious snakes implying the importance of active mechanisms [8]. They report experiments qualitatively showing the snake opening and closing its belly scales [8,10,11]. However, how such motion increases frictional anisotropy remains unknown.

In this study, we investigate how snakes use their scales to resist sliding. In Section 2, we describe a new method for recording the force and displacement of a snake scale during sliding tests. We present in

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Section 3 a theoretical model for predicting the frictional force of a single snake scale. In Section 4, we present evidence, based on our model predictions, that snakes actively apply an opening moment to their scales to prevent sliding. In Section 5, we give suggestions for future work.

2. Methods

2.1. Animal care

Two juvenile corn snakes *Pantherophis guttatus* (Fig. 1a, b) used in this experiment are cared for in captivity for the duration of our experiments ($N = 2$, $m_1 = 0.73$ kg, $m_2 = 0.85$ kg, $L_1 = 131.3$ cm, and $L_2 = 139.5$ cm). The snakes are fed weekly and housed in separate terrariums with controlled temperature and humidity conditions.

2.2. Friction measurement

We designed a device to measure the resistive force of a single snake scale while permitting visualization of the snake scale. The device consists of a series of vertical pillars of plastic film of thickness 0.12 mm transparency sheet (3 M Dual Purpose CG5000 transparency film) cut with a laser into dimensions 24.2 mm by 6 mm. We refer to this transparency sheet hereon as “plastic”. The array of pillars is then inserted into 2 mm deep grooves laser cut into a block of wood. Openings on the side allowed us to see the deflection of the entire pillar, which we through our theoretical model, used to predict force. Spacing between pillars of plastic film is chosen to reduce interaction between pillars but facilitate tripping of scales as the snake is pulled across the apparatus.

We use two corn snakes in this study and conduct 10 trials with each snake being conscious and unconscious. In the experiments, a snake is pulled manually over the film array with its ventral scales catching and displacing the pillars (Fig. 1a, b). We hold the snake with two hands, supporting its body weight such that its ventral surface grazes the tops of the pillars, as would be the case if the snake were climbing vertically. Sliding backwards in this case corresponds to sliding downwards while climbing which happens when the maximum load scales can support is exceeded. In this study, we are interested in investigating this load limit for an individual scale. We test ventral scales located within ±10% from the midpoint of the snake. All experiments are filmed from the side using a high definition digital video camera (Sony HDRXR200) at 30 frames/s. Image analysis via the open source Tracker is used to record parameters such as scale base and tip positions, scale base angle, and pillar tip position. Since we can precisely track these parameters, we can simulate any of the experimental trials regardless of their variability. However, using the side views we make sure we omit the trials in which the snake belly pushes on the pillars (rather than only tip of ventral scales touching the pillars).

2.3. Measurement of snake scale

Our theoretical model requires the shape of the snake scale, its material properties and frictional properties. We discuss measurement of each in turn. All measurements are performed on ventral scales of unconscious snakes. The scale width and length are measured with

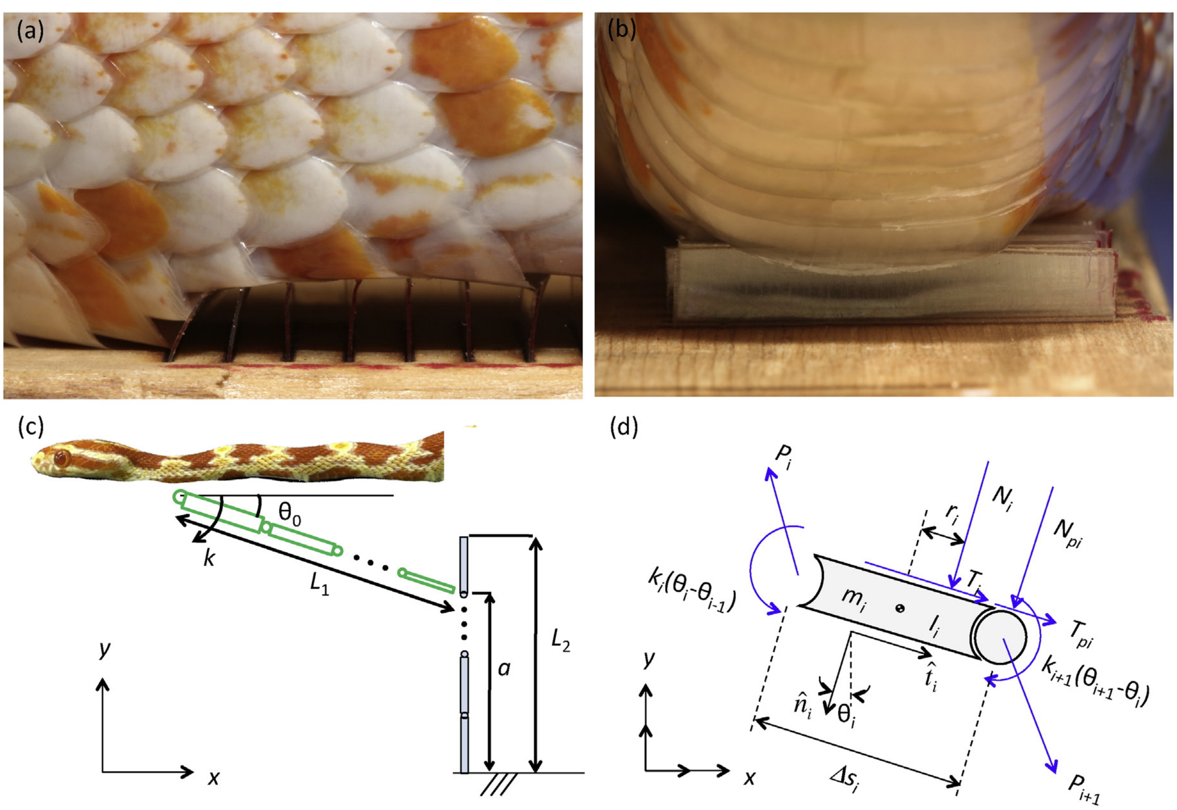

Fig. 1. Snake scale interacting with an array of pillars: (a) side view, (b) front view, and (c) schematic. Each segment is coupled to adjacent segments via torsional springs (depicted by circles at junctions). The solid black circles are a representation of additional links that are not shown in this schematic. L_1 and L_2 are scale and pillar lengths, respectively. θ_0 is initial scale base angle, k is scale base torsional stiffness, and a is height of contact. (d) Free body diagram of a segment. Blue arrows show forces and moments applied. m_i is the mass of segment i, a_i is the acceleration of the center of mass of segment i, P_i is the force that segment i exerts on segment $i-1$, N_i is the normal force exerted on scale segment i by a node of the pillar, T_i is the tangential force exerted on scale segment i by a node of the pillar, N_{pi} is the normal force exerted on scale node $i+1$ by a segment of the pillar, T_{pi} is the tangential force exerted on scale node $i+1$ by a node of the pillar, t_i is the unit tangent parallel to scale segment i and directed toward scale segment $i+1$, n_i is the normal to scale segment i, I_i is the mass moment of inertia scale segment i about an axis perpendicular to the plane of the figure and through the center of mass, θ_i is the angle that scale segment i makes with the horizontal, measured positive clockwise, Δs_i is the length of scale segment i, ri is the radial distance along scale segment i to the line of action of N_i, and k_i is the torsional spring constant acting between scale segments $i-1$ and i.