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Citation	The 9.5th International Symposium on Adaptive Motion of Animals and Machines (AMAM2021). 2021, p. 32
Version Type	VoR
URL	https://doi.org/10.18910/84872
rights	
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Snakes traversing rubble-like terrain

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1 Introduction

Snakes are able to deform their elongate bodies to move across various complex 3-D terrain such as boulders, forest floors, swamps, and tree branches. Previous terrestrial snake locomotion studies mostly focused on planar gaits or gaits with small out-of-plane body deformation on flat surfaces [1, 2]. A few studies observed their locomotion on flat surfaces with sparsely distributed obstacles such as peg arrays, in which body deformation is also planar [3]. It remained less understood how snakes traverse complex 3-D terrain with large obstacles using large 3-D body deformation.

Recent studies in our groups revealed that snakes can use vertical body bending to traverse large obstacles. For example, kingsnakes combine lateral undulation and vertical bending in three dimensions to traverse a large, smooth step [4, 5]. Corn snakes traverse a horizontal ladder using vertical undulation for propulsion [6]. Here, we test the hypothesis that vertical body bending is as important as lateral body bending during traversal of more complex rubble-like 3-D terrain.

2 Methods

First, we constructed a rubble-like arena using 96 low-friction acrylic obstacles (Figure 1A). Each obstacle has a horizontal footprint of 8.2 × 8.2 cm. Heights of all obstacles follow a normal distribution with a mean of 5.1 cm and a standard deviation of 1.7 cm. We attached BEEtag markers [7] to all top surfaces of obstacles which were tracked by 12 high-speed cameras. Their 3-D positions and orientations were reconstructed using direct linear transformation (DLT) [8] to obtain geometry of terrain surfaces.

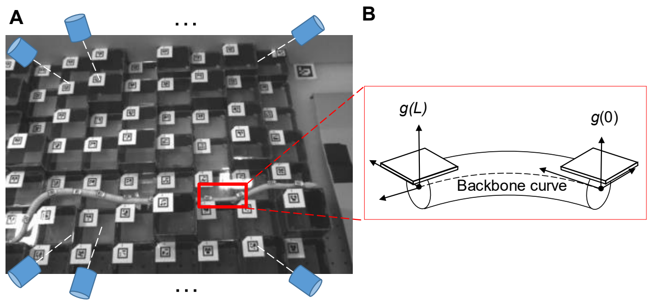

Figure 1: Experimental setup. (A) A corn snake traversing rubble-like arena. (B) Body interpolation method using tracked BEEtag markers.

Next, we challenged the generalist corn snakes *P. guttatus*, which live in diverse habitats such as forests and farmlands, to traverse the arena ($N = 3$ animals, $n = 32$ trials). The snakes' full length measured 82.2 ± 5.7 cm. To quantify the snake's kinematics during traversal, we attached 10 to 12 BEEtag markers to each snake and tracked them using the high-speed cameras at 50 frame/s and reconstructed their 3-D positions and orientations. We interpolated the animals' continuous bodies in three dimensions (both position and orientation) by modeling each body segment between two adjacent markers as an elastic rod [9]. To quantify body tapering, we measured the cross-sectional height of the snakes at different locations and interpolated values in between.

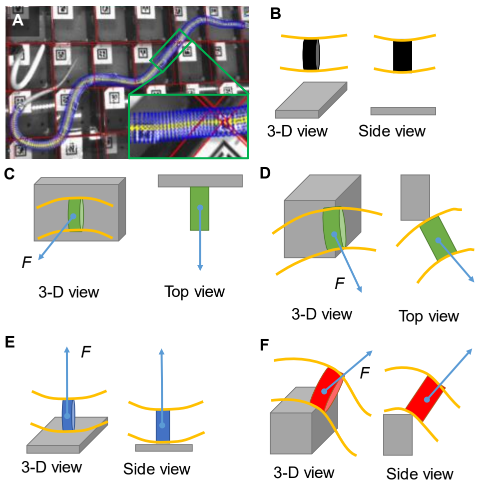

Figure 2: Contact conditions of each body segment. (A) Reprojection of sample points used for collision detection (blue), outlines of obstacles (red) and snake backbone (yellow). (B) Body segment is not contacting terrain. (C) Body segment is pushing laterally against a vertical wall with a contact force possibly normal to the wall. (C) Body part is laterally pushing a vertical edge with a contact force possibly horizontal 135° away from either vertical wall. (D) Body part is being supported by a horizontal surface with a contact force possibly pointing upward. (E) Body part is vertically pushing a horizontal edge with a contact force possibly normal to the edge and 135° away from either adjacent surface.

To determine contact between the snake body and the terrain surfaces, we sampled 200 infinitesimal body segments along the interpolated body and 24 points on the cross-sectional outline of each body segment (Figure 2A). Collision detection between these sample points and reconstructed terrain geometry was performed to locate contact points. By checking regions of contact points on the body and on the terrain surfaces, we classified body-terrain contact into 5 conditions (Figure 2). A body segment was determined as a lateral bending segment if it matches condition (B) or (C), or determined as a vertical bending segment if it matches condition (E).

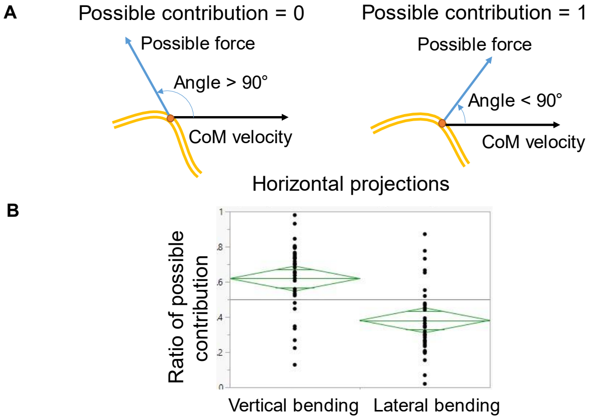

Figure 3: Possible contribution to propulsion. (A) Definition. (B) Ratio of possible contribution from each type.

With no force measurement available yet, we assumed possible contact forces for each point based on the normal directions of the surfaces it contacted ignoring friction (Figure 2C-F, blue arrows). We also assumed that the contact force exerted by each contact point has the same magnitude.

To gain initial insight into the possibilities of how much vertical or lateral bending may contribute to forward propulsion, we defined possible contribution for each body segment in contact with terrain (Figure 3A). Each of these body segments provides 1 possible contribution if the local possible contact force has a forward component when projected to current center of mass velocity in the horizontal plane, or 0 otherwise. Then we calculated the sum of possible contributions of all vertical or lateral bending body segments in each video frame, which reflects the number of body segments available for forward propulsion. Comparison of the sums could indicate which type of body segments is likely to contribute more.

3 Results

The animal traversed the rubble-like terrain by propagating a 3-D wave downward the body, as if moving in a tube (Figure 4). Despite the smooth surfaces with low friction, average slip angle during all trials were as low as 14°. The animal occasionally pushed laterally against vertical walls, but mostly pushed against horizontal ridges using vertical body bending. In addition, the animal tended to crawl through lower valleys.

Compared to lateral bending, vertical bending contributed more possible propulsion on average (Figure 3B, 62% versus 38%; $P < 0.0001$, ANOVA).

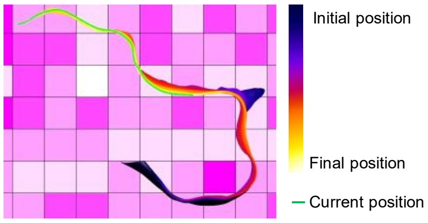

Figure 4: Time-lapse trajectories of snake body in one trial. Higher obstacles are marked with darker magenta.

4 Discussions

The observations and quantification of possible contribution provided evidence supporting our hypothesis that vertical bending is also important during traversal of a rubble-like terrain. Although the assumed force generation are certainly not accurate quantitatively, they provided insights into propulsion from these kinematics data.

To further confirm our hypothesis and reveal the physical principles underlying vertical bending, we plan to develop a sensorized complex terrain platform to measure contact force distributions in snakes. We are also developing a sensorized robophysical model to study how to utilize distribution of contact forces by 3-D body deformation (see other poster by Ramesh *et al.*, Development of a sensorized snake robot to study limbless locomotion in complex 3-D terrain).

5 Acknowledgements

This work is supported by a Burroughs Wellcome Fund Career Award at the Scientific Interface, a Beckman Young Investigator award, and Johns Hopkins University Whiting School of Engineering startup funds to C.L. The authors would like to thank Kaiwen Wang and Daniel Deng for the help during experiments. The authors declare no conflict of interest.

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