ELSEVIER

Journal of Biomechanics 32 (1999) 477–484

JOURNAL OF BIOMECHANICS

Nanoscale design of snake skin for reptation locomotions via friction anisotropy

J. Hazel[a], M. Stone[b], M.S. Grace[c], V.V. Tsukruk[a,*]

[a] *CMD Department, College of Engineering and Applied Sciences, Western Michigan University, Kalamazoo, MI 49908, USA*
[b] *Materials and Manufacturing Directorate, Air Force Research Laboratory/MLPJ, Wright-Patterson AFB, OH 45433, USA*
[c] *Department of Biology, University of Virginia, Charlottesville, VA 22903, USA*

Received in final form 20 December 1998

Abstract

Multi-mode scanning probe microscopy is employed to investigate the nanostructure of dermal samples from three types of snakes. Sophisticated friction modifying nanostructures are described. These include an ordered microfibrillar array that can function to achieve mission adaptable friction characteristics. Significant reduction of adhesive forces in the contact areas caused by the 'double-ridge' nanoscale microfibrillar geometry provides ideal conditions for sliding in forward direction with minimum adhesive forces and friction. Low surface adhesion in these local contact points may reduce local wear and skin contamination by environmental debris. The highly asymmetric, 'pawl-like' profile of the microfibrillar ends with radius of curvature 20–40 nm induces friction anisotropy in forward–backward motions and serves as an effective stopper for backward motion preserving low friction for forward motion. The system of continuous micropores penetrating through the snake skin may serve as a delivery system for lubrication/anti-adhesive lipid mixture that provides for boundary lubrication of snake skins.

Keywords: Snake skin; Skin lubrication and friction; Nanotribology; Scanning probe microscopy; Surface morphology

1. Introduction

Lateral undulations, sidewinding, and concertina motions are the three most important modes of snake locomotion (Gray and Lissmann, 1950). Concertina locomotion by snakes is made possible by the highly developed ventral cutaneous musculature, which generates a peristaltic wave along the snake body (Jayne, 1988). These waves of contraction include modulation of both the area and pressure of contact between the skin and ground (Jayne, 1986, 1988, Lillywhite, 1993). A key element of this event is tribological (frictional) behavior of snake skin, which allows precise change of local direction and pace of sliding.

Studies of macroscopic frictional properties of snake bodies showed a friction coefficient in the range from 0.2 to 0.4 for the forward motion on various dry surfaces (Gray and Lissmann, 1950). However, a substantial increase in the friction forces was observed on oiled surfaces (three–four times). On the other hand, a significant decrease of the friction coefficient was detected on rougher surfaces. Significant friction anisotropy was observed for forward and backward motions (two–three times higher for backward mode) although the friction coefficient for lateral movement against dry surfaces was similar (0.3–0.4). Obviously, tribological surface behavior is a key element in the adjustable friction anisotropy exhibited by snake skin during reptation locomotion.

Several scanning electron microscopy studies of snake skins have been reported in the literature (Stille, 1987; Gans and Baic, 1977; Chiasson et al., 1989). These observations revealed existence of a number of morphological features such as sharp spines designed to protect snake skins and interlocking longitudinal ridges to allow smooth sliding. The presence of a complex lipid film on a surface to control dermal wettability and permeability was indicated by several studies (Lillywhite and Sanmartino, 1993; Roberts and Lillywhite, 1980). However, questions of micro- and nanostructure of skin morphology and their mechanical functions were not addressed due to

* Corresponding author. Tel.: 616-387-6510; fax: 616-387-6517; e-mail: vladimir@wmich.edu.

0021-9290/99/$ – see front matter
PII: S0021-9290(99)00013-5