A study on the frictional response of reptilian shed skin

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Abstract. Deterministic surfaces are constructs of which profile, topography and textures are integral to the function of the system they enclose. They are designed to yield a predetermined tribological response. Developing such entities relies on controlling the structure of the rubbing interface so that, not only the surface is of optimized topography, but also is able to self-adjust its tribological behaviour according to the evolution of sliding conditions. In seeking inspirations for such designs, many engineers are turning toward the biological world to study the construction and behaviour of bio-analogues, and to probe the role surface topography assumes in conditioning of frictional response. That is how a bio-analogue can self-adjust its tribological response to adapt to habitat constraints. From a tribological point of view, Squamate Reptiles, offer diverse examples where surface texturing, submicron and nano-scale features, achieves frictional regulation. In this paper, we study the frictional response of shed skin obtained from a snake (Python regius). The study employed a specially designed tribo-acoustic probe capable of measuring the coefficient of friction and detecting the acoustical behavior of the skin in vivo. The results confirm the anisotropy of the frictional response of snakes. The coefficient of friction depends on the direction of sliding: the value in forward motion is lower than that in the backward direction. Diagonal and side winding motion induces a different value of the friction coefficient. We discuss the origin of such a phenomenon in relation to surface texturing and study the energy constraints, implied by anisotropic friction, on the motion of the reptile.

1. Introduction
Reduction of friction in moving assemblies is key to energy savings. This is because it reflects on the quantity of energy spent to combat frictional resistance to motion. Reduction of friction depends on many factors. One of the important factors is the topography of the rubbing interfaces. Custom engineering of the texture and topography of a rubbing interface, therefore, have acquired momentum within the last decade or so. To this effect many researchers envision a so called “deterministic surfaces” as the future of surface engineering. These surfaces not only would be of optimized topography but also their function would be an integral feature of the overall function of the system they enclose.
Construction of structured deterministic surfaces depends on understanding the interaction between surface topography, roughness parameters and frictional response. Structuring of surfaces in tribology has multiple goals. For lubricated surfaces it may be desirable to alter the topography in a manner that establishes a full hydrodynamic regime in within a short distance of sliding so that complete separation between surfaces is achieved. Controlled adhesion may also be a goal of surface structuring. Additionally, constructing a self cleaning surface or a hydrophilic or hydrophobic surface may be one of the required goals. In all, a structured surface for enhanced tribological performance should ideally be capable of tuning its frictional response to optimize system function. Achieving these goals is not necessarily easy, to date it may be fairly stated that generation of structured surface patterns is an art. In nature there is an abundance of examples of hierarchically structured naturally occurring surfaces that deliver super functionality. The diversity and richness of these examples have fuelled interest in the study of natural surface designs with the goal of mimicking them or deducing surface design rules for deterministic constructs. Of particular interest is investigation of the interaction between surface topography and friction response; and the topological design features of the surface that allow a natural surface to optimize its frictional behavior in response to changes in the surroundings or in the contacting terrain. A rich resource for such a purpose is frictional behaviour of squamata.

Squamata, or the scaled reptiles, comprises the largest order of reptiles. It includes lizards and snakes. Squamate reptiles number approximately 8000 living species and are a major component of the world's terrestrial vertebrate diversity. They are the most variably-sized order of reptiles, ranging from the 16 mm Jaragua Sphaero (Sphaerodactylus ariasae) to the 8 m Green Anaconda (Eunectes murinus). Their evolutionary history dates back to the early Jurassic or late Triassic, they have diversified on all major continents, and they occupy a remarkable diversity of ecological niches [1–5]. For sliding, the study of legless-locomotion-reptiles, i.e., snakes, is technically attractive.

Snakes have multi-modes of motion (slithering, crawling, serpentine movement etc). Transfer of motion between the body of the snake and the substrate depends on generation of sufficient tractions. Generation of traction and accommodation of motion is handled through the skin. Thus the skin of the snake transfers frictional traction transfer and accommodates the energy consumed in facilitating motion. Motion is initiated through muscular activity that comprises sequences of contraction and relaxation of appropriate muscle groups. The number, type and sequence of muscular groups responsible for the initiation of motion, and thus-employed in propulsion, will vary according to the particular mode of motion. It will also depend on the habitat and the surrounding environment. This also will affect the effort invested in initiation of motion and thereby also affects the function of the different parts of the skin. So that, in general, different parts of the skin will have different functional requirements. Moreover, the life habits of the particular species (e.g., defense, hunting, and swallowing) will require different topographical features within the different parts of the skin. These aspects render snakes ideal study objects when the role of functional surface in controlling friction is considered.

In this work, therefore, we report on the dynamical frictional behavior of shed skin of a snake (Python regius). The aim of the study is to characterize the frictional response of the ventral scales both in linear and diagonal motion.

2. Background

2.1. Structure of Snake skin
Snakes are entirely covered with scales of various shapes and sizes. Scales protect the body, aid in locomotion, help retain moisture, and alter the surface characteristics. Snake scales are formed by the differentiation of the snake's underlying skin or epidermis. Each scale has an outer surface and an inner surface. A snake hatches with a fixed number of scales. The scales do not increase in number as the snake matures nor do they reduce in number over time. Snakes periodically molt their scaly skins and acquire new ones. The scales however grow larger and may change shape with each molt.

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Reptilian skin has two principal layers: the dermis which is the deeper layer of connective tissue with a rich supply of blood vessels and nerves; and the epidermis, which in reptiles consists of up to seven sub-layers or “strata” of closely packed cells, forming the outer protective coating of the body. The “epidermis” has no blood supply, but its’ inner most living cells obtain their nourishment by the diffusion of substances to and from the capillaries at the surface of the “dermis” directly beneath them. There are seven epidermal layers, the “stratum germinativum”, the deepest layer lining cells which have the capacity for rapid cell division and the six layers which form each “epidermal generation”, the old and the new skin layers. These are: the clear layer and the lacunar layer, which matures in the old skin layer as the new skin is growing beneath; the (α)−layer, the mesos layer and the (β)-layer, these layers consist of cells which are becoming keratinized with the production of two types of keratin (α and β keratin). These cells are thus being transformed into a hard protective layer. Finally, there is the “oberhautchen” layer, which forms the toughest outer most layer of keratinized dead skin cells. The shedding of the old epidermal layer of the skin generally occurs as a single piece (molt) after a complex process. The shed epidermis of snake skin consists of four layers: the outermost Oberhautchen and the β-layer (mainly protein), the mesos layer (lipid-rich) and the inner α-layer.

2.2. Characterization of skin.
All observations reported herein pertain to shed skin obtained from a 115 cm, 14 years old male Ball Python (Python Regius) housed individually in a glass container with news paper substrate. We identified 12 (twelve) positions on the reptile hide for observation. Figure 1 depicts the general features of the skin. Dorsal skin is composed of several dark and light coloured blotches, whereas the ventral skin is mainly cream in colour with occasional black markings. Note that the micro features of the scales comprise fibrils of the size of a few microns. These are of in-consistent shape and spacing. Fibril tips point toward the tail, within the dark-coloured dorsal scales; fibrils are tapered and have a sharp tip. Scales within the bright coloured and the ventral regions have a more rounded tip and appear to be of uniform width throughout the fibril length. Moreover the density of the fibrils seems to be different within the different colour regions (denser within the dark coloured region). Since ventral fibrils are thought to be the origins of the frictional response of the reptile, we undertook further analysis of their geometry. The results are shown in figure 2 (a and b).

![Figure 1. General appearance of the Python regius and SEM details of the skin at three positions: Dorsal skin light colored (DSL), Dorsal skin dark colored (DSD) and the ventral skin (VS). Magnification x=15,000. Scale marker 1μm.](image-url)
3. **Friction behaviour**

All measurements utilized a patented tribometer that includes a tribo-acoustic probe sensitive to the range of friction forces and the acoustic emission generated during skin friction. The device is capable of measuring normal, tangential loads and also of detecting sound emission due to sliding. Detailed description of the tribometer is given elsewhere [6]. The skin used in measurements consisted of 150 mm long patches taken from four locations on the shed hide. Skin samples didn’t receive any chemical or physical treatment. For each patch, measurements were taken for the dorsal and ventral sides of the skin. Four directions of sliding were used: straight forward (SF), straight backward (SB), diagonal forward (DF), and Diagonal backward (DB). Figure (3-a) depicts the directions used to obtain the measurements and their orientation with respect to the head and tail of the species.

![Fig. 2](image-url)  
**Fig. 2.** Distribution of the fibril density, left hand side, and fibril length, right hand side, along the body of the reptile

Figure (3-b) presents a summary plot of the measured COF. Each value is an average of five consecutive measurements taken at the same direction of sliding and identical loading conditions. The results imply that resistance to forward motion is, in general, less than that for moving backwards, observe the difference between the value obtained for the SF direction and that for the SB direction. Anisotropy of the COF is also noted from the results. The COF when moving diagonally is different from that in straight motion. Resistance to motion, however, from tail to head (i.e., forward) is less than that from head to tail (i.e., backward) regardless of the direction of motion (forward or diagonal). These general trends are in line with measurements obtained by other researchers [7, 8] who confirmed the anisotropy in friction as well as the increase in resistance to backward motion (although on different species). However, in this work, dynamic measurements of the COF in the diagonal directions are reported for the first time in literature.

The origin of the frictional behaviour is rooted in the structure of the surface of the snake. In particular, the presence of fibrils within the scales aids the beast in conditioning its frictional response. The fibrils are asymmetric. The slope of fibril tips is gradual in the direction from head to tail and steep from tail to head. This asymmetrical tip-shape offers directional resistance to motion through acting as a ratchet which offers less resistance to the motion of the beast in the forward linear direction than that offered in the reverse direction.
The overall structure of the ventral scales affects friction. The connector tissue which links the scales acts as a spring which flexes when the animal attempts to move backwards. Flexing dissipates additional locomotion energy generated by the beast. This renders backward motion infeasible as it becomes cost prohibitive in terms of energy expenditure.

It is likely that the trends exhibited by the COF (anisotropy) are also a function of the chemical composition of the Oberchautchen layer. This layer is mainly composed of $\beta$ keratin, which is lamellar. Other natural materials such as camel and horsehair, which have the same keratin, composition are known to exhibit a so-called differential friction effect (DFE). In DFE the frictional work required by a fibre to slide over another fibre is greater in the direction of tip-to-root than the converse. However in the absence of additional data a conclusion cannot be reached.

Conclusions

We presented a study of the frictional characteristics of reptilian shed skin (Python regius). Results showed the directional dependency of the COF. In the forward motion (Tail-to-Head) the COF was less than that measured in the opposite direction (Head-to-tail). A similar trend was reflected in the values obtained for the COF in diagonal sliding.

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