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Research paper

Dynamic impact testing of hedgehog spines using a dual-arm crash pendulum

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ARTICLE INFO

Article history:
Received 29 December 2015
Received in revised form
24 February 2016
Accepted 20 March 2016
Available online 26 March 2016

Keywords:
Impact pendulum
Hedgehog spines
Energy absorption
Biomimicry
Keratin
Humidity

ABSTRACT

Hedgehog spines are a potential model for impact resistant structures and material. While previous studies have examined static mechanical properties of individual spines, actual collision tests on spines analogous to those observed in the wild have not previously been investigated. In this study, samples of roughly 130 keratin spines were mounted vertically in thin substrates to mimic the natural spine layout on hedgehogs. A weighted crash pendulum was employed to induce and measure the effects of repeated collisions against samples, with the aim to evaluate the influence of various parameters including humidity effect, impact energy, and substrate hardness. Results reveal that softer samples—due to humidity conditioning and/or substrate material used—exhibit greater durability over multiple impacts, while the more rigid samples exhibit greater energy absorption performance at the expense of durability. This trend is exaggerated during high-energy collisions. Comparison of the results to baseline tests with industry standard impact absorbing foam, wherein the spines exhibit similar energy absorption, verifies the dynamic impact absorption capabilities of hedgehog spines and their candidacy as a structural model for engineered impact technology.

1. Introduction

Hedgehog spines are naturally impact resistant. In the wild, hedgehogs climb trees and plants in search of food (Matthews, 1963; Vincent and Owers, 1986). They often fall (or jump to avoid predators) from heights exceeding ten meters. A falling hedgehog rolls into a ball and uses its dorsal muscles to erect its spines before impacting the ground at speeds up to 15 m/s (Matthews, 1963, 1974; Vincent and Owers, 1986). Despite the velocity at impact, the animal survives unscathed due to the shock-absorbing capabilities of its spines, which buckle under load (Vincent and Owers, 1986; Karam and Gibson, 1994). Clearly, these spines serve a vital purpose beyond their ability to stab predators with their tapered ends (Matthews, 1963), especially considering how difficult it is to remove a hedgehog spine from a hedgehog (Carlier, 1893), versus a porcupine quill from a porcupine. The porcupine quill, which functions solely as a weapon, extracts from the pelt easily (Cho et al., 2012). Made of alpha-keratin,

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http://dx.doi.org/10.1016/j.jmbbm.2016.03.019

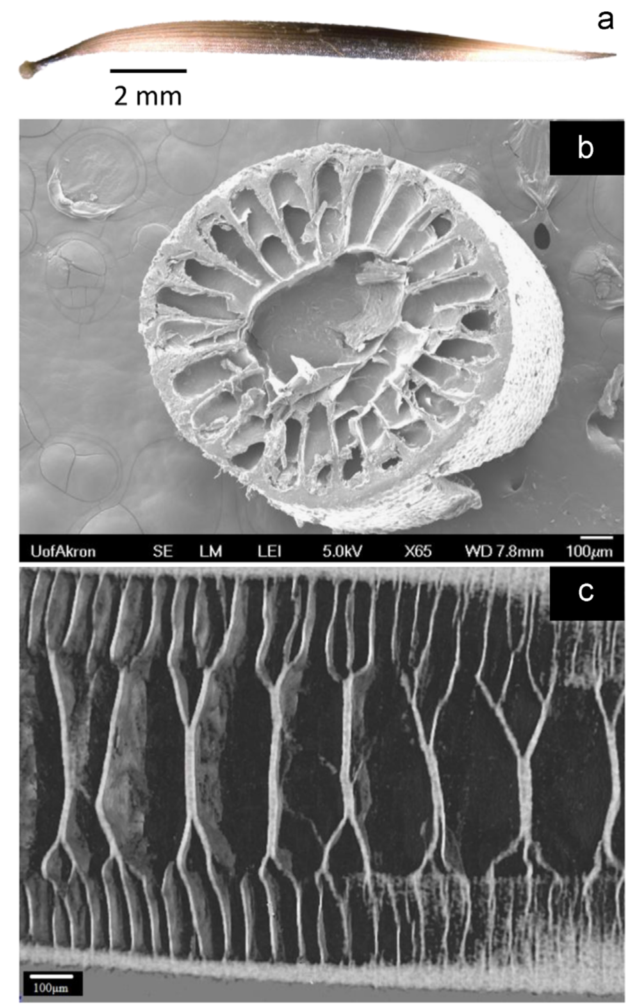

Fig. 1 – (a) Photograph of a hedgehog spine, showing the bulbed end on the left, which attaches to the animal; (b) SEM of a spine's lateral cross-section; (c) CT scan of a spine's longitudinal cross-section.

hedgehog spines have a unique internal morphology (Fig. 1) (Gibson et al., 2010). When force is applied axially to an individual spine, it begins to "bow" laterally—closely following the Euler buckling model—once the critical buckling load is achieved. If greater force is applied, the spine will continue to bow until roughly 200 times the critical buckling load is applied, at which point the spine ovalizes (characterized by the Brazier effect) and fails, buckling locally. In testing the longitudinal strength of spines with internal septa removed, Vincent and Owers (1986) discovered that spines failed under far less axial load than with septa present. They concluded that it is due to the internal morphology that failure is delayed to such a great magnitude beyond the critical buckling load, as circumferential septa resist tensile load and reinforce the spine's cylindrical shape (Brazier, 1927; Calladine, 1983; Vincent and Owers, 1986; Ashby, 2005; Gibson et al., 2010).

Measuring 1 mm diameter, 15–20 mm length (Vincent and Owers, 1986) and weighing an average 3.5 mg, a hedgehog spine is a potential model for innovation of high strength-to-weight ratio, impact resistant structures. It is likely that engineered structures based on hedgehog spines would be more mechanically-efficient in terms of specific strength (Karam and Gibson, 1994; Gibson et al., 2010), material-efficient, and lighter weight than conventional structures (Beukers and van Hinte, 2005). Impact related studies in both engineered and natural armor materials have attracted great attention in recent time (Chen et al., 2011; Song et al., 2011; Huang et al., 2011; Chintapalli et al., 2014; Rudykh et al., 2015; Bruet et al., 2008).

Few experimental studies have been conducted on the mechanical properties of hedgehog spines. Vincent and Owers (1986) and Karam and Gibson (1994) conducted compression and bending tests on hedgehog spines, finding that the critical Euler buckling force for a single spine is roughly 6 N and that it takes 200 times the critical buckling load to initiate the Brazier effect (Vincent and Owers, 1986). Aside from additional verification by the aforementioned researchers, as well as some similar studies on the static mechanical properties of porcupine quills (Chou and Overfelt, 2011; Chou et al., 2012; Yang et al., 2013; Torres et al., 2014), there are no other documented mechanical tests on hedgehog spines and no literature on dynamic behavior of hedgehog spines during impact. However, understanding hedgehog spines' dynamic properties is of utmost importance for assessing their impact protection capabilities, which depend largely on an object's acceleration and mechanical energy absorption (Guskiewicz and Mihalik, 2011). Durability—consistent performance across multiple impacts—is also important for many applications such as concussion mitigation in football helmets (Pellman et al., 2004). However, hedgehog spine durability has not been investigated. Furthermore, Vincent and Owers (1986) and Karam and Gibson (1994) only tested static properties of individual spines instead of many spines grouped together similar to the arrangement on a hedgehog pelt (Fig. 2), which typically have thousands of densely packed spines. Yet, there is reason to believe from observational evidence that spines' systematic grouping enhances their impact protection capabilities. Also, it is known that keratin's mechanical properties are affected by relative humidity of the material, wherein increased humidity generally softens keratin, while decreased humidity makes keratin harder and more brittle (Curiskis and Feughelman, 1983; McKittrick et al., 2012). In similar context, porcupine quills, which are also made of keratin and consist of a hard outer shell (cortex) and compliant porous core (medulla), exhibit considerably lower modulus and strength with increased

Fig. 2 – Densely packed spines embedded in the pelt of a dead hedgehog.