Journal of the Mechanical Behavior of Biomedical Materials 75 (2017) 413–422

Contents lists available at ScienceDirect

Journal of the Mechanical Behavior of Biomedical Materials

journal homepage: www.elsevier.com/locate/jmbbm

Static flexural properties of hedgehog spines conditioned in coupled temperature and relative humidity environments

Emily B. Kennedy[a], Bor-Kai Hsiung[a], Nathan B. Swift[b], Kwek-Tze Tan[c,*]

[a] Department of Biology, Integrated Bioscience Ph.D. Program, University of Akron, Akron, OH 44325, USA
[b] Department of Physics, Science Technology Entrepreneurship Master's Program, Case Western Reserve University, Cleveland, OH 44106, USA
[c] Department of Mechanical Engineering, University of Akron, Akron, OH 44325, USA

ARTICLE INFO

Keywords:
Three-point bending
Flexural behavior
Hedgehog spines
Coupled temperature and humidity
Biomimicry

ABSTRACT

Hedgehogs are agile climbers, scaling trees and plants to heights exceeding 10 m while foraging insects. Hedgehog spines (a.k.a. quills) provide fall protection by absorbing shock and could offer insights for the design of lightweight, material-efficient, impact-resistant structures. There has been some study of flexural properties of hedgehog spines, but an understanding of how this keratinous biological material is affected by various temperature and relative humidity treatments, or how spine color (multicolored vs. white) affects mechanics, is lacking. To bridge this gap in the literature, we use three-point bending to analyze the effect of temperature, humidity, spine color, and their interactions on flexural strength and modulus of hedgehog spines. We also compare specific strength and stiffness of hedgehog spines to conventional engineered materials. We find hedgehog spine flexural properties can be finely tuned by modifying environmental conditioning parameters. White spines tend to be stronger and stiffer than multicolored spines. Finally, for most temperature and humidity conditioning parameters, hedgehog spines are ounce for ounce stronger than 201 stainless steel rods of the same diameter but as pliable as styrene rods with a slightly larger diameter. This unique combination of strength and elasticity makes hedgehog spines exemplary shock absorbers, and a suitable reference model for biomimicry.

1. Introduction

Hedgehogs are agile climbers (Matthews, 1952). In the wild, these small mammals scale trees and plants to heights exceeding 10 m while foraging insects (Matthews, 1952; Vincent and Owers, 1986). When a hedgehog needs to descend from an above ground perch quickly–to escape a predatory owl, for example–it will roll into a ball and simply drop to the ground (Matthews, 1952; Vincent and Owers, 1986). The hedgehog survives impact because its spines (a.k.a. quills) absorb shock. The shock absorbing function of hedgehog spines distinguishes them from porcupine quills, which can support considerable loads (Yang et al., 2013; Yang and McKittrick, 2013), but have a primary function of self-defense via predator tissue penetration (Kyung Cho et al., 2012). Tissue penetration is the primary function of many slender structures in nature, such as honeybee and paper wasp stingers (Zhao et al., 2015), and mosquito proboscises (Aoyagi et al., 2008). The impressive shock absorbing properties of slender hedgehog spines is unique.

A thorough investigation of static flexural properties is necessary to provide a fundamental understanding of the way hedgehog spines absorb impact energy because the spines bend under impact load. A combination of material properties and internal structure lends resilience. Spines typically return to pre-deflection orientation after the load is removed and stored energy is released. Three-point bending is the technique of choice for this study. Vincent and Owers (1986) conducted four-point bending on hedgehog spines, but this technique required they reinforce the load-bearing surfaces of the spines with plastic tubing to prevent premature failure at anvil contact points. This manipulation may have impacted their data. Three-point bending allows flexural testing of unmodified hedgehog spines. Despite the shortcomings of the four-point bending technique, results of the Vincent and Owers study provide strong evidence of hedgehog spines' shock absorbing function. These researchers observed a load-to-failure of 0.392 ± 0.0276 GPa (Vincent and Owers, 1986). Spines buckled elastically, resisting permanent deformation unless exposed to 200 times the critical buckling load (Vincent and Owers, 1986; Wang et al., 2016).

In this study, we also test the effect of precise temperature and humidity conditioning parameters on flexural properties of individual hedgehog spines, which are made of alpha keratin. Researchers have found keratin's flexural strength and modulus are inversely related to

---

* Corresponding author.
E-mail address: ktan@uakron.edu (K.-T. Tan).

http://dx.doi.org/10.1016/j.jmbbm.2017.08.009
Received 11 May 2017; Received in revised form 3 July 2017; Accepted 4 August 2017
Available online 05 August 2017

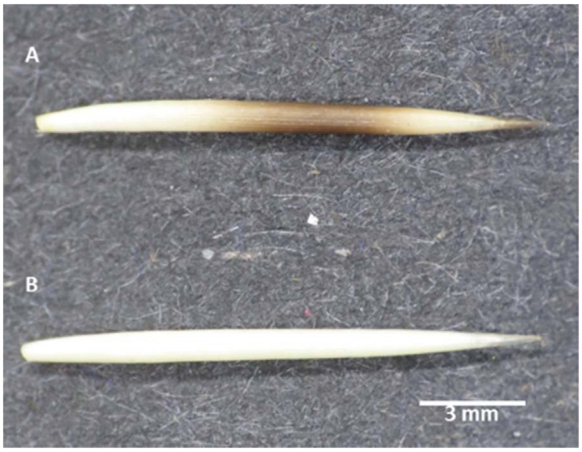

Fig. 1. Multicolored vs. white hedgehog spines. A multicolored hedgehog spine (A) and a white hedgehog spine (B).

temperature and relative humidity (Wang et al., 2016). For example, increasing temperature weakens rat stratum corneum (Papir et al., 1975) and marine snail (whelk) egg capsules (Miserez et al., 2009), two other keratinous biological materials. Likewise, increases in relative humidity result in decreased tensile strength as well as axial and circumferential moduli of keratinous North American porcupine quills (Chou and Overfelt, 2011). Swift et al. (2016) investigated the effect of humidity conditioning on hedgehog spines using a weighted crash pendulum to impact 130-spine arrays mounted in thin substrates. Compared to dry samples, wet samples exhibit increased durability (i.e. ability to withstand multiple impacts without visible damage) but reduced energy absorption. We advance understanding of the effect of conditioning parameters on hedgehog spines by further differentiating and better controlling humidity conditions, adding temperature as a potentially interacting variable, and focusing on mechanics of *individual* hedgehog spines rather than spine arrays.

Hedgehog pelts are covered in a mix of uniformly distributed multicolored and white spines (2.44 ± 0.44:1, N = 2112) (Fig. 1). We decided to examine effects of spine color on hedgehog spine mechanics because no earlier studies have considered this obvious variable. The midsections of the predominant multicolored hedgehog spines appear darker, perhaps due to higher concentration of melanin pigment, which absorbs light over a wide range of wavelengths (Menon and Haberman, 1977). Though there is currently no experimental evidence that melanin pigment is present in the midsections of multicolored hedgehog spines, we infer that there could be, due to the darker color. A higher concentration of melanin correlates with increased mechanical strength of other biological tissues, such as plant cell walls (Karam and Gibson, 1994), insect cuticle (Riley, 1997), bloodworm jaws (Moses et al., 2006a, 2006b), and feather barbs (Butler and Johnson, 2004). The midsections of multicolored hedgehog spines may have pooled melanin for added strength because under loading, spines ‘domino’ into one another with the midsections being the most common contact point. Thus, we test the hypothesis that multicolored spines are stronger than white spines.

Finally, we compare the flexural properties of hedgehog spines with conventional engineered materials to determine the suitability of hedgehog spines as a model for biomimicry. In the field of mechanical engineering, biomimicry has led to a number of technological advances including human bone-inspired building frames with reduced seismic vulnerability (Mendez, 2010), woodpecker-inspired electronics housing (Yoon and Park, 2011), nacre-inspired deformable glass (Valashani and Barthelat, 2015), and mantis shrimp-inspired high-performance carbon fiber–epoxy composites (Grunenfelder et al., 2014). Hedgehog spines, a less studied biological tissue, could offer additional insights for the design of lightweight, material-efficient, impact-resistant structures (Gibson et al., 2010; Ma et al., 2008).

This work thus provides scholarly contributions in the following areas of investigation:

1. Analyzing the effect of various temperature treatments on static flexural properties of hedgehog spines.
2. Examining the effect of various relative humidity treatments on static flexural properties of hedgehog spines.
3. Expounding the effect of spine color on static flexural properties of hedgehog spines
4. Elucidating interaction effects of various temperature and relative humidity treatments, as well as spine color, on static flexural properties of hedgehog spines.
5. Evaluating and comparing specific strength and stiffness of hedgehog spines vs. conventional engineered materials.

2. Materials and methods

2.1. Sample preparation

An uncured hedgehog pelt, donated by West Coast Hedgehogs (Corvallis, OR) was removed with all spines attached from a female African Pygmy (*Atelerix albiventris*), aged 1.5 years, which died earlier that day of natural causes. The hedgehog had shed its juvenile spines and grown a mature coat of adult spines. Upon receipt, the pelt was stored in a freezer at − 20 °C for three months to prevent deterioration. Spines were clipped from the thawed pelt at the spine-pelt connection point. Seventy-two mature spines of approximately equal dimensions (~ 16 mm in length and ~ 1 mm in diameter), were selected for testing. These spines included 36 multicolored and 36 white. Pelt location played no part in spine selection since spines sampled from all regions of the pelt exhibited highly similar length and diameter (Swift et al., 2016).

Prior to conditioning, individual specimens were weighed with a CAHN 21 Automatic Electrobalance (CAHN Instrument Company, Paramount, CA) (3.76 ± 0.38 mg, N = 72). Spines were conditioned in each coupled temperature and relative humidity environment (Table 1) before mechanical testing. Temperature and relative humidity values were chosen based on past studies of keratinous biological materials (Chou and Overfelt, 2011; Miserez et al., 2009; Papir et al., 1975). We do not attempt to recreate hedgehog habitat conditions. Highest and lowest conditioning parameters are quite extreme to make it easier to detect statistically significant differences in spine mechanics across conditions. Using extreme parameters, we can interpolate intermediary mechanical behavior, including within biologically-relevant ranges. For each unique temperature and relative humidity combination, six specimens (three multicolored and three white) were placed in an open Styrofoam cube and conditioned for 48 h (per ASTM D790-15e2) in a Z8-Plus (Cincinnati Sub-Zero, Cincinnati, OH) temperature and humidity chamber. Upon removal from the chamber and prior to lidding, a two-way humidity pack was added to the Styrofoam cube containing the spines in an attempt to maintain humidity at conditioned level.

2.2. Three-point bending

Three-point bend tests were conducted on the 72 conditioned

Table 1
Conditioning parameters and their abbreviations.

	Relative humidity (RH)			
Temperature	**35%**	**60%**	**70%**	**85%**
1 °C – Low	LT35	LT60	LT70	LT85
23 °C – Room	RT35	RT60	RT70	RT85
80 °C – High	HT35	HT60	HT70	HT85