Dynamic Impact Testing of Hedgehog Spines Using a Dual-Arm Crash Pendulum

Nathan B. Swift^a, Bor-Kai Hsiung^b, Emily B. Kennedy^b, Kwek-Tze Tan^{c*}

^a Department of Physics, Science Technology Entrepreneurship Master's Program, Case Western Reserve University, Cleveland, OH 44106, USA

^b Department of Biology, Integrated Bioscience PhD Program, The University of Akron, Akron, OH 44325, USA

^c Department of Mechanical Engineering, The University of Akron, Akron, OH 44325, USA

* Corresponding author: Tel: [+1-330-972-7184](tel:+13309727184); Fax: [+1-330-972-6027](tel:+13309726027); E-mail address: ktan@uakron.edu

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.

Keywords: Impact pendulum; Hedgehog spines; Energy absorption; Biomimicry; Keratin; Humidity

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 (Carlier 1893) versus a porcupine quill, which functions solely as a weapon (Cho *et al.* 2012). Made of alpha-keratin, hedgehog spines have a unique internal morphology (Figure 1) (Gibson, Ashby, and Harley 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, Ashby, and Harley 2010).

Measuring 1 mm diameter, 15-20 mm length (Vincent and Owers 1986) and weighing an average 3.5mg, a hedgehog spine is a potential model for innovation of a 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, Ashby, and Harley 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, Ortiz and Boyce 2011; Huang, Durden and Chowdhury 2011; Chintapalli *et al.* 2014; Rudykh, Ortiz and Boyce 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, Overfelt, and Miller 2012; Yang, Chao and McKittrick 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 (Figure 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 humidity under axial loading (Chou and Overfelt 2011; Chou, Overfelt, and Miller 2012; Torres *et al.* 2014). Humidity's effect on strength and energy absorption, durability, and failure point of hedgehog spines, however, has not been investigated. Adding to that, impact performance of hedgehog spines has not been compared to standard impact protection materials.

In this paper, a dual-arm "crash pendulum" is employed to measure the amount of energy absorbed by spine arrays embedded in a substrate across a variety of parameters, including substrate hardness, kinetic impact energy, relative humidity of the spines, and the effect of multiple hits. This work aims to fill the gaps in knowledge about hedgehog spines' dynamic mechanics. The investigation involving a harder substrate examines how spines alone absorb impact energy by breaking since the epoxy provides fixed and rigid support boundary condition. The softer PU substrate, however, provides a simply support boundary condition, and works more as a system with the spines, contributing to impact absorption when allowing bending at the base of the spines, which more closely resembles spine-in-pelt behavior.

This work aims to provide scholarly contributions in the following areas:

1. First experimental demonstration to show that hedgehog spines function as an impact energy absorber.
2. First study of hedgehog spines as a group system, rather than individual spines, like in previous studies.
3. Identify key coupling elements and parameters to improve and influence the impact absorption performance of hedgehog spines system.
4. Intimate emphasis on Biomimicry and reveal how engineered structural materials can benefit through Biomimicry approach.

2. Methodology

2.1 Sample Preparation

Intact spines were collected from a naturally deceased three-year old female African Pygmy hedgehog (*Atelerix albiventris/algirus*) donated to the study from Lawrence, KS. The pelt with all spines attached was skinned from the animal immediately following its death and stored in an oven set at 60° C for two weeks to facilitate plucking (Carlier 1893; Matthews 1963). Spines were individually plucked as needed for each sample, with each spine averaging about 15mm in length. Spines sampled from all regions of the pelt exhibited similar length and diameter

($l=15.70 \pm 0.63$ mm, $d=0.98 \pm 0.06$ mm, $N=53$) so region of origin played no part in spine selection. Geographical uniformity of spines is corroborated by Vincent & Owers (1986). Spines could not be left in the pelt for impact testing due to the variable size, thickness and brittleness of the pelt as it decomposed, making it difficult to mount to the apparatus and adversely affecting data reliability. Using molded substrates, on the other hand, provided a consistent, flat, and sturdy base with unvarying mechanical properties. Test samples were generated by first mounting 130 spines vertically with the sharp end into a piece of packing foam. Next, the foam with spines was flipped and placed over a 5cm diameter circular substrate mold so that the bulbous ends of the spines were held vertically embedded in the 3-5mm thick substrate as it cured for 24 hours (see schematic of process in Figure 3(a), S1). The 5cm diameter substrates had sufficient surface area to yield statistically greater energy absorption than the no material baseline. Mounting 130 spines in the 5cm diameter substrates approximately mimicked the average spine density on the natural model: 6.6 spines per square centimeter. Based on Vincent and Owers (1986) as well as the authors' own measurements, spine density ranges from 3.9-11.6 spines per square centimeter, depending on how tightly the animal is rolled into a ball. Two different substrate materials were used: MetLab #M135 (MetLab Corp, NY, USA), a hard epoxy rated Shore 82D provides a fixed and rigid boundary condition to largely isolate the spines' absorption capabilities from that of the substrate, and Forsch URS5180 (Forsch Polymer Corp, CO, USA), a softer, more pliable Shore 80A Polyurethane (PU) that provides a simply supported boundary condition by allowing bending moment at the spine/substrate interface. The softer substrate more closely mimics hedgehog flesh and may contribute to the impact absorption. For each sample, the spines were mounted with the bulb end down into the substrate, again mimicking the natural model. A typical finished sample is shown in Figure 3(b).

To test humidity parameters, some samples were placed in a 100% relative humidity chamber for 48 hours after the substrate was cured. These conditioned samples had estimated 85-90% relative humidity during the tests (samples were taken out of the chamber and mounted on the pendulum immediately before each test. A typical test with up to ten repeated impacts was conducted and finished within a 15 minute period), while the unconditioned samples had 48-51% relative humidity according to local weather data.¹ Despite a single hedgehog having thousands of spines, only six samples were generated. A large fraction of spines broke during extraction and we required intact spines for sample preparation. Also, we selected spines to eliminate variation in spine length and diameter (accepted range for $l=15.5$ - 16.0 mm, $d=0.96$ - 1.00 mm).

For a baseline comparison, a layer of foam from a Riddell Speed Classic football helmet was prepared for testing (hereafter referred to as 'Foam'). It was cut down to match the footprint and thickness of the spine samples.

¹ The Weather Channel. 2015. "Weather History for KAKR: Monday, July 20, 2015." *Weather Underground*. http://www.wunderground.com/history/airport/KAKR/2015/7/20/DailyHistory.html?req_city=Akron&req_state=OH&req_statename=&reqdb.zip=44301&reqdb.magic=1&reqdb.wmo=99999

2.2 Testing Apparatus

Impact absorption testing on spines was conducted using a two-arm "crash pendulum" (Figure 4) similar to the setup in Ucar and Cengiz (2012). The system was designed to produce an axially impact loading without gravity effect during impact (Ucar and Cengiz 2012). The crash pendulum can produce impact loading throughout the collision at adjustable velocity and therefore kinetic energy by adjusting the starting height, h ($h = 0$ when the pendulum arm hangs straight down at rest). The two pendulum arms with weights bolted to the ends each swing with a radius of $l = 3.26\text{m}$, connected to hinges by two aluminum extensions in a "V" shape. The total mass of each pendulum arm is $m = 43.32\text{kg}$. Just above the two weights at roughly the center of mass was a rigid 1018 steel sample-mounting surface facing inward toward the other arm. The flat mounting pieces on the two arms were aligned to touch when the pendulum was at rest, hanging vertically under their hinges. Samples were mounted to one pendulum using double-sided tape. Additionally, a Canon PowerShot SD4500 IS high-speed video camera was mounted on a tripod facing the two pendulum arms, and a backboard with calibrated markings was placed behind the arms to record data throughout each collision.

2.3 Pendulum Impact Experimental Technique

Mechanical symmetry between the right and left pendulum arms of the apparatus was established by experimentally testing collisions in both directions. All following trials on the pendulum were conducted by raising the left pendulum and dropping it toward the right pendulum (Figure 4(a)), which initially sat at rest with the sample attached to its collision plate (Figure 4(b)). All trials were conducted with a left arm starting height (h) at one of two points: 4 degrees for 3 Joule collisions (low energy) and 6.5 degrees for 8 Joule collisions (high energy) (Figure 4(a)-I), then analyzed using two independent techniques.

Using the high-speed camera and calibrated backboard, stopping points for the two pendulum arms were measured post-collision (hereafter referred to as 'potential energy difference experimental technique') (Figure 4(a)-III). Using the assumption that total kinetic energy of the pendulum arms immediately before and after the collision equals the starting and final potential energies, respectively of the arms, the total potential energy was calculated from the arms' starting and stopping angles, where for any given pendulum angle:

$$U = mgl(1 - \cos \theta) \quad (1)$$

where U is the total potential energy in Joules of the given pendulum arm at its starting or stopping point; m is the total mass in kilograms of the pendulum arm; g is the acceleration due to gravity; l is the length in meters from the pendulum's hinge to its center of mass; and θ is the pendulum arm's angle in degrees from vertical rest. The small mass addition of the sample mounted to the right pendulum was considered negligible compared to the much larger total mass of the pendulum arm.

The total potential energy (U) of the arms at the stopping points was compared to the initial potential energy of the left arm at the starting point to determine the energy absorbed (ϵ) by the material during the collision:

$$\epsilon = U_{Li} - U_{Lf} - U_{Rf} \quad (2)$$

and normalized absorbed energy (ϵ_{norm}),

$$\epsilon_{norm} = \frac{\epsilon}{U_{Li}} \quad (3)$$

where U_{Li} is the starting potential energy of the left pendulum, U_{Lf} is the final potential energy of the left pendulum after collision, and U_{Rf} is the final potential energy of the right pendulum after collision (Ucar and Cengiz 2012). It is assumed that due to the low velocity of the pendulum arms, air resistance can be ignored (Mohazzabi 2011) and all starting potential energy of the left arm was converted into kinetic energy immediately before collision. Likewise, it is assumed that all kinetic energy of the two arms immediately after collision was converted back into final potential energy of the two arms when they came to a stop. Other uncertainties that cannot be easily measured, such as the effect of arm vibration or friction in the hinges are accounted for by comparing experimental results to 'Foam,' as well as placing no samples between the two crash pendulum arms so that only the apparatus itself absorbs energy (hereafter referred to as 'No Material'), which will be discussed in section 3.4.

Collisions were repeated on a given sample up to ten times or until the sample was destroyed beyond functionality, as determined through visual assessment (Table 1). In addition, collisions were repeated on the two baselines: 'Foam' and 'No Material', for a performance comparison that accounted for vibrational/frictional uncertainties in the apparatus, as well as to confirm the accuracy of the apparatus by calculating standard error across all hits, which was found to be under 3%.

The pendulum arms' starting and stopping angles in both directions from vertical 'rest' position were recorded manually at the time of experiment and then verified using the high-speed camera footage. These data points were then converted to potential energy U using Equation 1. Finally, the total energy absorbed (ϵ) and normalized absorbed energy (ϵ_{norm}) were plotted against the baselines over consecutive hits of the same sample in order to evaluate sample durability. The research team recorded visual post-mortem observations of sample damage.

The velocity and acceleration of the two pendulum arms throughout the collision were found by analyzing the high-speed camera footage with ProAnalyst software and applying fundamental equations of motion for calculation (hereafter referred to as 'kinetic energy difference experimental technique'). High-speed video footage was recorded by a Canon PowerShot SD4500 IS at the framerate of 240 fps during each pendulum impact trial. Color stickers were applied to the pendulums around the sample-mounting locus for motion tracking. The stickers mirrored each other in terms of their locations on the left and right pendulums (Figure 4(c)).

ProAnalyst Motion Analysis Software (Xcitex Inc., Cambridge, MA, USA) was used to track each pendulum's stickers frame-by-frame in the high-speed video footage. Coordinate origin was set to the lower left corner of each video recording. Spatial distance in each video was calibrated using a known distance between backboard markings. Pendulum position coordinates (x, y) were exported after each video analysis. Distance travelled for each pendulum between frames (1/240 sec) was calculated using $\sqrt{\Delta x^2 + \Delta y^2}$, and the speed was then calculated accordingly. Speed was plotted as a function of time for each pendulum (Figure S2) and the resulting curves were smoothed. Acceleration-time curves were generated (Figure S3) by taking first derivative of the speed-time curves (Figure S2) in GraphPad Prism statistical software (GraphPad Software, Inc., La Jolla, CA, USA). The calculation of kinetic energy different experimental technique is explained in Figure S4. A summary of energy absorption and acceleration values obtained from high-speed video analysis is presented in Table S1.

3 Results and Discussion

In this section, the impact test results, as performed according to Table 1, are discussed in terms of the following parameters:

1. *Humidity* compares performance of the "dry" spines at 48-51% relative humidity (room environment) versus "humid" spines at 85-90% humidity.
2. *Impact energy* compares performance of spines at 3 Joules versus 8 Joules kinetic energy of the left pendulum immediately before impact.
3. *Substrate* compares performance of spines embedded in the Shore 82D epoxy versus those embedded in Shore 80APU substrates.
4. *Baseline comparison* compares spine samples' performance to 'Foam' and 'No Material'.

3.1 Humidity

Two samples of 130 spines each embedded in Shore 82D epoxy are tested for this comparison. The hardness of the epoxy substrate almost entirely isolates the spines' movement and function, since a fixed and rigid boundary condition is applied. Sample A has spines with approximately 48-51% relative humidity due to storage in normal room conditions, while sample B contains spines at 85-90% relative humidity after being stored in a 100% humidity chamber for 48 hours prior to the experiment. Each is subjected to five consecutive collisions by the crash pendulum, with impact kinetic energy of 3 Joules.

The impact test results are analyzed independently by two different methods as described in section 2.3 (potential energy difference and kinetic energy difference). Each method has pros and cons: While calculating the kinetic energy difference is the most quantifiable way to analyze the results objectively, and many useful parameters can be extrapolated from the analysis (i.e.

speed, acceleration, etc.), it does not account for the residual kinetic energy (velocity v_{Lf}) of the left pendulum after collision. On the other hand, estimating energy absorption using the potential energy difference experimental technique accounts for V_L post-collision, but relies on a visual assessment of pendulum swing angle based on the backboard reference to determine h , and any angle θ less than 0.5 degree cannot be discerned by this method. The energy absorption results based on both methods, which provide a fuller picture than either method alone, are shown in Figure 5.

Results from both methods showed good agreement in trends of energy absorption over multiple impacts—the energy absorption performance of sample A (dry) constantly decreases over the course of multiple impacts, while that of sample B (humid) remains relatively consistent. It is noted that most spines in sample A broke and shattered during the second collision, whereas those in sample B resumed their original form after collision. The brittleness of sample A is attributed to the properties of keratin, wherein the material hardens and stiffens when dried out, and softens and becomes more pliable when wet (Curiskis and Feughelman 1983).

In the third through fifth collisions, the energy absorption of sample A is less than during initial impact and continually degrades, likely due to the fact that most of the spines having already been destroyed by the second collision (Figure 6(a)). In contrast, sample B appears to maintain relatively consistent absorption capabilities throughout the five-collision trial (Figure 6(b)). The softer humid spines appear to be more resilient over repeated low-impact energy collisions, though they are unable to absorb as much kinetic energy during the initial collision compared to dry spines. In general, it can be concluded that stiffer spines may offer greater impact energy absorption capabilities, but at the cost of multi-hit durability. The overall estimated normalized absorbed energy (ϵ_{norm}), is higher when calculated from the kinetic energy difference (Figure 5(b)) because it does not account for post-collision residual velocity v_{Lf} .

3.2 Impact Energy

Next, the influence of different impact speeds is evaluated by introducing two new samples of spines—sample C (dry) and D (humid), both prepared in epoxy substrates. In addition, since the spines in sample B (humid) remained intact after the low energy collisions (Figure 6(b)), they were further investigated to determine their durability by subjecting them to higher energy impacts for additional data points. Again, each sample was subjected to five repeated collisions, each with 8 Joules kinetic impact energy. Sample C was destroyed after two collisions so its use was discontinued. The energy absorption results are presented in Figure 7.

During the first collision, sample C absorbed a greater amount of energy than either humid spine sample (B and D). However, sample C was destroyed after only two hits, much more rapidly than both samples with humid spines (Figure 8(a)). This indicates that the greater impact absorption of the dry spines was due to permanent damage. The two humid spine samples (B and D), on

the other hand, did not shatter and resumed their original form after each collision (Figure 6(b), 8(b)), demonstrating the resiliency of the softer, humid spines. This is especially so for sample B, which endured a total of ten collisions. It is worth noting, however, that unlike in the low energy test (Figure 5), the humid spines in the high-energy test underwent gradual energy absorption depletion over consecutive hits (Figure 7). Additionally, while all samples absorbed more total energy than during the low energy test, they absorbed a smaller percentage of the initial impact energy (normalized absorbed energy (ϵ_{norm})) during the high-energy test versus the low energy test. This suggests that the capability of hedgehog spines to absorb energy becomes saturated during high-energy collisions, resulting in greater damage over multiple hits at higher impact speeds.

3.3 Substrate

In order to more accurately model the hedgehog impact absorption capabilities, spine samples E(dry) and F(humid) were embedded in a softer, more pliable Shore 80A PU substrate. Like the pelt on a hedgehog, the softer substrate may contribute to the impact absorption capabilities of the spine system by increasing the spines' freedom to rotate at the junctions of the substrate and spine bases and allowing load transfer into the substrate via the embedded bulbous ends of the hedgehog spines (Vincent and Owers 1986). The two samples were first subjected to five consecutive collisions in low energy tests, and subsequently to five consecutive collisions in high energy tests, since they were still intact (sample F showed no signs of damage while sample E had very minimal damage).

At first glance, the energy absorption results analyzed by two independent methods do not seem to agree with each other in low energy impact tests. The calculated result using the kinetic energy difference experimental technique (Figure 9(b)) shows that the energy absorption performance for both sample E and F is relatively consistent throughout five collisions during the test. In contrast, the result calculated using the potential energy difference experimental technique (Figure 9(a)) shows a drastic dip at the third and fourth collision before starting to recover. Recall that the difference between these two methods is the inclusion of the left pendulum's residual energy when calculations are performed using the kinetic energy difference experimental technique. By combining results from both methods, the data suggests that the energy transferred from the left pendulum to the right across five different collisions remained consistent during the low energy test (Figure 9(b)). The left pendulum's residual energy after each collision steadily increases and peaks at the third and fourth impact before returning to the initial state (Figure 9(a)). The increase of the left pendulum's residual energy can be explained by the softer substrate. In the samples with a softer substrate, spines have more freedom to rotate at the junctions of the substrate and spine bases. Therefore, the early collisions cause the spines to "flatten," or get pushed and reoriented closer to parallel to the substrate. It is suspected that the movement of the spines limits the amount of energy that can be transferred to the right pendulum during the short collisions, and allows more energy to be

kept on the left pendulum at the same time. This agrees with our observation from the samples after the test: while few spines — especially those in the humid samples — broke or shattered, it was noted that many spines were flattened (Figure 10), something that did not occur with samples in epoxy substrates. A similar trend was observed in the high energy test (Figure 9(c)), though the change in absorption across collisions is less dramatic. This indicates that the early high energy collisions “flattened” the spines further even when the sample had already endured five collisions in the low energy test. The dip likely signifies the point where the spines have the highest freedom to move before reaching maximum “flatness” .

Evidently, despite the researchers’ effort to closely mimic the spine-pelt system of the hedgehog, the PU substrate samples still lacked a control mechanism to keep spines erect from the surface during repeated hits, analogous to the animal’s dorsal muscles. Indeed, the rigid epoxy substrate can adequately keep spines erect after impact, as it allows virtually no spine movement. The results suggest that the first hit reoriented the spines embedded in PU because of the greater “wiggle room” in the elastic substrate, and for each hit following, the spines were pushed closer to parallel to the substrate. On a hedgehog, this could also happen, except the animal has muscles attached to the base of the spines which it contracts to erect the spines hit after hit (Reeve 1994). *As an elastomer, the PU substrate comes closer than epoxy to mimicking the hedgehog pelt system by allowing load transfer into the substrate via the embedded bulbed ends of the hedgehog spines, similar to how impact loads are likely transferred into the hedgehog skin.*

3.4 Baseline Comparison

In each of the above experiments, energy absorption results of the samples are plotted against those of a sample of foam from a Riddell Speed Classic football helmet cut to match the footprint and thickness of the spine samples (‘Foam’), and a second baseline where nothing was placed between the two crash pendulum arms and only the apparatus itself absorbed energy (‘No Material’). The purpose is two-fold: the ‘Foam’ baseline helps measure how hedgehog spines perform as an impact material versus industry standard impact absorbing foam, and ‘No Material’ demonstrates the amount of energy absorbed by the apparatus alone due to friction, vibration, or any other unaccounted-for uncertainty, thus giving to the data perspective as the apparatus’ “zero point.” Despite inherent experimental uncertainties, the results from repeated collisions with ‘Foam’ and with ‘No Material’ show consistency throughout the experiment, confirming the repeatability of the pendulum technique. A t-test analysis of the energy absorption between ‘Foam’ and ‘No Material’ shows that the crash pendulum apparatus has the resolution to tell them apart and further supports the results (Figure 11). Spine samples generally performed similarly to ‘Foam’; indeed some absorbed slightly less while others absorbed slightly more. This confirms hedgehog spines’ inherent dynamic impact absorption capabilities.

3.5 Protection vs. Durability

In the human brain, it is known that certain acceleration of the head is likely to cause injury such as concussion (Ommaya and Gennarelli 1974). Therefore, an impact material that minimizes the acceleration experienced during a collision by absorbing as much kinetic energy as possible can reduce the likelihood of concussion, or other similar injury and damage. Figure 12 compares the acceleration of the pendulum during impact for each sample across all collisions. Overall, during low energy collisions (Figure 12(a)), all samples except the dry epoxy sample experienced significantly lower acceleration when compared to 'No Material.' It seems that at slower collision speeds, the individual parameters tested above on the spine samples make little difference to acceleration. Interestingly, for the high-energy collisions (Figure 12(b)), the exact opposite pattern occurred — only the dry epoxy sample experienced significantly lower acceleration when compared to 'No Material.' One explanation for the seemingly impressive performance of the dry epoxy is that the sample only lasted for two collisions before complete destruction, during which it absorbed more energy than any other sample. The most significant takeaway is that on average, the spines absorb about the same energy as 'Foam,' and therefore reduce acceleration throughout the collision by about as much as 'Foam.'

The other important metric of this study is multi-hit durability. That is, the number of hits that a given sample can endure while maintaining consistent impact absorption performance. In general, there is an observed trade-off. A sample either absorbs a large amount of impact energy during the collision, even outperforming 'Foam' on occasion as with sample C in Figure 7, but at the cost of poor durability — wherein performance deteriorates rapidly after the first couple of hits. On the other end of the spectrum, the softer spine samples exhibit far greater durability, with nearly consistent absorption throughout all collisions, yet energy absorption is roughly equal, if not lower than 'Foam.' An ideal impact protection material balances these two parameters to match the needs of a given application. Perhaps further optimization of the impact technology could concurrently increase performance of both metrics so that one need not be sacrificed to realize the other.

4. Conclusions

This study is the first to investigate the impact energy absorption capability of hedgehog spines beyond anecdotal biological evidence, measuring absorption trends over multiple impacts in a lab setting. Past studies have just suggested the possibility of applying the structural model to impact protection applications rather than demonstrating them. Additionally, no other study has investigated the effect of the densely packed spine arrangement analogous to the hedgehog model, nor have any parametric studies examined the effect of humidity conditioning on hedgehog spines. Our Results show that humidity softens keratin, making spines more durable but less energy absorbent. Greater impact speed decreases

durability, but not initial energy absorption. It is also revealed that softer, elastic substrate adds energy absorption but samples deform more rapidly.

When samples are arranged in an orientation analogous to the natural model, hedgehog spines demonstrate impact absorption capabilities that confirm their role in the protection of hedgehogs during falls. This study demonstrates that in certain conditions, hedgehog spines can absorb as much, if not more, than industry standard impact-absorbing foam. However, there is a definite balance between impact absorption and multi-hit durability, as samples that absorb greater amount of impact energy remain intact for fewer hits due to greater damage, while other samples that absorb less impact energy have greater resilience and can endure significantly more collisions. However, these results only confirm the capabilities of the spine system as a whole. Further studies are still needed to understand the specific roles in impact absorption and durability played by the spines' internal structure, the layout of multiple adjacent spines, the material of the spines, the specific contribution by the substrate material, and a methodology to better control the 'flattening' of spines against the substrate, as each of these variables could alter results.

This investigation is one of the first of likely many steps towards designing and optimizing higher performing engineered impact and structural materials. By demonstrating how hedgehog spines exhibit similar impact energy absorption as a sample of foam from a Riddell Speed Classic football helmet, the authors provide evidence that hedgehog spines are a viable biomimetic model for a commercial impact resistant material. After all, the spines used in this study were harvested from a dead animal, and despite the researchers' best efforts to maintain them, they may have deteriorated prior to testing. Specially designed and synthetically engineered spine structures—built using 3D additive manufacturing or other means—could be optimized for even better impact protection, as demonstrated with the microstructure found in Chiton teeth (de Obaldia *et al.* 2015). Biomimicry has proven time and again to be a reliable and fruitful innovation technique for inspiring new products such as VELCRO, which was developed based on how burrs stick to animal fur (Dickinson 1999). Perhaps a hedgehog-inspired impact protection technology is a forthcoming feat of biomimicry.

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Figure 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.

Figure 2: Densely packed spines embedded in the pelt of a dead hedgehog.

Figure 3: (a) Schematic of sample preparation; (b) A sample of hedgehog spines mounted vertically in a polyurethane (PU) substrate prior to testing.

Figure 4: (a) Schematic of the pendulum apparatus arm motion during the course of one collision trial, with initial starting position (I), moment of collision (II), and post-collision back-swing (III); (b) Photo of the apparatus at rest; (c) Zoom-in detailing the colored stickers for video tracking and the location of the mounted sample (yellow arrow).

Figure 5: Energy absorbed over repeated low energy (3J) collisions. (a) Energy absorption calculated using the potential energy difference experimental technique. (b) Energy absorption calculated using the kinetic energy difference experimental technique (see supplementary). 'Foam' and 'No Material' are plotted as mean $\pm$ s.d. Symbol (●) indicates low energy collisions. Blue is humid, red is dry.

Figure 6: (a) Spines in Sample [A] show substantial breakage after five low-energy collisions; (b) In contrast, the spines in Sample [B] remain mostly intact after five low-energy collisions and five additional high-energy collisions.

Figure 7: Energy absorbed over repeated high energy (8J) collisions. (a) Energy absorption calculated using the potential energy difference experimental technique. (b) Energy absorption calculated using the kinetic energy difference experimental technique (see supplementary). 'Foam' and 'No Material' are plotted as mean $\pm$ s.d. Symbol ($\blacktriangle$) indicates high-energy collisions. Blue is humid, red is dry.

Figure 8: (a) Spines of dry Sample [C] show significant breakage after just two 8 Joule collisions; (b) Most spines of humid Sample [D] remain intact with just minor damage after five consecutive 8 Joule collisions.

Figure 9: Energy absorbed by samples embedded in polyurethane (PU) substrates over repeated collisions. (a,c) Energy absorption calculated using the potential energy difference experimental technique). (b,d) Energy absorption calculated using the kinetic energy difference experimental technique (see supplementary). 'Foam' and 'No Material' are plotted as mean $\pm$ s.d. Symbol (●) indicates low energy collisions; (▲) indicates high-energy collisions. Blue is humid, red is dry.

Figure 10: (a) Side and (b) Top view of Sample [E]. Although some spines broke, many were pressed flat against the PU substrate.

Figure 11: Column plot (mean $\pm$ s.d.) showing significantly different impact absorption ability of 'Foam' and 'No Material' across all collisions. (a) Energy absorption in low energy tests; (b) Energy absorption in high-energy tests. In both low and high-energy tests, 'Foam' always shows significantly higher energy absorption ability over 'No Material.' ** indicates $P < 0.01$, **** indicates $P < 0.001$.

(a)

(b)

*Figure 12: Column plot (mean±s.d.) showing maximum acceleration experienced by the impacted (right) pendulum across all collisions. (a) Compared to 'No Material,' all samples except Epoxy Dry (sample A) experienced significantly lower acceleration in low energy tests. (b) Compared to 'No Material,' only sample A (Epoxy Dry) experienced significantly low acceleration in high-energy tests. * indicates $P<0.05$, ** indicates $P<0.01$.*

Table 1: List of test samples, their relevant characteristics, and total collisions endured.

Sample	Substrate	Humidity	Total Collisions (Impact Energy)
A	Epoxy	Dry	5 (Low)
B	Epoxy	Humid	5 (Low); 5 (High)
C	Epoxy	Dry	2 (High)
D	Epoxy	Humid	5 (High)
E	PU	Dry	5 (Low); 3 (High)
F	PU	Humid	5 (Low); 5 (High)