Microstructure-derived flexibility in the acorn weevil exoskeleton

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We report novel modifications to the composite microstructure of the exoskeleton in the snout of acorn weevils (Coleoptera: Curculionidae) belonging to the genus *Curculio* Linnaeus, 1756.

As a weevil (snout beetle), members of the genus *Curculio* are typified by the presence of a highly elongate structure on the head, called the rostrum (snout). This structure is a hollow, cylindrical extension of the exoskeleton of the otherwise nearly-spherical head, which bears at its apex the terminal chewing mouthparts. The space inside of the rostrum contains the esophagus, various muscles and tendons used for feeding, and hemolymph that serves as a rough equivalent to blood in insects. By contrast, the solid shell of the rostrum is comprised entirely of cuticle, which can be considered a laminate composite consisting of various arrangements of chitin fibers embedded in a protein matrix (see section I). Acorn weevils use this structure to excavate sites for egg-laying (oviposition) and feeding on a variety of fruits, including acorns, Japanese camellia, hazelnuts, pecans, chestnuts, and chinquapins.

During oviposition, a female engages in a unique "drilling" behavior that causes significant, apparently elastic, deformation of the rostrum. The female will insert the snout into an incision made with the mandibles, eating the material as she proceeds, while rotating her head and body around the bore-hole. Once the apex of the snout is inserted, she will push up and forward with her front legs, forcing the rostrum to bend until it is nearly straight. The female will maintain tension on the rostrum in this position, continuing to ingest the substrate and rotate around the bore-hole, while slowly inserting the rostrum further into the excavated channel. Once the rostrum is fully inserted, usually up to the eyes, she will pull her snout from the bore-hole and deposit several eggs into the site. By maintaining constant tension on the rostrum and rotating around the bore-hole, the female is able to flex the snout into a near-perfectly straight configuration and thereby produce a linear channel into the fruit. While this behavior has been observed in many species of *Curculio*, we have lacked a fundamental understanding of how female *Curculio* rostra can withstand the repeated, often extreme bending (over 90°) incurred during the process of oviposition.

We have found that the composite profile of the rostrum is strongly differentiated from the head capsule and other body parts, with modification of both the relative layer thicknesses and fiber orientation angles of cuticle regions (viz. exocuticle and endocuticle), which we describe in detail below. We posit that these modifications enable the snout to be flexed until straight while remaining within the elastic limits of the material and without evident alteration of the mechanical properties of the individual components of the cuticle across the structure and between species. Thus, the flexibility of the rostrum appears to be derived *exclusively* from modification of the composite architecture of the exoskeleton.

Support for this hypothesis has come from three lines of evidence:

1. Examination of the cuticle microstructure across the length of the snout has revealed consistent modification to the composite structure of the rostrum among *Curculio* species.
2. Tensile testing of the rostrum has demonstrated that the mechanical strength of the cuticle components are consistent along the length of the structure and between species.
3. Fatigue testing has shown that a highly curved rostrum is capable of flexing hundreds of thousands of times without damage to the structure, and is apparently elastic.

We additionally describe the fracture mechanics of the snout, as pertains to both cuticle composite structure and tensile behavior, and consider how modification of the cuticle may reduce the risk of rostral fracture during oviposition. To our knowledge, this is the first time that a modified composite profile has been reported as

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a means of enhancing structural elasticity in the insect exoskeleton.

I. MICROSTRUCTURE

Display 1: Pictures of heads, macrofiber arrangement, and exo-endo ratio at base and apex, across species. Explain how everything is laid out across the length of the rostrum, emphasizing that this is key to predicting and understanding the mechanical behavior of the snout during bending. No change in total thickness, only relative layer thickness, No resilin either.

II. TENSILE TESTING AND FRACTURE MECHANICS

The predicted behavior of the snout is borne out by the data, where UTS is strongly correlated with the cross-sectional area of the endocuticle across species.

III. FATIGUE TESTING OF *CURCULIO CARYAE*

IV. CONCLUSION

V. METHODS

Methods, including statements of data availability and any associated accession codes and references, are available in the online version of this paper.

REFERENCES

[1] Leslie Lamport, *LaTeX: a document preparation system*, Addison Wesley, Massachusetts, 2nd edition, 1994.

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AUTHOR CONTRIBUTIONS

ADDITIONAL INFORMATION

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to M.A.J.

COMPETING FINANCIAL INTERESTS

The authors declare no competing financial interests.

METHODS

Method 1

Method 2

Method 3

Statistical analysis

Code availability

Data availability

REFERENCES

[1] Leslie Lamport, *LaTeX: a document preparation system*, Addison Wesley, Massachusetts, 2nd edition, 1994.