Bioinspired Horse Hoof Models for Impact Resistant Materials

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Background

Bioinspiration is the utilization of biological materials as blueprints for new, synthetic materials. Optimized through a millennia of evolution, the horse hoof is the subject for creating bioinspired high impact resistant materials.

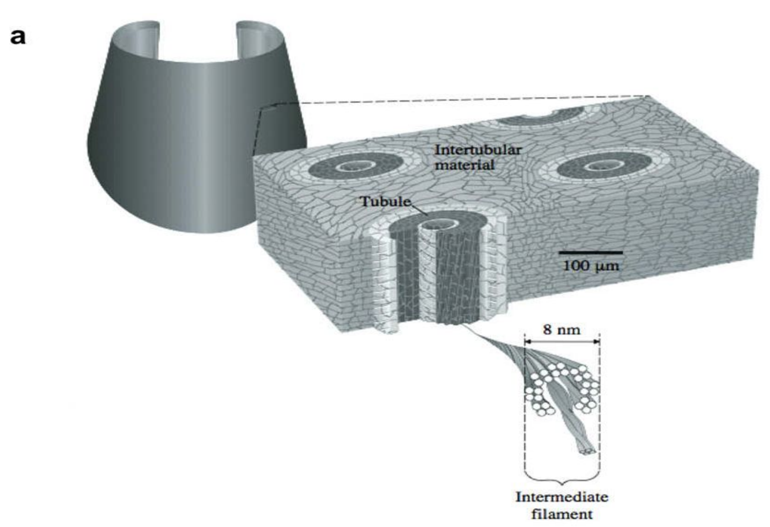

Figure 1: Microscopic computer generated view of a small slice of the hoof wall. [1]

Horse hooves consist of a hierarchical assembly of microstructures that make up the exterior wall. The horse hoof microstructure is composed of a keratin based fibrous nanostructure as seen in Figure 1.

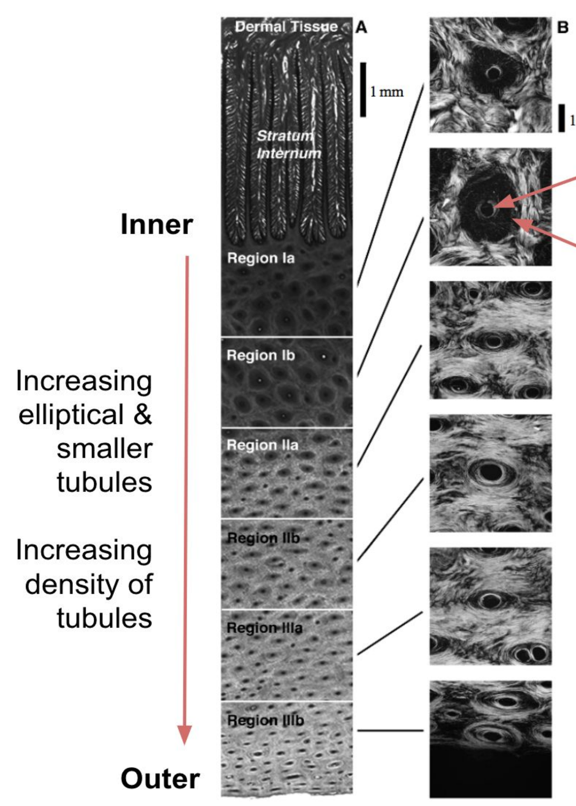

Figure 2: High magnification top down image of the hoof wall from exterior to interior that shows tubule composition throughout the wall. [2]

The filaments formulate the prominent tubular structure that varies from the exterior to interior of the hoof wall. Figure 2 exhibits the variation in patterns through the hoof.

Previous studies focused primarily on testing samples of the real hoof. In particular, compression tests showed how the tubules in the hoof helped to deflect cracks. The tubules direct fractures towards the exterior wall, away from the sensitive interior tissue.

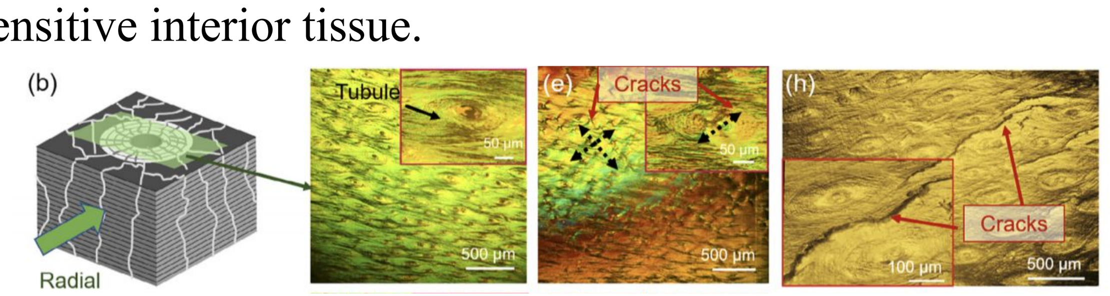

Figure 3: Results from previous compression tests performed on samples of the actual hoof, outlining crack deflection. [3]

Additionally, other studies gathered data on tubule dimensions using electron microscopy. These measurements documented the sizes of tubules in microns.

Motivation

Horses are heavy creatures that impact the ground at high speeds, making their hooves specialized to protect interior flesh. Studying hooves can lead to creating better impact resistant materials. Impact resistance means having the ability to absorb high amounts of energy or shock and thus be less likely to break or deform. Impact resistance can address the need for materials in applications such as helmets, personal protective equipment, car bumpers, and aerospace applications.

Objective

To design bioinspired models with two aims:

1. Learn more about functionality of hoof microstructures
2. Dictate guidelines for future bioinspired models and impact resistant materials

Method

Gather data on dimensions of tubular microstructure from previous studies

↓

Scale up dimensions from microns to macroscale

↓

Use data to model samples using Computer Aided Design software

↓

3D Print the models

↓

Conduct physical impact and compression testing on the models

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Analyze results to make comparisons with models and real hoof samples

The models were created with 64 tubules that serve as an inspired representation of the hoof wall from exterior to interior. These models were then sized to meet 3D printing practicality and testing capabilities.

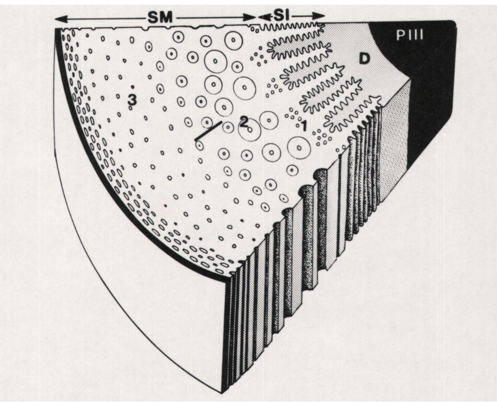

Figure 4: Computer generated visualization of the hoof wall that depicts the independent variables. [4]

Models feature independent patterns and variables in the hoof:

- Tubule density gradient
- Cortical layers surrounding the tubule cavity (stiffer)
- Tubule shape gradient
- Lamellar layers, intermediate filament (flexible)

Results

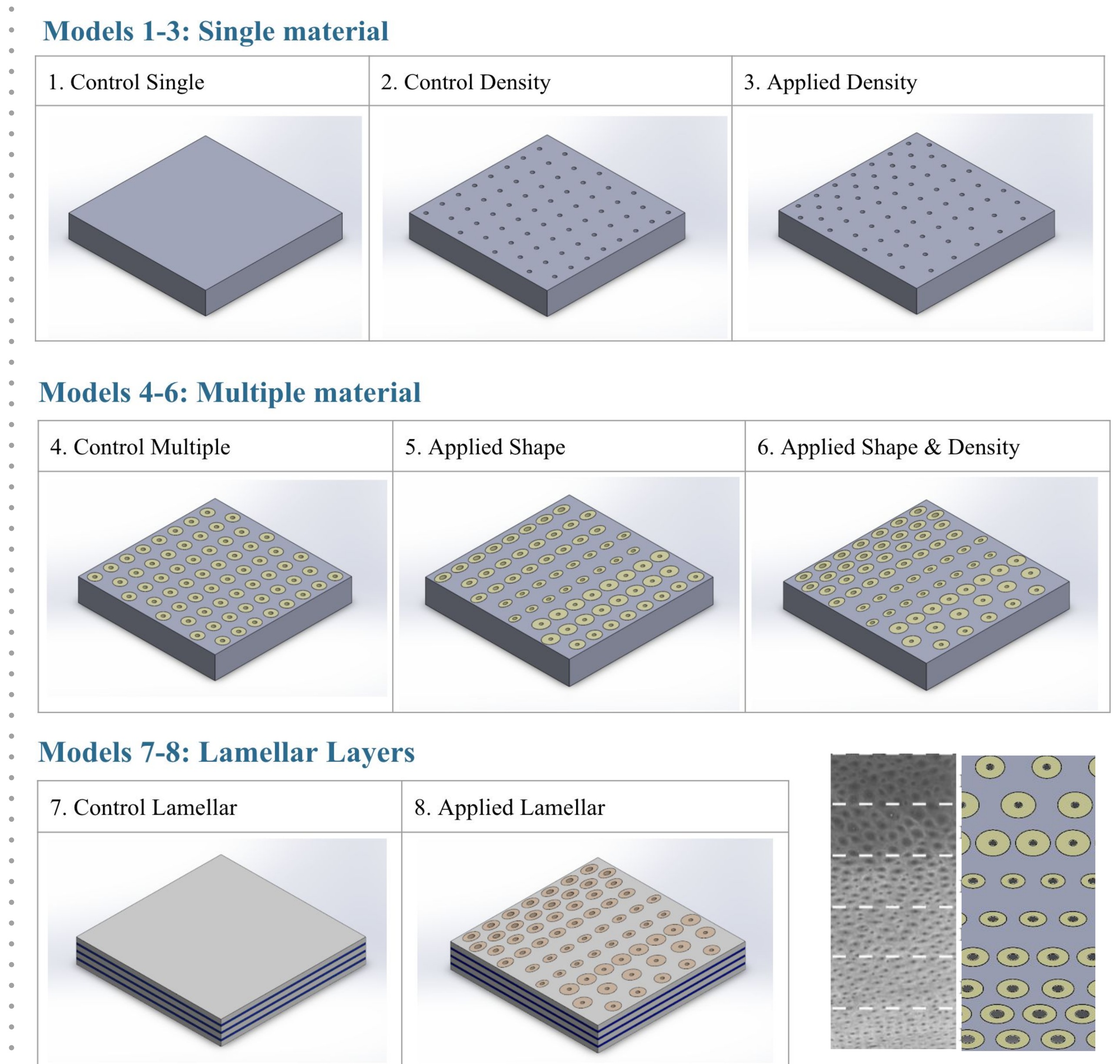

Figure 5: Isometric views of the set of bioinspired models with varying aspects of the hoof microstructure.

Figure 6: Top down views of the hoof wall(left) and Model 6(right).

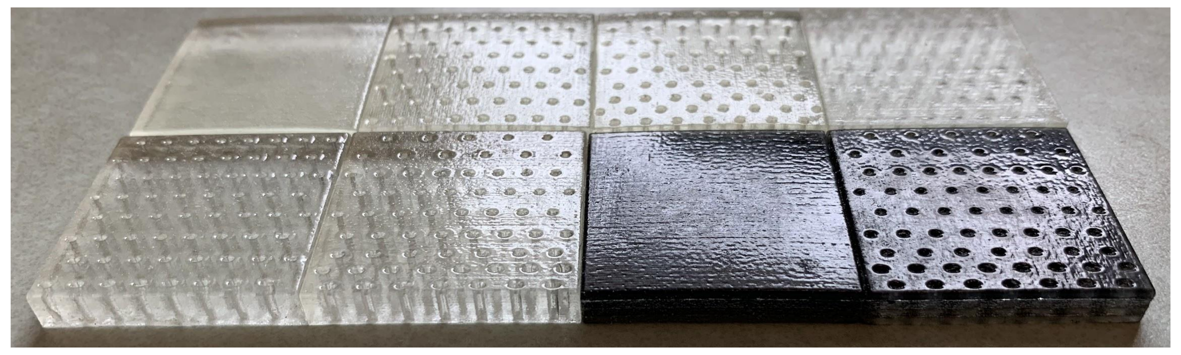

Figure 7: 3D Printed sample of each bioinspired model. Top Row: Model 1-4. Bottom Row: Model 5-8.

Physical 3D printed models were printed using PolyJet method as 30x30x5cm samples. Print materials are photopolymers: VeroClear (E=2 GPa), Rigur (E=1.2 GPa), TangoBlack (E = 0.9 MPa) to simulate similar ratios seen within the real hoof wall samples.

<u>Preliminary Results for Physical Testing</u>

Initial drop tower impacting testing results are promising.

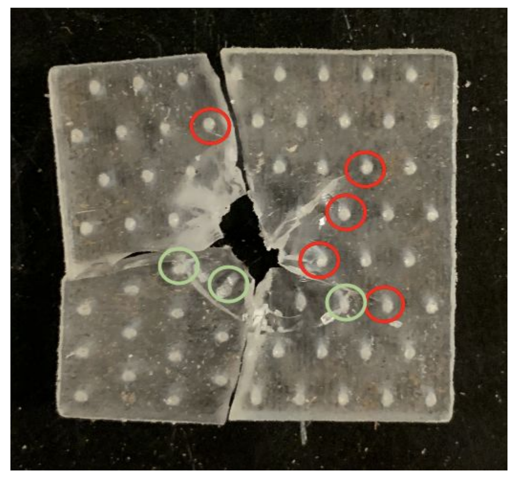

Figure 8: Fracture results from drop tower impacting testing Model 3.

As predicted, the tubules do show visual signs of crack deflection behavior similar to the behavior seen in the real hoof. In Figure 8, green circles indicate tubules that helped to guide/deflect the cracks. Red circles indicate tubules where the crack interface is actually arrested by the tubule.

Both crack deflection mechanisms are also present in the real hoof, validating these synthetic models to the extent of this initial testing. After seeing this proof of concept, testing is continuing.

Discussion

In testing phase, the models have shown great promise in results. Expected results from the physical tests will provide insight on how the models fracture which can lead to greater understanding of the functionality of the tubular structure. With these results, comparisons can be made with previous results from studies done on real hoof samples. When comparing mechanical performance, it is expected that the bioinspired models would outperform the actual hoof samples because of the improved mechanical properties of the synthetic materials. Through this general comparison, the design of the bioinspired models can be validated.

Future work includes exploring:

- Different scale and number of tubules (ie. a single tubule or an arrangement of four tubules) like seen in Figure 9
- Finite element analysis and simulations for the models like seen in Figure 10
- Hooves of other species

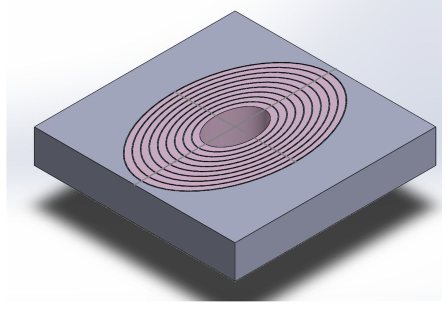

Figure 9: Isometric concept model of a singular tubule.

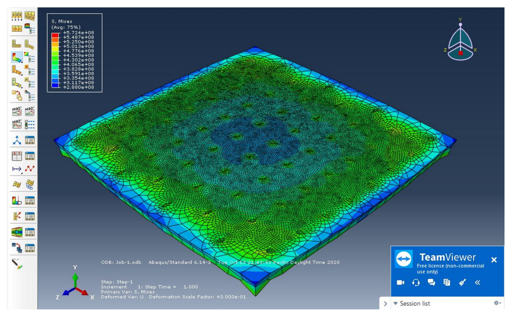

Figure 10: Visualization of the concept for ABAQUS finite element simulation.

Conclusion

As an ongoing research project, the bioinspired models are soon to be characterized and validated. The models have the potential to make a strong contribution to both bioinspiration and the study of the horse hoof. This project, as an intersection point of materials science, biology, and mechanical engineering, will help to catalogue property findings and cultivate design guidelines for new synthetic materials. The study of the microstructure of the horse hoof through model design will provide novel insights in the burgeoning field of bioinspiration and will contribute to the next generation of impact resistant materials.

Acknowledgements

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References

[1] Tombolato, L., Novitskaya, E., Chen, P., Sheppard, F., & McKittrick, J. (2010). Microstructure, elastic properties and deformation mechanisms of horn keratin. Acta biomaterialia, 6 2, 319-30

[2] M.A. Kasapi, J.M. Gosline, Design complexity and fracture control in the equine hoof wall, J. Exp. Biol. 200 (1997) 1639–1659.

[3] Huang, W., Yaraghi, N. A., Yang, W., Velazquez-Olivera, A., Li, Z., Ritchie, R. O., Kisailus, D., Stover, S. M., & McKittrick, J. (2019). A natural energy absorbent polymer composite: The equine hoof wall. Acta Biomaterialia, 90, 267–277. https://doi.org/10.1016/j.actbio.2019.04.003

[4] Leach DH, Zoerb GC. Mechanical properties of equine hoof wall tissue. American Journal of Veterinary Research. 1983 Nov;44(11):2190-2194.

[5] Naleway, Steven & Porter, Michael & Mckittrick, Joanna. (2015). Structural Design Elements in Biological Materials: Application to Bioinspiration. Advanced materials (Deerfield Beach, Fla.). 27. 5455-5476. 10.1002/adma.201502403.

[6] B. Wang, W. Yang, J. McKittrick, M.A. Meyers, Keratin: structure, mechanical properties, occurrence in biological organisms, and efforts at bioinspiration, Prog. Mater Sci. 76 (2016) 229–318.

[7] J. McKittrick, P.Y. Chen, S.G. Bodde, W. Yang, E.E. Novitskaya, M.A. Meyers, The structure, functions, and mechanical properties of keratin, JOM 64 (2012) 449– 468.

[8] M.A. Meyers, P.-Y. Chen, A.Y.-M. Lin, Y. Seki, "Biological materials: Structure and mechanical properties," Progress in Materials Science 53(1) 1-206(2008).