Optimization of hard–soft material interfaces: A 3D printed imitation of bone–tendon connections

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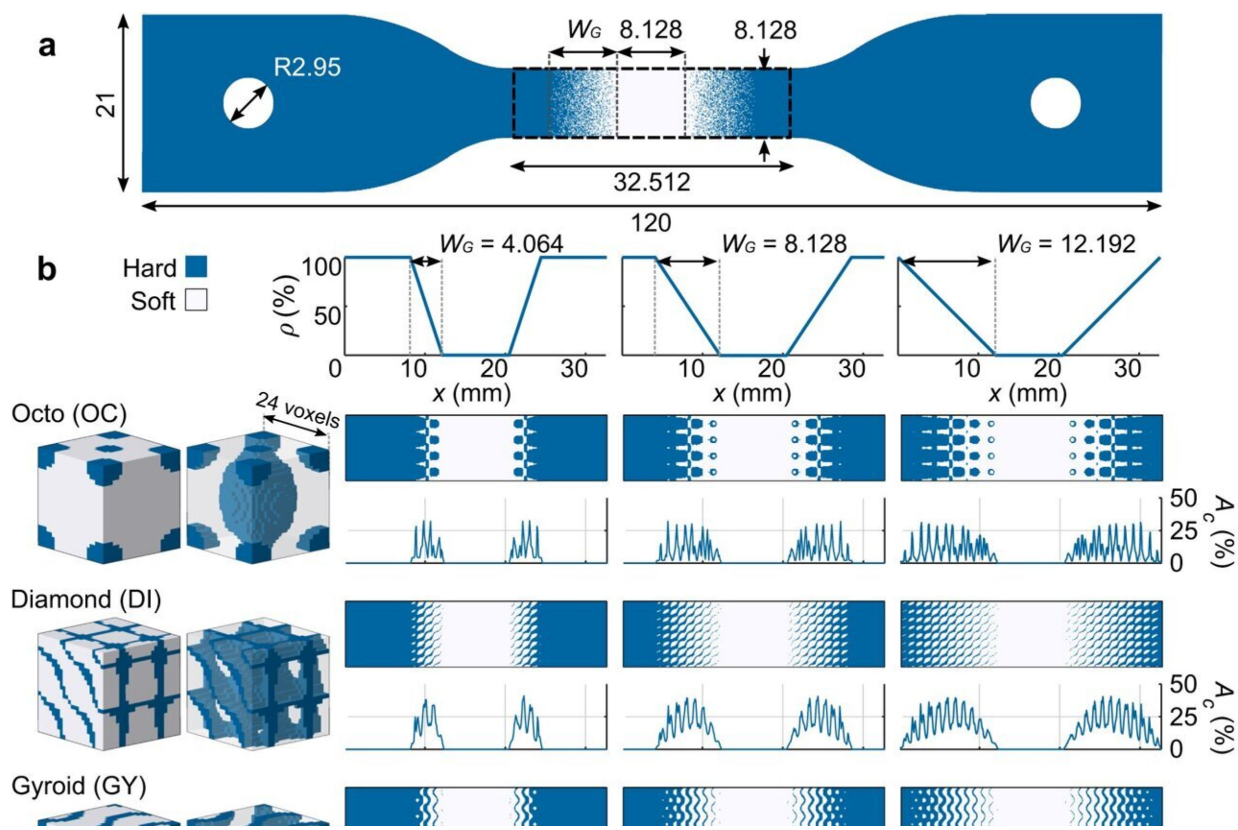

The soft–hard interface designs tested under tensile conditions. a The standard tensile test specimens furnished with a functional gradient connecting the hard and soft polymer phases through linear functions of hard phase volume fraction (*p*) (out-of-plane thickness = 4 mm). **b** All the initial designs with different functional gradient widths (W_G) and their calculated percentage of the soft–hard normal contact area (A_c). We combined three different values of the gradient length (W_G) with five different unit cell geometries (i.e., Octo, Diamonds, Gyroids, collagen-like helices, and randomly distributed particles). Credit: *Nature Communications* (2023). DOI: 10.1038/s41467-023-43422-9

Most people can relate to having a laptop charger break right where the flexible cable meets the solid adapter. This is just one example of how difficult it is to effectively interface hard and soft materials. Using a unique 3D printing process, TU Delft researchers produced hybrid multi-material interfaces that reached a remarkable closeness to nature's design of bone–tendon connections. Their research findings, recently published in *Nature Communications*, have numerous potential applications.

Despite the great difference in hardness between bones and tendons, their intersections in the human body never fail. It is this bone-tendon connection that inspired a team of researchers from the faculty of Mechanical, Maritime and Material Engineering (3mE) to explore ways to optimize the hard and soft interfaces of man-made materials.

Design inspiration

Whenever there is a mismatch between two connected materials, it results in a stress concentration, explains Amir Zadpoor, Professor of Biomaterials and Tissue Biomechanics. That means the mechanical stress goes to the connection point and usually results in failure of the softer material. One of the things seen in nature is a gradual change in properties at an interface.

"A hard material doesn't suddenly become a soft material," says Zadpoor. "It changes gradually, and that smooths out the stress concentration." With that in mind, the researchers used different geometries and a multi-material 3D printing technique to increase the contact area between hard and soft interfaces, thereby emulating nature's design.

Another design consideration is that the force that a soft material can tolerate before failure is lower than that of a hard material. "It's only relevant to make the interface as strong as the soft material, because if it's stronger, the soft material will fail anyway and that's your theoretical limit," says Dr. Mauricio Cruz Saldivar, the first author of the manuscript.

The researchers were able to enhance toughness values of interfaces by 50% as compared to a control group. Approaching the limit of what is theoretically possible is one of the main contributions of this research, according to the team. But the study also resulted in a set of design guidelines for improving the mechanical performance of bioinspired soft-hard interfaces, principles which are universally applicable.

A whole product in one go

The technique developed by the team also enables the making of a whole product at once. This is important because products with multiple materials are generally attached by adhesives. Parts might be assembled or mechanically connected like in automotive or aerospace applications.

"But what we are trying to do is remove the extra steps that are involved, and have everything in one go," says assistant professor Zjenja Doubrovski. "That makes it possible for us to combine even more exotic materials together, for example, materials that have more damping resistance versus materials that are stronger." And this combination enables a higher range of applicability.

Future applications

Many things can be done with this technology. Potential applications include medical devices, soft robotics, and flexible devices. But the team also aims to explore making interfaces with living cells to enable procedures like connecting implants to the surrounding soft tissue.

"Eventually, we would like to regenerate bone and the connection between the bone and the muscle," says assistant professor Mohammad J. Mirzaali. "That would mean integrating living cells into this interface, which would add multiple layers of complexity to the construct." Ultimately, the results of this work leave the door wide open to a range of future studies.

More information: M. C. Saldívar et al, Bioinspired rational design of bi-material 3D printed soft-hard interfaces, *Nature Communications* (2023). DOI: 10.1038/s41467-023-43422-9

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