

LETTER TO THE EDITOR

## A Definition of Soft Materials for Use in the Design of Robots

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### Editor's Note

As part of our mission to be a central forum for issues in soft robotics, we publish roundtable discussions and opinion pieces that are important to the community. We are also interested in facilitating discussions of key issues through open letters and responses. The following letter is open for discussion. It provides a working definition of soft materials for use in robotic applications. We welcome short responses that can be sent directly to the *Editor-in-Chief*.

Dear Editor:

THE FIELD OF soft robotics is concerned with the use of soft materials for new applications in robotics. But what do we mean when we say “soft”? When assigning a label to anything, it is helpful if that label gave descriptive information about that particular object; that is, the name should give us information about the function of the object and how it is unique and differs from other objects. In the case of soft materials, the term “soft” can mean different things in different contexts. For example, the journal *Nature*, when categorizing articles, uses the definition: “Soft materials are materials that can be easily deformed by thermal stresses or thermal fluctuations at about room temperature.”<sup>1</sup> The National Institute of Standards and Technology (NIST), when describing the measurement techniques of properties of soft materials, defines soft materials as “primarily organic, amorphous, and ... highly viscous fluids.”<sup>2</sup> In general, however, the common use of the word “soft” can refer broadly to the characteristics of any type material as it undergoes large deformation. Conversely, when we say “hardness” we are referring to the ability of a material to resist permanent deformation.<sup>3</sup> When we refer to materials as being either “soft” or “hard,” we compare them to other similar materials over a limited range of applied stress regardless of their crystal structures, glass transition temperatures, internal energies, or molecular compositions. That is, when the hardness tester drives an indenter into carbon steel, we see that it is soft in comparison with sapphire, but they are both very hard in comparison with wood or gelatin. So, the terms “soft” and “hard” appear relatively well defined when comparing similar materials, but a more

global definition for “soft materials” is needed for an unambiguous discussion of soft robots.

The distinction between the physical “soft matter” and the engineering “soft material” is important. Engineering materials are the result of chemistry, processing, and resulting microstructure. Matter is only the result of chemistry. A physical definition of soft matter is when the intermolecular kinetic energy is close to  $kT$  (i.e., at room temperature).<sup>4</sup> This means that there is sufficient thermal energy in the environment to easily break and reform bonds in the material. However, an engineering material cannot be described so simply because it is often a composite structure that is processed from matter into a form that can be used in the design of a product. A good example of this distinction is glass. Silica is the matter that forms glass and it is not considered soft matter. Indeed, in pure form, as an engineering material, it is hard and brittle when cast into sheet or bar form. However, encased in an elastomer matrix, glass fibers provide strength and rigidity in a new composite material, which could be considered soft.

The softness of this composite is only possible because softness is a bulk, extensive property of materials. Consider a thin film of our glass fiber/elastomer composite as it undergoes deformation in six degrees of freedom. When stress is applied in the in-plane orthogonal directions  $\sigma_x$  and  $\sigma_y$ , there is some deformation. The same stress in the out-of-plane direction  $\sigma_z$  will produce a comparably small deformation. If we bend the film about the  $x$  and  $y$  axes, we see considerable deflection, but about the  $z$  axis there is very little deformation before buckling and cracking of the fibers occur. By contrast, with a volume  $dx dy dz$  where  $dx = dy = dz$ , stresses applied in all three directions ( $x$ ,  $y$ , and  $z$ ) result in deformations of the same order of magnitude if the fibers are arranged

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randomly. If the fibers are oriented in a particular direction, they add rigidity in that direction. A similar example can be extrapolated to metamaterials, wherein even though the intensive mechanical properties of the materials may show high resistance to deformation (high modulus), the material structure formed may be very soft due to low stiffness provided by the lattice structure.<sup>5</sup>

Part of this issue is that we need to move the description of engineering materials away from terms originally developed for metals. Flexible, rigid, tough, and hard. These words are relative to a set of macroscopically homogeneous materials, usually found in the form of billets, like metals. The anisotropic glass-reinforced elastomer in the mentioned example can be flexible in certain directions and rigid in others because of its extensive properties. These properties can sometimes contribute to our common language definition of “soft” because of our human experience with the material. If the range of applied stress is in the range of the forces exerted by the human hand, and the resulting deformations are readily perceptible and of the order of the deformations of our sensory organs (e.g., our skin), the material will appear soft to us. This notion aids our design of soft robots because we want the robot to be safe around humans in any level of interaction (e.g., working alongside or use in surgery). An alternative, but related, definition might be to extend this idea to consider a structure soft if the stresses typically imposed by the environment create similar or greater deformations in the structure than the environment. This would require the material to be softer than the environment it is interacting with and would not necessarily limit the designer to a small set of matter and engineering materials. Now our soft robot will conform to the environment, be robust, and impact resistant.

Knowing this, let us define “soft materials” concisely: *A bulk or composite collection of matter that undergoes deformations of similar or greater magnitude than the deformation of the environment, either plastically or elastically, within the force regime applied by its environment.* This way, we can include materials such as foams, steel wool in a sock, water in a bag, and other creative materials for building our soft robots.

## References

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