EML Webinar Overview: Extreme Mechanics of Soft Materials for Merging Human-Machine Intelligence

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Abstract

Long-term, high-efficacy and highly compatible interfaces between human bodies and machines are critical to both addressing grand societal challenges such as healthcare and answering great scientific questions such as understanding human brain. We propose to understand and exploit *soft materials technology* – polymers, elastomers, hydrogels and biological tissues with designed properties – to form the interfaces between human bodies and machines. In this Extreme Mechanics Letters (EML) webinar[1], we discussed the design of soft materials to achieve extreme mechanical properties, which are crucial to forming such long-term, high-efficacy and highly compatible interfaces that can potentially merge humans and machines and their intelligence ultimately.

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Introduction

Whereas human tissues and organs are mostly soft, wet and bioactive; machines such as electronic devices and robots are commonly hard, dry and biologically inert. What if we can form long-term, high-efficacy and highly compatible interfaces between human bodies and machines to potentially merge humans and machines and their intelligence? Such interfaces can be crucial to both addressing grand societal challenges such as healthcare and answering great scientific questions such as understanding human brain.

For example, wearable electronics, medical equipment and implantable medical devices are medical machines that attempt to merge with human bodies over timescales ranging from hours, to days, to months and years. While these medical machines have been dramatically advanced over the last few decades, their interfaces with human bodies remain mostly the same, for example, metal electrodes on tissues. The primitive interfaces often severely hamper the medical machines' effectiveness and duration in monitoring, diagnosis and therapy of healthy people and/or patients. While medical machines together with artificial intelligence hold great promise to revolutionize healthcare[2,3]; long-term, high-efficacy and highly compatible interfaces between the machines and human bodies will indeed play a key role in this revolution. As another example, although more and more powerful computers are continually being developed, the interfaces between computers and human brains are still limited to merely a few thousand neurons among human brain's approximately 86 billion neurons[4]. Simultaneous interrogation of millions of neurons over the long term such as months to years will potentially give a new understanding of human brain. However, such understanding will rely on the development of long-term, high-bandwidth and highly compatible brain-machine interfaces. Besides the abovementioned examples, the merging of humans and machines will potentially revolutionize other fields such as artificial intelligence, robotics and virtual reality, making similar levels of impacts on the society and science.

Despite the great promise, the merging of human bodies and machines is extremely challenging, largely because of the dramatically different properties between human bodies and machines. Existing machines mostly rely on engineering materials such as metals, silicon, glass, ceramics and plastics to communicate and interact with human bodies. On the other hand, the major compositions of human bodies are polymers and water, which usually constitute soft materials or hydrogels with moduli ranging from a few pascals to a few megapascals. The hard, dry and inorganic characteristics of engineering materials are intrinsically unmatched or incompatible with the soft, wet and living nature of biological tissues and organs.

Soft Materials Technology

We propose to understand and exploit *soft materials technology* – polymers, elastomers, hydrogels and biological tissues with designed properties – to form the interfaces between human bodies and machines (**Fig. 1**)[5-7]. On one hand, we design soft materials that possess mechanical and physiological properties similar to various tissues and organs of human bodies to form long-term and highly biocompatible interfaces with human bodies[8]. On the other hand, we integrate or embed machines such as sensors, actuators, batteries, microprocessors and microrobots in the soft-material interfaces to achieve high-efficacy high-bandwidth communication and interactions with human bodies.

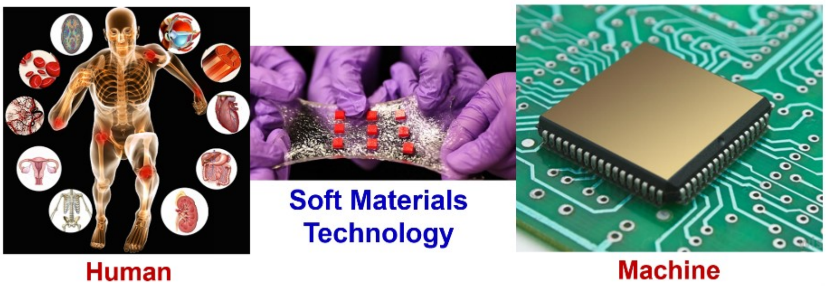

Figure 1. We propose to understand and exploit *soft materials technology* – polymers, elastomers, hydrogels and biological tissues with designed properties – to form long-term, high-efficacy and highly compatible interfaces between human bodies and machines[5].

Extreme Mechanics of Soft Materials

In developing the soft materials technology, we can leverage the great achievements in biology, materials and machines over the last few centuries. In particular, since the major compositions of the soft materials are polymers and water, the knowledge from polymer chemistry and physics is of foundational importance to soft materials technology[9-12]. Furthermore, because the soft-material interfaces will act as part of human bodies and part of machines over the long term, we need to design extreme mechanical properties for the soft materials to guarantee their long-term integrity and robustness in dynamic physiological environments in human bodies. In this EML webinar[1], we discussed three topics on extreme mechanics of soft materials with examples of applications in interfacing humans and machines: 1). adhesion – bioadhesives for instant strong adhesion of wet dynamic tissues and machines to replace sutures and staples; 2). fatigue – fatigue-resistant hydrogel coatings for medical devices; 3). actuation – ferromagnetic soft robots to empower minimally invasive surgeries.

Adhesion. Bioadhesives have potential advantages over sutures and staples for wound closure and integration of implantable devices onto wet tissues including ease of use, air-

/water-tight sealing, and minimal tissue damage[13,14]. However, most commercially-available bioadhesives suffer from limitations including weak bonding, slow adhesion formation, and/or poor mechanical match with wet biological tissues. To address the challenge of weak bonding, we proposed[15] to integrate tough dissipative hydrogel matrices[16-19] and strong interfacial linkages[20-22] to form the bioadhesives (**Fig. 2a**). Following this principle, we and others designed hydrogel adhesives that can adhere on diverse engineering materials including metals, glass, ceramics, elastomers, other hydrogels, and tissues, achieving interfacial toughness over 1000 Jm^{-2} (compared to common performance of ~20 Jm^{-2})[15,23-27].

To address the challenge of slow adhesion formation, we proposed a dry-crosslinking mechanism, where a dry polymer network quickly absorbs interfacial water on tissue surfaces and then form instant physical bonds and strong covalent bonds with the tissues (**Fig. 2b**)[28,29]. Once adhered to wet tissues, the bioadhesive becomes a tough hydrogel with mechanical compliance comparable to those of soft tissues. Following this principle, we designed bioadhesives, in the form of dry double-sided tapes, which can form tough adhesion with diverse tissues and devices within 5 s (compared to common performance of a few minutes)[28,29]. The tissue double-sided tapes have found diverse applications in adhering tissues and devices. For example, we adhered drug patches and stretchable strain sensors on beating animal hearts within 5 s, which maintained their robust adhesion and functions over multiple hours to days (**Fig. 2c**)[28].

Overall, the design principle for the tough and fast bioadhesives can be summarized in one equation,

$$\Gamma = \Gamma_0\left(t \geq t_{water}\right) + \Gamma_D \tag{1}$$

where Γ is the interfacial toughness, Γ_0 and Γ_D are the contributions from interfacial linkages and bulk dissipation to the interfacial toughness, respectively, and t_{water} is the time required to remove the interfacial water before the adhesion can be formed.

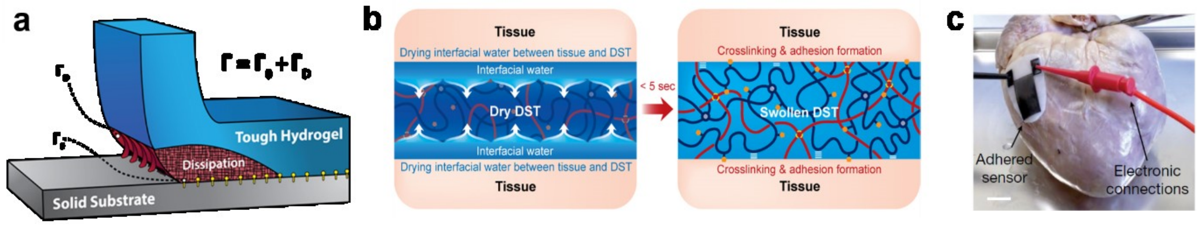

Figure 2. Adhesion of soft materials: design principles for (a) tough and (b) fast adhesion of hydrogels with wet tissues and devices[15,28]. (c) a stretchable strain sensor adhered on a beating *ex vivo* porcine heart by the tough and fast bioadhesive[28]. *Source:* Figures adapted from (a)[15], (b) [28] and (c)[28].

Fatigue. Hydrogel coatings of devices are one most common embodiment of the soft-material interfaces between human bodies and machines. The hydrogel coatings can often be subjected to cyclic mechanical loads in long-term applications. While bulk mechanical dissipation can toughen hydrogels under a single cycle of load[16-19], the dissipation will be depleted over cyclic loads, making the tough hydrogels susceptible to fatigue fracture[30-32]. To address this challenge of fatigue failure, we and others proposed to design intrinsically high-energy phases (IHEPs) such as nanocrystals, micro-/nano-fibers, and macro-fibers in hydrogels (**Fig. 3a**)[33-36]. Since the energy required for fracturing the IHEPs are much higher than that for fracturing individual amorphous polymer chains, fatigue cracks can be pinned by the IHEPs, giving high fatigue thresholds over 1000 Jm^{-2} (compared to common performance of ~50 Jm^{-2})[33-35]. Note that the IHEPs in hydrogels have been named as other terms such as elastic dissipaters[35].

In addition, we further proposed to bond the IHEPs on interfaces to form fatigue-resistant adhesion and coatings of hydrogels on diverse engineering materials including metals, glass, ceramics and elastomers[37]. Following this design principle, we achieved tough and fatigue-resistant hydrogel coatings on various medical devices such as ingestible sensors, pacemakers and Foley catheters (**Fig. 3b**)[37-39].

Overall, the design principle for fatigue-resistant hydrogels and fatigue-resistant adhesion of hydrogels can be summarized in one equation,

$$G_c = \Gamma_0 \tag{2}$$

where G_c is the measured fatigue threshold or interfacial fatigue threshold, and Γ_0 is the energy required for fracturing a unit area of the IHEP hydrogel in front of the fatigue crack (without the contribution from depleted bulk dissipation under cyclic loads).

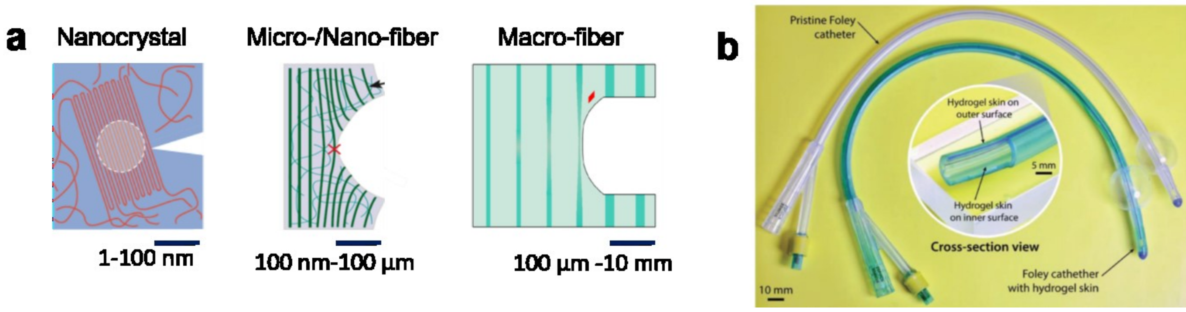

Figure 3. Fatigue of soft materials: (a) design principles for fatigue-resistant hydrogels by making the fatigue crack pinned by intrinsically high-energy phases including nanocrystals[33], micro-/nano-fibers[34] and macro-fibers[35]. (b) tough and fatigue-resistant hydrogel coatings on medical devices such as a Foley catheter[38]. *Source:* Figures adapted from (a)[33-35] and (b)[38].

Actuation. Soft robots that can operate in previously inaccessible lesions in human bodies will potentially revolutionize minimally invasive surgeries, enabling doctors to remotely diagnose and treat patients[40]. In particular, magnetic fields offer a safe and effective method for actuating such soft robots that closely interact with human bodies[41]. Despite their great promise, existing magnetic soft robots often have simple geometries and/or simple ferromagnetic-domain patterns, limiting their functions and innovations. We proposed to three-dimensionally (3D) print the ferromagnetic domains and geometries of ferromagnetic soft materials and robots (**Fig. 4a**)[42]. The resultant ferromagnetic soft robots are more complex than previous ones in terms of their geometries and patterns of ferromagnetic domains[42].

We further discovered that the presence of ferromagnetic soft materials does not substantially alter the applied magnetic fields, since the permeability of magnetized ferromagnetic soft materials is similar to that of air (**Fig. 4b**)[42]. Taking advantage of this discovery, we developed a quantitatively predictive model for the large deformation of ferromagnetic soft materials and robots under magnetic fields (**Fig. 4b**)[42,43]. In the model, the effect of applied magnetic fields on the deformation of ferromagnetic soft materials can be accounted for by one additional term in the Cauchy stress of the material,

$$\boldsymbol{\sigma}^{\text{magnetic}} = -\frac{1}{\mu_0 J}\mathbf{B}^{\text{applied}} \otimes \mathbf{F}\tilde{\mathbf{B}}^{r} \tag{3}$$

where $\boldsymbol{\sigma}^{\text{magnetic}}$ is the additional magnetic Cauchy stress, $\mathbf{F}$ is the deformation gradient and $J = \det \mathbf{F}$, μ_0 is the permeability of air, $\tilde{\mathbf{B}}^{r}$ is the residual magnetic flux density in the ferromagnetic soft material in the undeformed state, and $\mathbf{B}^{\text{applied}}$ is the applied magnetic flux density for actuation (**Fig. 4b**).

This quantitatively predictive model can readily guide the design and control of ferromagnetic soft materials and robots for various applications. For example, we designed a guidewire robot made of the ferromagnetic soft material (**Fig. 4c**)[44]. Under remotely applied magnetic fields, the guidewire robot can bend toward any desired direction on demand, navigating through the complex branches in the human vascular system (**Fig. 4c**)[44]. With this capability, the guidewire robot can be potentially used to treat endovascular diseases such as acute ischemic stroke in a tele-operated and/or autonomous manner, greatly empowering minimally invasive surgeons.

Furthermore, the synergistic achievements in artificial intelligence, fifth-generation (5G) telecommunications, and medical robots that operate in human bodies will potentially converge in recent years to revolutionize healthcare of the society, especially in the sector of minimally invasive surgeries[40]. The mechanics and models for actuation of soft materials will play an essential role in the design and control of soft medical robots. For example, model-based large-scale simulation data assisted by machine-learning algorithms can be potentially used to design new structures and robots in an experience-free manner[45] and/or to autonomously control the robots in human bodies[40,44].

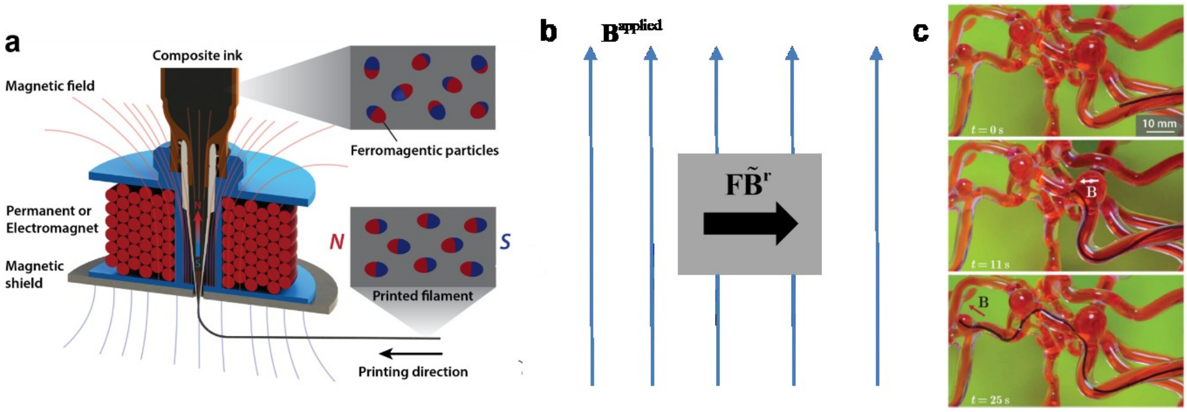

Figure 4. Actuation of soft materials: (a) three-dimensional printing and (b) model of ferromagnetic soft materials and robots[42,43]. (c) a guidewire robot made of the ferromagnetic soft material navigating in a cerebrovascular phantom[44]. *Source:* Figures adapted from (a)[42], (b)[43] and (c) [44].

Summary

This paper summarizes the topics discussed in an EML webinar given on May 6th 2020[1]. While soft materials technology holds great promise to provide long-term, high-efficacy and highly compatible interfaces between human bodies and machines, we need to design, exploit and understand many more properties of the soft materials other than the ones discussed in this webinar to reach the full potential of such interfaces.

For example, hydrogels with high electrical conductivity and/or high capacitance are being designed and studied for long-term, high-efficacy and biocompatible neural interfaces[46-

[49]. It is highly desirable for acoustic soft-material interfaces between human bodies and machines to possess tunable and/or gradient acoustic impedances to match those of tissues and machines[50]. Hydrogel optical fibers that interface with human bodies rely on the design of hydrogels with high transparency (for low light absorption and scattering) and high refractive index (for low bending loss)[51,52]. While the superior mechanical and physiological match between soft-material interfaces and biological tissues can potentially alleviate foreign-body reaction of human bodies to machines[53], the chemical and biological properties of the soft materials still need to be further designed or improved for long-term biocompatible interfaces with human bodies[54].

In addition, since the soft-material interface will play a multifunctional role as part of human bodies and part of machines over the long term, they will likely require multiple mechanical, physical, chemical and biological properties integrated in one soft material system in a synergistic (instead of exclusive) manner. To this end, understanding the design principle for each property will greatly facilitate the coordination and integration of multiple attributes in the soft material by design.

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