ARIECA
201 N Braddock Ave. • Suite 334
Pittsburgh, PA 15206
(919)741-7549 • partner@arieca.com

# LMEE: Unlocking the Potential of Soft Materials

Movies are full of smart clothing that can monitor and respond to changes in a host's body. Fundamental limitations of real materials keep many of these clever ideas in the realm of science fiction. That is beginning to change. Leveraging the latest research in liquid metal embedded elastomers (LMEE), materials are being developed that will make science fiction a reality.

Future materials will require the ability to comfortably conform to the human body while effectively conducting heat and electricity. In nature, these are conflicting characteristics. Materials that have good electrical and thermal properties suffer from mechanical rigidity, which impairs the wearable experience. Conversely, soft, conforming materials have poor electrical and thermal properties. These conflicting properties force undesirable trade-offs on designers of new materials. New discoveries in the field of LMEE demonstrate that this trade-off can be broken[i], opening vast new possibilities for innovative designs.

## Mechanical Properties

To appreciate the nature of the trade-off, we need to quantify a material's ability to conform to movement, which is measured by a parameter called the Young's Modulus (Y). Young's Modulus is the ratio of stress a material experiences when it is strained (stretched). The mathematical relationship is simple: Y = {stress}/{strain}.

Young's Modulus is measured in units of Pascals. Although mathematically simple, Young's Modulus can be confusing. It was formulated in the $19^{th}$ century and is a measure of stiffness; a higher modulus means a material is stiffer. That is, for a given force a higher modulus material will stretch less. This is illustrated in **Figure 1**, which shows the Young's modulus for natural materials as well as materials used in engineering.

Since we desire easily stretchable materials, our desired goal is to create materials with as low a modulus as possible. It is important to recognize that a material that is easier to stretch is also easier to compress. This property, the ability to stretch or compresses with little external force, is essential for wearable materials. We want materials that move with a host's body without requiring the exertion of significant energy. Unfortunately, conventional methods of improving a material's electric properties comes at the expense of an increased modulus.

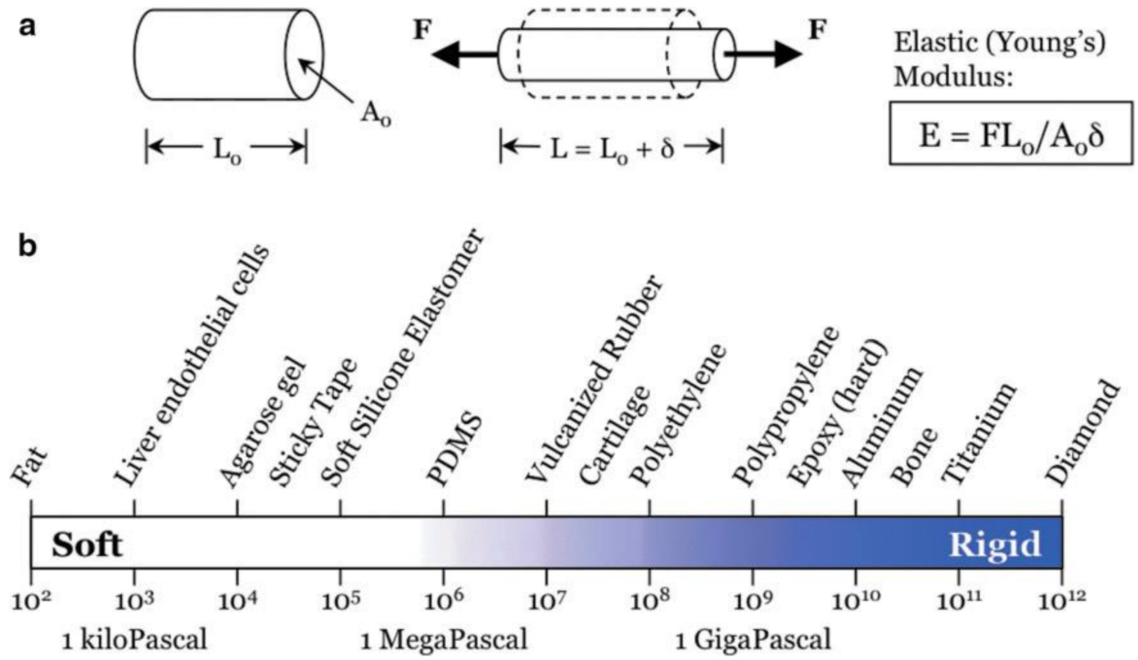


Figure 1: (a) The elastic (Young's) modulus scales with the ratio of the force F to the extension d of a prismatic bar with length L0 and cross-sectional area A0. (b) Young's modulus for various materials.[ii]

## Electrical Properties

Electronics, either in the form of sensing, actuating, or communicating will be an essential aspects of future wearables. Establishing a reliable electrical connection between multiple components in a manner that doesn't adversely impact the wearable experience is required. Conventional conductive materials have two major disadvantages. First, solid metal material does not conform well to the human body, reducing freedom of motion. Second, conductive rubbers that are soft and stretchable exhibit a dramatic change in electrical resistance when stressed or compressed. Since the volume of a wire will remain constant during stretch or compression, the cross-sectional area of the wire varies inversely with length. Thus, the electrical resistance varies with the square of the length change. For conductive rubbers with rigid filler particles, the change in resistance can be even more extreme due to strain-induced separation of the conducting filler particles. This increases complexity in designing flexible circuits.

A unique property of LMEE is that its liquid filler and microdroplet architecture can accommodate stretching without significantly increasing electrical resistance[iii]. The comparison of the resistance of a conventional wire and one fabricated from LMEE is shown in **Figure 2**.

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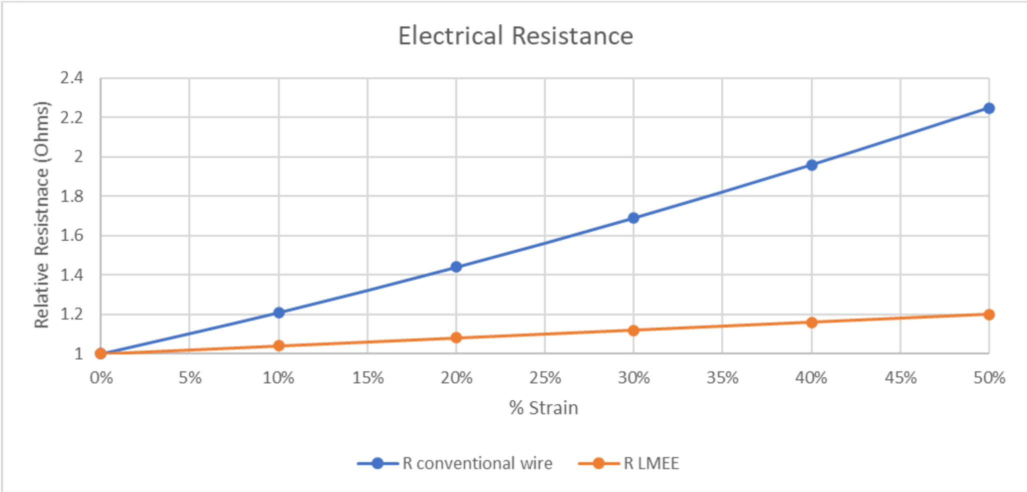


Figure 2: Resistance when strained

## Thermal Properties

Embedding more functionality into wearables will increase generated heat, reducing comfort levels, which in turn may limit adoption. This places significant thermal management demands upon the designer. Unfortunately, thermal conductivity is constrained by the same trade-offs as electrical conductivity. That is, materials that excel at conducting heat are typically stiff and reduce comfort. The liquid metal filler system of LMEE avoids this trade-off and can easily adapt to motion while maintaining excellent thermal conductivity. A comparison of common materials is shown in **Figure 3**[iv].

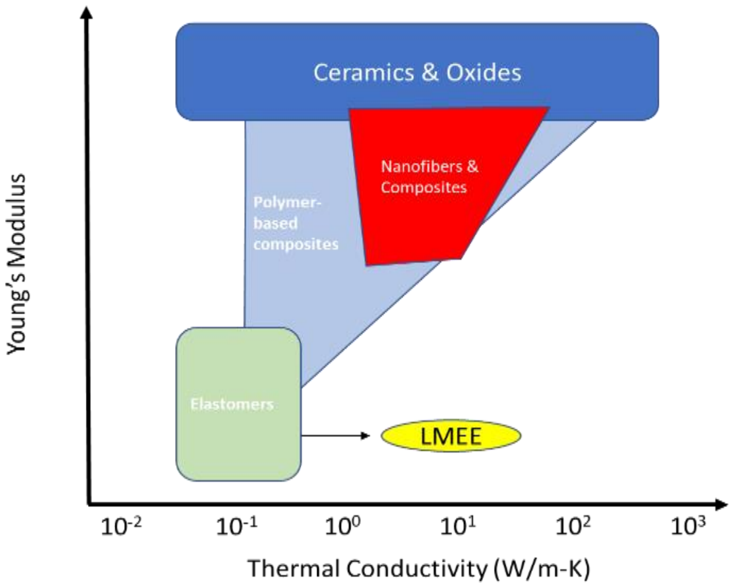


Figure 3: Thermal Conductivity – Conformability Trade-off

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## Exciting Possibilities

The introduction of LMEE creates exciting new possibilities. By enabling low modulus materials with superior thermal and electrical properties, designers of wearables will no longer struggle with trade-offs between comfort and performance. They will now be able to realize both simultaneously. It will be like combining the striking prowess of Thierry Henry with the rugged slide tackling of Tony Adams. Thanks to LMEE, an explosion of futuristic new wearables is just around the corner. We can't wait for it to arrive.

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[i] Pan, Markvicka, Malakooti, Yan, Hy, Matyjaszewski, Majidi, "A Liguid-Metal-Elastomer Nanocomposite for Stretchable Dielectric Materials," *Advanced Materials*, vol. 31, pg. 1900663 2019.
[ii]Majidi, "Soft Robotics: A Perspective – Current Trends and Prospects for the Future," *Soft Robotics*, vol. 1, pg. 5-11, 2013.
[iii]Markvicka, Bartlett, Huang, Majidi, "An autonomously electrically self-healing liquid metal-elastomer composite for robust soft-matter robotics and electronics", *Nature Materials*, vol. 17, pg. 618-624, 2018
[iv]Kazem[†], Bartlett[†], Powell-Palm[†], Huang, Sun, Malen, Majidi, "High Thermal Conductivity in Soft Elastomers with Elongated Liquid Metal Inclusions", *Proceedings of the National Academy of Science*, vol. 114, pg. 2143-2148, 2017. ([†]co-1st authors)