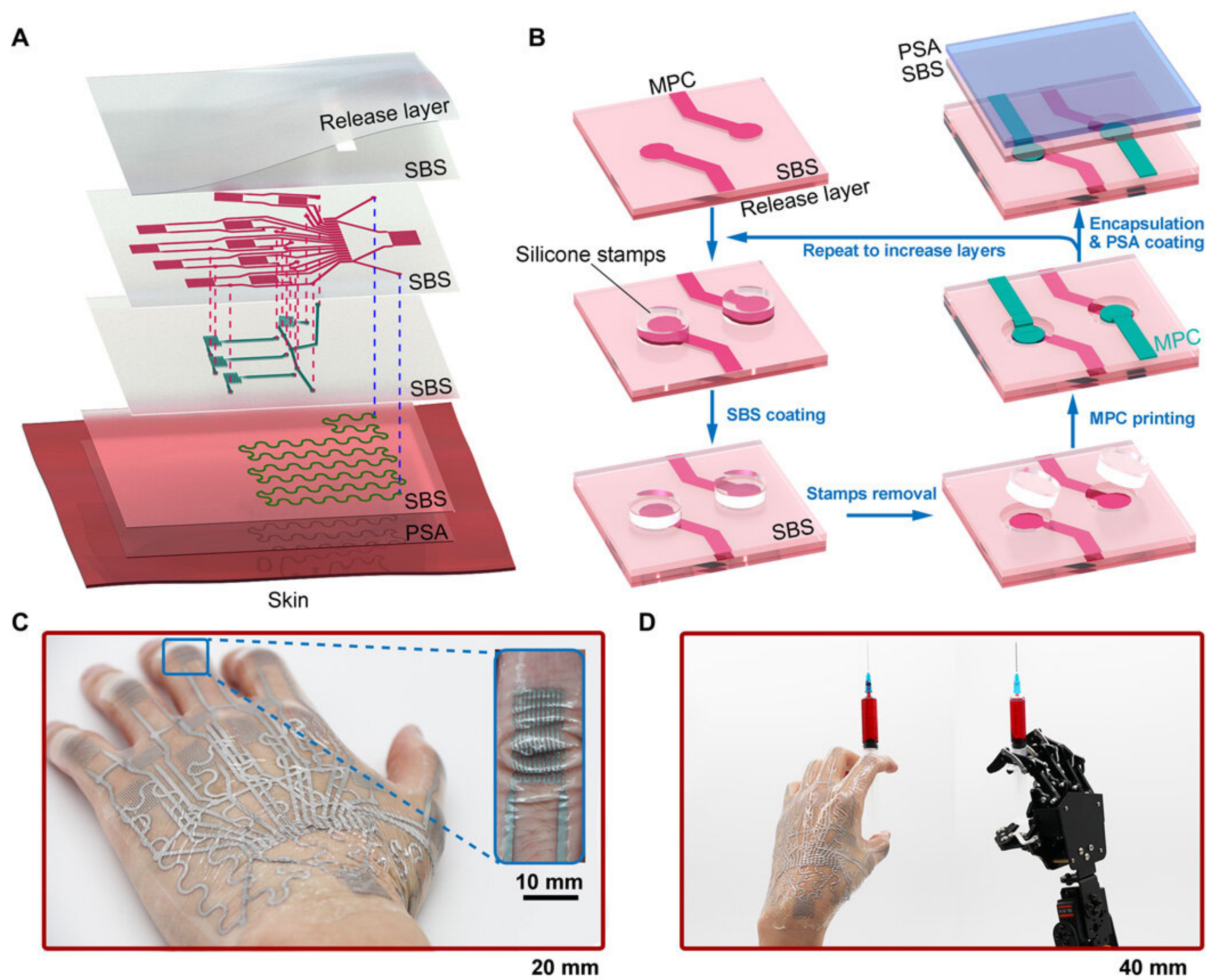
Electronic transfer tattoo with a crease amplification effect

January 27 2021, by Thamarasee Jeewandara



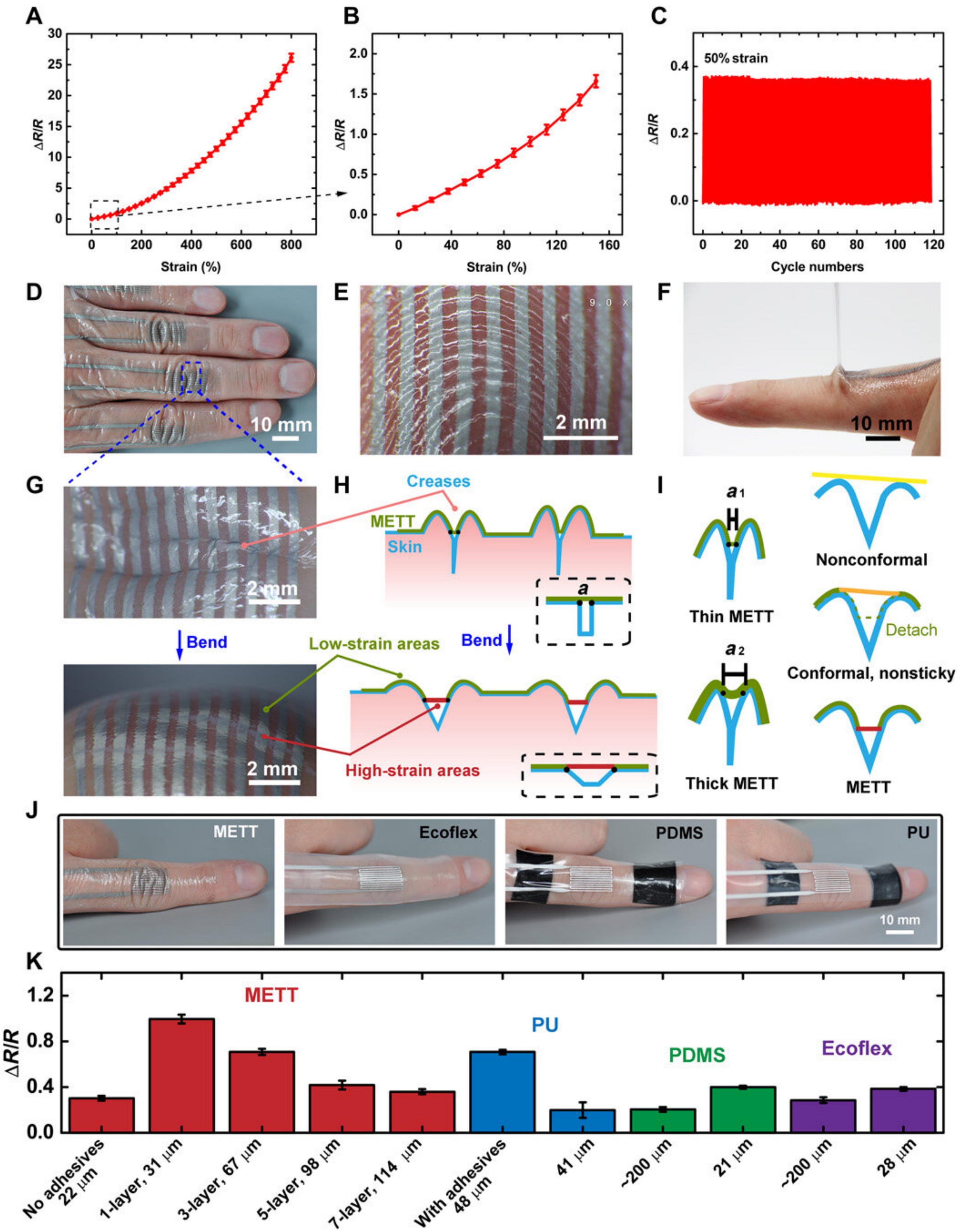
Schematic illustrations and optical images of the three-layered METT. (A) Exploded schematics of the METT containing three circuit layers. (B) Schematic illustrations of the layer-by-layer fabrication of the METT. (C) Optical image of the METT after transferring onto the skin; inset, the METT can be embedded into the creases on the finger joints. (D) Optical image of the METT for remotely controlling a robotic hand. Photo credit: Lixue Tang, Southern University of Science and Technology. Credit: Science Advances, doi: 10.1126/sciadv.abe3778

Electronic tattoos can have applications during health and movement sensing on human skin. Nevertheless, the existing versions are nonconformal, sticky and multi-layered. In a new report, Lixue Tang and a research team in biomedical engineering and nanoscience in China achieved the multilayer integration of an 800 percent stretchable, conformal and sticky electronic tattoo. The construct allowed the crease amplification effect, which amplified the output signal of the integrated sensors by three times. The team showed the possibility of transferring the tattoo to a different surface to formed a firm attachment without solvent or heat. The researchers used a straightforward method to fabricate the tattoo based on a layer-by-layer strategy with two materials used to fabricate the circuit mode within the tattoo. The three-layered tattoo integrated one heater and 15 strain sensors for temperature adjustment to monitor movement and to remotely control robots.

Wearable devices

Wearable or implantable devices can seamlessly integrate with human tissues to improve the quality of life during real-time health monitoring applications. Most wearable devices are made of soft silicon substrates and are compatible with human tissues including skin, brain and heart. The materials are also chemically inert without causing damage to human tissues; however, they cannot form firm attachments to human skin to achieve stability. Current electronic tattoos can therefore be directly printed as electronic circuits on the skin or as commercial transfer tattoos. Such single-layered strategies cannot achieve circuits with multiple functions due to the inevitable overlap with complex circuits. To balance existing incompatibilities, Tang et al. developed a multilayer electronic transfer tattoo (METT), which they embedded into small features including finger creases and fingerprints on the skin for firm attachment during repeated deformations.

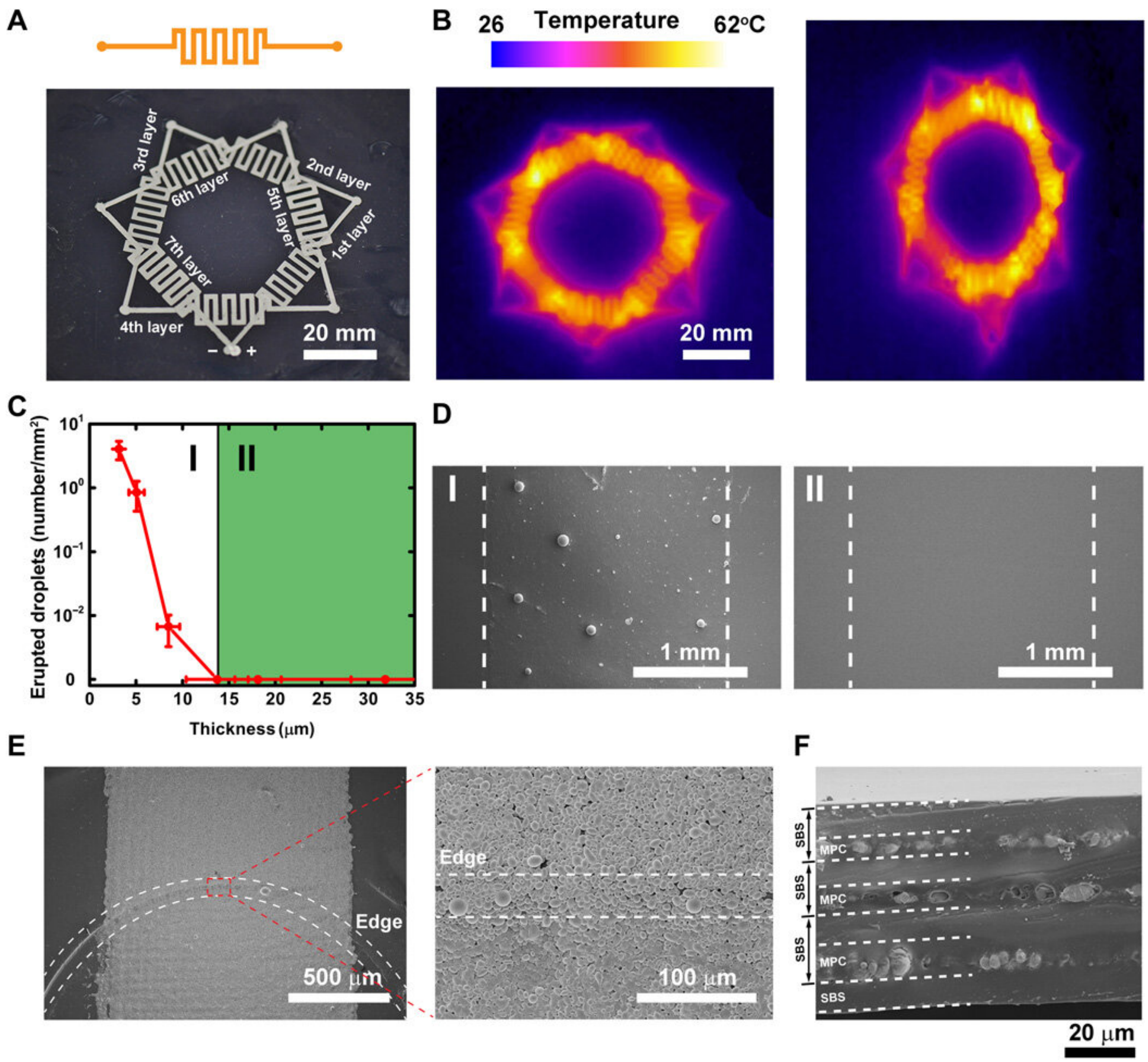
The conformal and sticky structure of the METT allowed crease amplification effects; where the strain focused on the crease of the skin, leading to the amplification of the output signal of the strain sensors on the tattoo. The tattoo showed excellent stretchability and repeatability. As a result, large local deformations caused by crease amplification did not cause degradation of the strain sensors or of the interconnects made of metal-polymer conductors (MPC). The researchers pushed the limit of the liquid metal-based electronic tattoo allowing the integration of any number of strain sensors or other functional components, and integrated 15 strain sensors and one heater in an attempt hitherto impossible for single-layered electronic tattoos. Using the METT, the team demonstrated a remotely controlled robot hand.



The METT is conformal and sticky, which can enable the crease amplification effect. (A) ΔR/R of the MPC in METT versus different tensile strains from 0 to 800%. Error bars in this paper represent SE. (B) ΔR/R of the MPC in METT versus tensile strains from 0 to 150%. (C) Real-time monitoring of the strain sensor in METT by stretching the METT from a strain of 0 to 50% for about 100 cycles. (D) Photograph of the METT embedded in the creases of fingers. (E) The METT can be embedded in the fingerprint. (F) Photograph of peeling off the METT from the skin. (G) Enlarged view of the METT attaching to the proximal interphalangeal joints (PIPs) during bending. (H) Schematic illustrations of the crease amplification effect; "a" presents the initial length of the suspended part. Dashed box, the crease model. (I) Schematic illustrations of different substrates with different thicknesses on the crease. The initial length of the suspended part, a1 orange > yellow. (J) Photographs of the strain sensors on the skin of finger joints with reference. (K) A comparison of the output signals of the MPC strain sensors on different substrates with different thicknesses when bending the index finger to 105°. Photo credit: Lixue Tang, Southern University of Science and Technology. Credit: Science Advances, doi: 10.1126/sciadv.abe3778

Developing the multi-layered electronic transfer tattoo (METT)

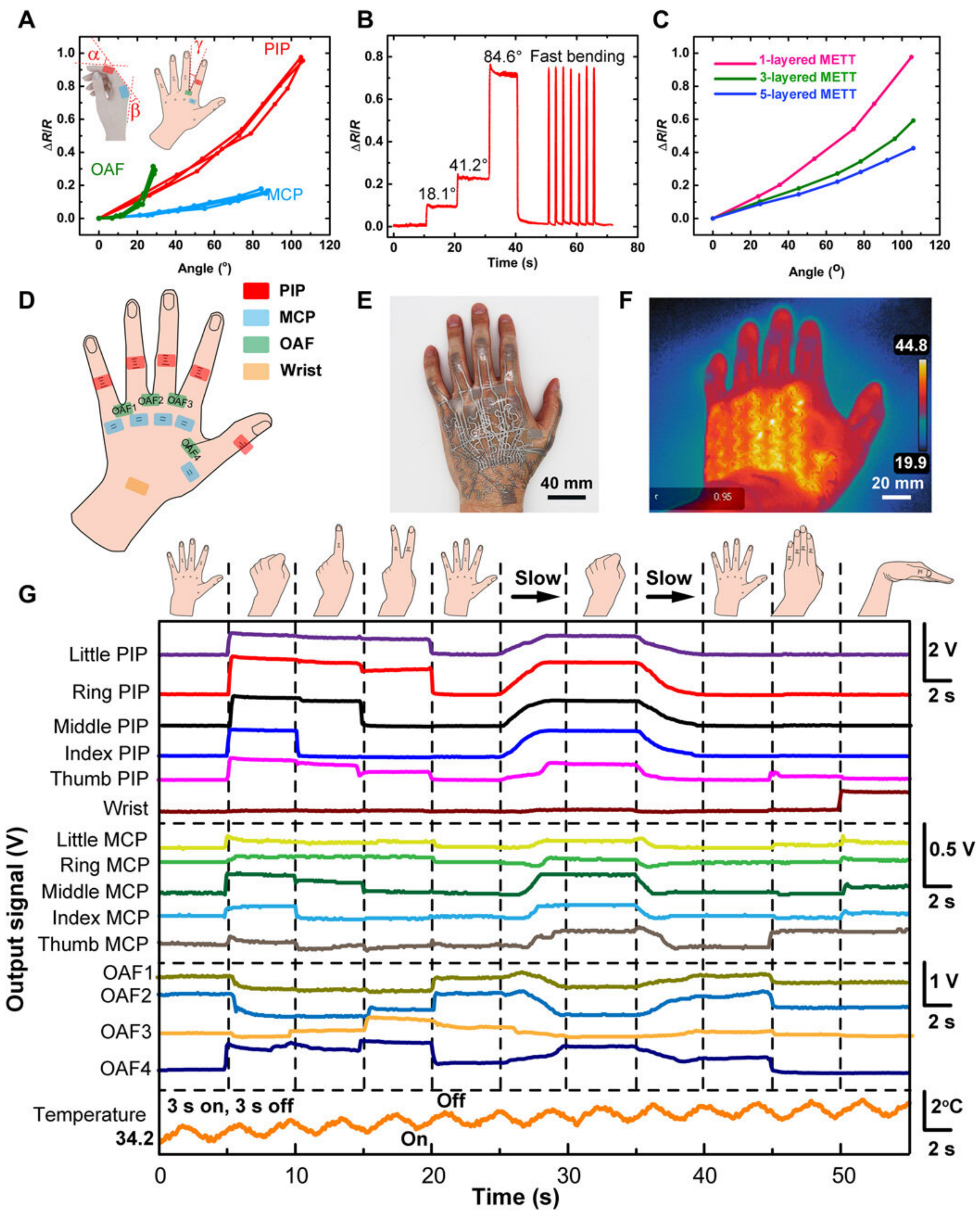
The METT contained three parts including an adhesive layer, a release layer and circuit modules between the two. When Tang et al. applied pressure, the adhesive layer allowed the METT to form tight and conformal attachment to the skin. The circuit layer maintained a thin poly(styrene-butadiene-styrene) (SBS) film with stretchable conductors embedded therein. The circuit module within the three-layered METT made of the metal-polymer conductors contained three circuit-layers with strain sensors and one heater on the third circuit layer. The MPC provided excellent conductivity and stretchability to the device, while the SBS film supported the conductors and electrically isolated them in different layers. When Tang et al. attached the tattoo to the skin via pressure and removed the release layer, the circuit modules of the METT transported onto the skin for firm attachment.



The scalability of the METT. (A) Optical image of the seven-layered heater. (B) The thermal image of the heater without deformation (left) and with 30% strain (right). (C) The numbers of the erupted liquid metal droplets depend on the thickness of the SBS layer after the stretch cycles. (D) Scanning electron microscopy (SEM) characterization of the surface of the SBS corresponding to (C); the thickness of the SBS in I (left) and II (right) is 4.8 and 18.13 μm, respectively. (E) SEM characterizations of the electric connection point. The dotted lines present the edge of the electric connection point, which is covered by liquid metal particles. (F) Cross section of a three-layered METT. Credit: Science Advances, doi: 10.1126/sciadv.abe3778

The METT fabrication strategy

The team created a layer-by-layer fabrication strategy to create the METT, starting from the outermost layer to the tattoo on the skin. They then directly printed the metal polymer conductors (MPC) on to the SBS (poly(styrene-butadiene-styrene) film and formed a vertical electrical connection with other layers to increase the number of circuit layers. The MPC was not conductive after printing at first due to the nonconductive oxide layer on the liquid metal particles; however, surface stretching broke the surface to generate conductive paths. The METT firmly attached to the skin after applying pressure and a soft and thin circuit module remained on the skin. The three-layered construct could monitor 15 degrees of freedom of the hand to transfer the dexterity of the human hand to a robotic hand with similar degrees of freedom.

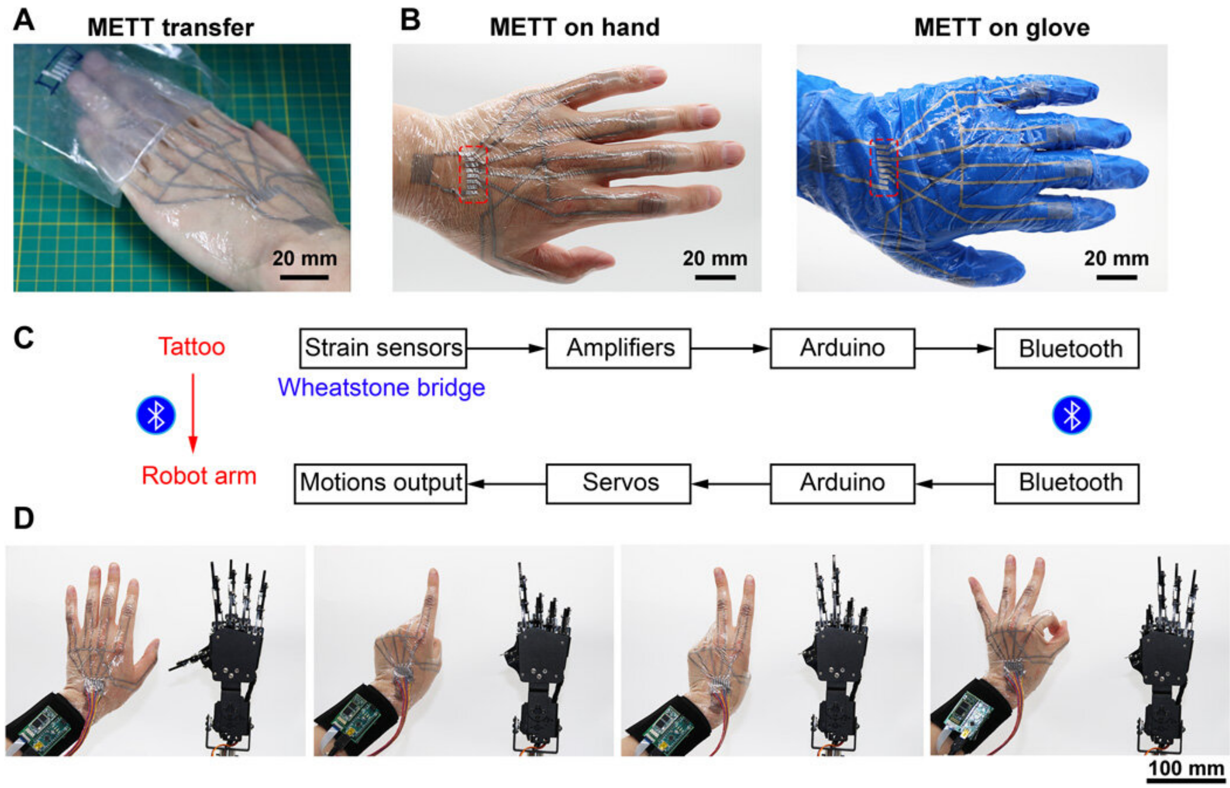


The METT can monitor the movements of the hand. (A) ΔR/R of strain sensors in different position versus angles. Inset: The schematic illustration of the measurement positions of the strain sensors. (B) Resistance response of the

METT attached to PIP in different bending angles. (C) ΔR/R of strain sensors in the METT with different layers depending on the bending angles of the index PIP. (D) Schematic illustration of the measurement positions of the strain sensors. (E) Optical images of the three-layered METT attaching to the hand. (F) The thermal image of the three-layered METT on hand. (G) The real-time signal changes of the 15 strain sensors and temperature changes of the heater on the METT with different hand movements. Photo credit: Lixue Tang, Southern University of Science and Technology. Credit: Science Advances, doi: 10.1126/sciadv.abe3778

Testing the electromechanical performance of the device

The team then tested the electromechanical performance of the metal polymer conductor-based strain sensors in the METT. The resistance of the material increased with increasing tensile strain and facilitated easy stretching of up to 800%, far exceeding deformation of the skin. The sensors also showed excellent repeatability after being stretched for 1000 cycles. Tang et al. calculated the modulus of METT to be close to the skin modules. The stretchable METT was conformal and sticky, thereby causing the crease amplification effect. This allowed the team to embed the METT into creases on the skin, such as fingerprints. The skin within creases were not completely covered by the METT; instead, it remained attached firmly within creases to ensure strains focused on the regions of interest when bending the fingers. The results allowed the focused strain to amplify notably compared to strain sensors under an average strain, highlighting the crease amplification effect. The scientists also employed pressure-sensitive adhesives to improve the crease amplification effect of the METT, where the material could remain firmly attached to the skin even during vigorous exercise.



The METT can control the robotic hand remotely. (A) Photograph of transferring the tattoo onto the hand. (B) Photograph showing METT on the skin (left) and disposal glove (right). Dotted frame, the external contact pads. (C) System-level block diagram of the robot controlling system. (D) The METT can remotely control the movements of the robotic hand. Photo credit: Lixue Tang, Southern University of Science and Technology. Credit: Science Advances, doi: 10.1126/sciadv.abe3778

METTs to detect hand movement

Tang et al. next demonstrated the scalability of the METT by constructing a seven-layered tattoo as a stretchable heater containing seven serpentine-shaped heaters on seven different layers connected in series to the power supply. However, the increased number of layers decreased the conformability of the tattoo. Electronic tattoos were therefore sufficient with two layers alone for most functions. Tang et al. also developed and studied the cross-section of a three-layered tattoo with liquid metal particles embedded within its architecture to form conductive networks in each layer. The researchers used the METT to measure the motions of the hand with sensors positioned on the skin and simultaneously measured the movement of the human hand in 15 degrees of freedom. Then they developed a two-layer METT to remotely control a robotic hand with 6 degrees of freedom in real time. The team amplified and transferred the signals caused by bending the fingers to the robotic hand through Bluetooth to control systems in medical research and in the military field.

In this way, Lixue Tang and colleagues attained multi-layered electronic tattoos for crease amplification. They formed a layer-by-layer fabrication strategy to form the METT with different layers while retaining the effects. Using a three-layered METT, the team measured 15 degrees of freedom of the hand and developed a strategy to perform delicate and complex tasks remotely with a robotic control system.

More information: Tang L. et al. Multilayered electronic transfer tattoo that can enable the crease amplification effect, *Science Advances*, DOI: 10.1126/sciadv.abe3778

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