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Enhancing humans and machines with ubiquitous electroadhesives

Jianglong Guo,[1] Jinsong Leng,[2,*] and Jonathan Rossiter[3]

SUMMARY

Electroadhesion technologies empower devices with controllable adhesion and have distinctive benefits, compared to other alternatives, including increased adaptability, reduced complexity, low energy consumption, and comfortable interaction capabilities. Here, we discuss how electroadhesives can be exploited to augment functionalities of humans and machines, and enhance the growing connections between them.

Humans are on the cusp of the fourth industrial revolution where robotics will play a key role in rehabilitating, enhancing, and extending our lives. In response, comfortable, adaptive, reliable, and robust robotic materials and structures must be ubiquitously developed and used to interact with, put on, and implant in humans. Here, we identify, explore, and discuss how electroadhesion technologies can deliver a range of high performance, facile, and efficient capabilities to enhance both humans and machines, and the growing connections between them, as highlighted in Figure 1.

Electroadhesion (EA), discovered by Johnsen and Rahbek in the 1910s,[1] is the electrostatic attraction between two contacting materials, induced by an electric field.[1–5] Electroadhesives employ a pair of coplanar[2,5] (one coplanar electroadhesion example can be the EA shoe in Figure 1) or parallel[3,4,6] (one parallel electroadhesion example can be the EA clutch in Figure 1), or coplanar-parallel, or gecko-like hairy electrodes, encapsulated in, or bonded to, a dielectric, to generate electrostatically induced adhesive forces. Electroadhesive matter is typically thin and can be based on rigid, flexible or stretchable materials. Compared with other adhesion alternatives including magnetic, pneumatic, and bioinspired mechanisms, EA (1) provides systems with enhanced adaptability, through controllable adhesion to everyday materials in varied and changing environments; (2) reduces system complexity, enabling compact devices with simple and lightweight structures and controls; (3) offers systems with lower energy consumption, enabling untethered and long-endurance tasks; and (4) causes minimal damage to and can be compatible with delicate materials, permitting applications in, on, and with humans (after proper dielectric encapsulations) and other high-valued objects. Due to recent advances in soft-smart materials and structures, EA has recently come to the fore as a promising technology for robotic gripping,[5] robotic locomotion,[7,8] wearables,[6] haptics,[9] and medical implants.[4]

Material compliance gives electroadhesives important skin/textile-like properties that are highly suited to wearables, on-body, and soft robotic applications. Many people suffer from muscle weakness and disability, and require a new generation of rehabilitation, assistive, and augmentation devices. Therefore, embedding EA into wearables, for example, in the form of parallel EA clutches within robotic clothing,[6] is an appealing approach. EA clutches are an integral component of strong, lightweight, and low-power exoskeletons; by controlled clutching, energy can be stored and recovered within a gait cycle, yielding increases in metabolic efficiency for athletes and increased mobility in older people. The EA clutch developed by Diller et al. achieved three-times higher (shear force of 12.5 kPa using 240 V) torque density and two orders of magnitude lower power consumption (0.6 mW) per unit torque, based on depositing a polymer-ceramic composite on an aluminum-sputtered bi-axially oriented polyethylene terephthalate film.[6] Conventional parallel-EA clutches exploit dry dielectrics and require hundreds or even thousands of volts that may pose health and safety issues. The limitation might be overcome by the ultra-low voltage, separable, ionoelastomer P-N junction developed by Kim et al.,[3] where a shear adhesive stress of 5 kPa was achieved using only 1 V, although this low-voltage driven parallel EA solution is difficult to be used for conventional coplanar EA designs. Recently, low-voltage parallel EA driven hydrogel electroadhesives have been developed by Borden et al. for reversible adhesion and deadhesion between cationic gels and animal tissues,[4] showing that EA has the potential to be used on and in the human body.

Electroadhesives can be readily integrated into robotic devices, and can significantly augment robotic grasping,[5] locomotion,[7,8] active adhesion,[2,10] sensing, and active cleaning.[10] EA is a potentially revolutionary robotic gripping technology, as highlighted by the 1.5 g soft EA composite

[1]School of Science, Harbin Institute of Technology (Shenzhen), Shenzhen, China
[2]Center for Composite Materials and Structures, Harbin Institute of Technology, Harbin, China
[3]SoftLab, Bristol Robotics Laboratory, University of Bristol, Bristol, UK
*Correspondence: lengjs@hit.edu.cn
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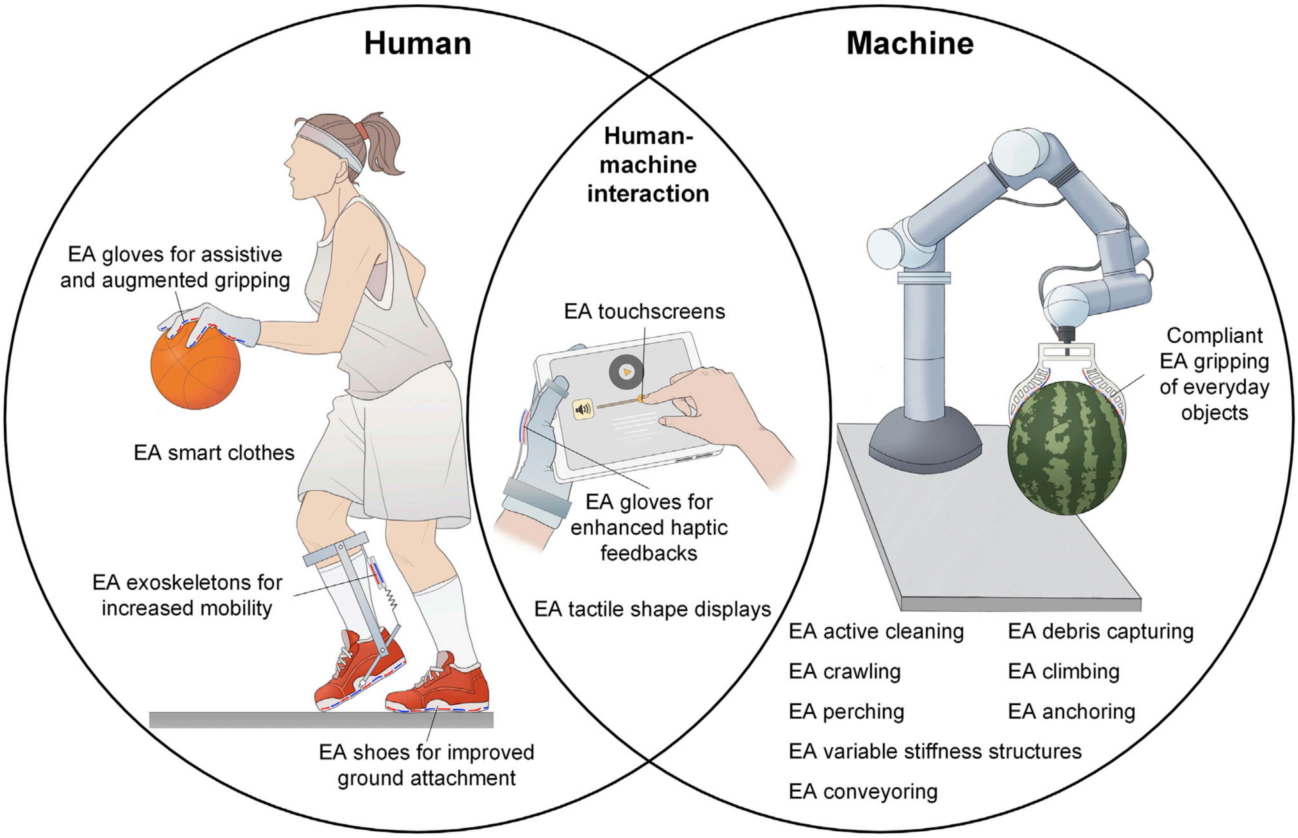

Figure 1. Electroadhesion devices to enhance humans, machines, and human-machine interactions.
On the human side: the inset shows a parallel EA clutch for ankle exoskeleton wearables, a coplanar EA glove for enhanced gripping, and a coplanar EA shoe for better grip on earth and in space. On the machine side: the inset exhibits a compliant soft EA gripper for shape-adaptive grasping of everyday objects. At the human-machine intersection: the inset demonstrates an EA interaction between a human finger and touchscreen, and a soft glove embedded with parallel EA clutches for enhanced haptic feedbacks. The red electrodes in the EA gloves, clutches, grippers denote positive voltages, and the blue electrodes denote negative voltages or ground.

gripper, presented by Shintake et al., that can be used to lift a range of complex objects which were over 80 times heavier than its own weight.[5] EA provides an electrically controllable adhesion for lightweight crawling and climbing robots so that they can move through complex and challenging terrains such as arbitrary inclines on commercial jet engines, and carry cameras and other sensors for inspection and detection uses. Low energy consumption makes EA practical for long endurance active adhesion for perching and anchoring uses. Graule et al. demonstrated an EA enhanced insect scale flying robot that can 'perch' by electrostatically attaching to a range of materials including a natural leaf.[2] Untethered robotic EA devices can be readily made using lightweight high voltage amplifiers and associated electronics. While low-voltage coplanar EA devices based on micro-scale electrodes are suitable for pick-and-place of lightweight and small objects, lifting large-scale and heavy materials using coplanar EAs still requires several hundreds or thousands of volts. It should be noted that, although the current running through EA pads is usually small (in the range of μA to mA), careful design and encapsulation are still suggested to be used to alleviate concerns for high voltage applications and make the technology industry-ready.

Haptic devices are essential tools for future human-machine interactions, and electroadhesive matter can be leveraged to bridge the gap between human and machines through active haptics (examples include EA touchscreens and tactile displays).[9] Both alternate-current and direct-current voltages can be applied to induce electrostatic attractive forces which can be used to modulate friction between surfaces and skins, thus creating useful tactile sensations. By changing the frequency of the applied EA voltage, the spatial distribution of charges close to the contact interface can then be modulated. This modulation can be used to vary the friction forces between the surfaces and skins and to generate different tactile perceptions. Shultz et al. employed broadband EA techniques for variable friction surface haptic displays (by exciting fast-adapting type I/II afferents) and audio-haptic displays (by sound emitting from stimulated fingertips).[9]

Although EA has been studied and used for over a century, there are several limitations associated with EA technologies hindering their wider applications. First, response times of most published electroadhesives are still quite long (in the order of seconds or longer) due to residual charges trapped in dielectrics. Currently, in terms of publications, only a few parallel EAs have shown the capability of rapid deadhesion (in the range of milliseconds). Complex and intelligent high voltage control, which is not readily available, should be applied to enable quick and robust adhesion and deadhesion in varying environments. Second, compared to other alternative adhesives, most published electroadhesives output relatively low forces (compared to other alternative adhesives) and their attractive forces are relatively unstable due to varying environmental conditions and changing interfacial contacts. Third, for lifting heavy and large objects using coplanar EA, relatively high voltages (usually >1 kV) are still required, posing potential health/safety issues. High voltage also brings difficulties in designing lightweight high voltage power sources and control systems that are suitable for miniature and untethered applications.

To address the aforesaid limitations and unleash the vast potential of EA, multidisciplinary research and development, from fundamental applied physics, materials, and contact mechanics to advanced manufacturing and control, is required. First, a comprehensive understanding and characterization of the EA physical mechanism, including charge injection and polarization mechanisms, and its accurate modeling are necessitated for better EA geometrical and structural design for enhanced adhesive forces. Better EA understanding and modeling, especially the inclusion of varying environmental conditions, dynamic polarizations, and interfacial mechanics, can then be used for improved EA control to enable quicker adhesion and release. Second, advanced and mass-producible fabrication methods and readily processable materials are needed to produce compliant EAs with greater and more stable adhesive forces in different environments and longer life cycles. Prolonging EA life cycles may require the integration of self-healing capabilities into EA materials and structures. Full characterization is essential before they can be used in everyday applications. Third, low-cost, compact drive electronics and control architectures are needed for the safe and effective integration of EA materials with humans and into lightweight, untethered devices.

As an active adhesion with electrically controlled reversibility and tunability, EA has yet to be fully exploited, but has the potential to revolutionize our lives. In terms of human augmentation, the following future applications may be studied and exploited. Many older adults suffer from falling on the grounds. It is highly desirable to equip them with lightweight and controllable anti-skidding shoes. Also, it is challenging for people to walk upright in outer space stations and on the planets. By using novel materials that can output higher and more stable EA forces and advanced control that can enable fast adhesion and deadhesion of coplanar EAs, one may wear EA shoes for controlled and enhanced attachments to the ground (see Figure 1), helping people to maintain stability on earth and in space, and to even enhance athletic performance. Some individuals may have disabilities on everyday material grasping. Wearing soft gloves that embedded with controllable adhesives may assist or augment their grasping capabilities. By lowering the voltage requirements and after proper encapsulation of coplanar EAs, one may wear EA gloves for enhanced gripping of everyday materials. Restricting the movement of certain people (such as the ones in prison) in a controlled and comfortable way may be desired. Integrating variable stiffness EA materials and structures into textiles may bring a smart cloth that can easily and quickly change from soft state for comfortable wearing to stiff state for motion locking. By employing high performance materials and advanced interfacial structure texturing techniques, one may produce ultra-low voltage and ultra-high force soft EA clutches that can be more safely and effectively integrated into future soft-smart clothes to bring the next generation compact and lightweight exoskeletons with enhanced assistance and rehabilitation capabilities.

For machine augmentation uses, potential applications may include the following aspects. EA technologies are extremely suitable for lifting lightweight materials and objects such as sheets, films, and especially porous textiles. Pneumatic grippers are commonly used in current industries, although they cost a significant amount of energy and produce unwanted noises. Lightweight, low energy consumption, and quiet EA grippers can be extensively used to replace those bulky and energy-draining pneumatic ones. Examples include the automatic pick-and-place of adhesive bandages, paper or plastic cups and boxes, and packaged food. Most real-world objects usually have irregular surfaces. Current EA grippers, however, can only be used to grasp flat, concave or convex surfaces. It is a pressing challenge for current electroadhesives to lift more complex surfaces such as freeform turbine blades and pears. One may combine new intelligent materials with EA technologies to bring ultra-complex shape morphing EAs that can conform, adhere to, and lift uncooperative surfaces. EA has shown to be workable under zero gravity and high vacuum. Morphing EA grippers may be highly suitable for material handling in space such as debris capturing and intravehicular pick-and-place tasks. Special attention should be taken here on applying materials that can resist ultra-high/low temperature and intensive ultraviolet irradiations especially for extravehicular space applications. It should be noted that integrating electroadhesives into traditional grippers may further supplement and augment their functionalities. Combining electroadhesives with pneumatic and magnetic grippers can overcome their intrinsic limitations (for example, pneumatics cannot be used in vacuum and magnetics cannot be used on nonferrous materials) and enable an unprecedented versatile and highly adaptable gripper for grasping objects both on earth and in space.

Reconfigurability is an important ability for robots to adapt to new circumstances and complete changing tasks. Lightweight reconfigurable robots require lightweight and low energy consumption active attachment mechanisms. EA provides a promising and intriguing solution for super-lightweight reconfigurable structures and mobile robots that can self-assembly and disassembly rapidly, which is especially attractive to robotic swarms who requires fast depart and quick rejoin to deal with varying tasks. Electroadhesive matter can not only be used as an active adhesion but also as an intrinsic sensor. Embedding self-sensing ability into electroadhesives may bring a new generation of untethered intelligent EA anchors which are not only useful for long endurance and compact static inspection tasks but also for EA crawlers and climbers, if equipped with certain actuators, for mobile robotic detection tasks. Lightweight, compact EA mobile robots are especially attractive for untethered unmanned inspections in space and non-destructive detection of critical spacecraft parts. Combining other sensors with electroadhesives may bring more intelligent EA systems that can enable wider applications.

With regard to future human-machine interactions based on EA technologies, one appealing application is to integrate intelligent soft EA clutches into future clothes. These compliant electrostatic clutches, due to their nature of lightweight and comfortableness, may bring enhanced kinesthetic haptic feedbacks (see Figure 1) for better future Metaverse experiences. In addition, ultra-low voltage and ultra-high force EA tactile displays have the potential to bring the next generation cost-effective tactile displays; and by embedding self-sensing ability into these devices, we can have intelligent refreshable EA tactile shape displays that may be highly useful for visually impaired people to recognize shapes in a more reliable and robust way. These future applications—combined with the essential endeavors of modeling, materials, manufacturing, and control—will not only bring wider interest in the technology but also help achieve the ultimate goal of safe, comfortable, reliable, and robust electroadhesion for ubiquitous applications (here we call ubiquitous electroadhesion) with humans and machines, and for natural human-machine interactions.

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AUTHOR CONTRIBUTIONS

J.G. wrote the draft. J.R. and J.L. commented and fully revised the manuscript.

DECLARATION OF INTERESTS

The authors declare no competing interests.

1. Johnsen, A., and Rahbek, K. (1923). A physical phenomenon and its applications to telegraphy telephony etc. J. Inst. Elect. Eng. *61*, 713–725.

2. Graule, M.A., Chirarattananon, P., Fuller, S.B., Jafferis, N.T., Ma, K.Y., Spenko, M., Kornbluh, R., and Wood, R.J. (2016). Perching and takeoff of a robotic insect on overhangs using switchable electrostatic adhesion. Science *352*, 978–982.

3. Kim, H.J., Paquin, L., Barney, C.W., So, S., Chen, B., Suo, Z., et al. (2020). Low-voltage reversible electroadhesion of ionoelastomer junction. Adv. Mater. *32*, 2000600.

4. Borden, L.K., Gargava, A., and Raghavan, S.R. (2021). Reversible electroadhesion of hydrogels to animal tissues for suture-less repair of cuts or tears. Nat. Commun. *12*, 4419.

5. Shintake, J., Rosset, S., Schubert, B., Floreano, D., and Shea, H. (2016). Versatile soft grippers with intrinsic electroadhesion based on multifunctional polymer actuators. Adv. Mater. *28*, 231–238.

6. Diller, S., Majidi, C., and Collins, S.H. (2016). A lightweight, low-power electroadhesive clutch and spring for exoskeleton actuation. Proc. IEEE Int Conf Robot Autom. 682–689.

7. Liang, J., Wu, Y., Yim, J.K., Chen, H., Miao, Z., Liu, H., Liu, Y., Liu, Y., Wang, D., Qiiu, W., et al. (2021). Electrostatic footpads enable agile insect-scale soft robots with trajectory control. Sci. Robot. *6*, eabe7906.

8. Rivaz, S.D., Goldberg, B., Doshi, N., Jayaram, K., Zhou, J., and Wood, R.J. (2018). Inverted and vertical climbing of a quadrupedal microrobot using electroadhesion. Sci. Robot. *3*, eaau3038.

9. Shultz, C., Peshkin, M., and Colgate, J.E. (2018). The application of tactile, audible, and ultrasonic forces to human fingertips using broadband electroadhesion. IEEE Trans. Haptics *11*, 279–290.

10. Lee, Y., Song, W.J., Jung, Y., Yoo, H., Kim, M.-Y., Kim, H.-Y., and Sun, J.-Y. (2020). Ionic spiderwebs. Sci. Robot. *5*, eaaz5405.