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Review

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Recent progress in biocompatible miniature supercapacitors

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Abstract

With the advancement of wearable and implantable health and medical electronics, biocompatible miniature energy storage devices were developed rapidly. In particular, biocompatible miniature supercapacitors (BMSCs) have the advantages of conventional supercapacitors, such as high-power density, fast charging/discharging rate, and long operating lifetime, as well as strong selectivity of biocompatible materials. They are expected to play an important role in personalized electronic integration systems. Biocompatibility involves the biosafety of materials and relates to the mechanics and geometrical forms. For example, BMSCs should be thin and compact, ensuring ease of portability and comfort for users. They should also be flexible and stretchable to conform to the skin or tissue, providing stable power to electronics even under deformation. Furthermore, biodegradability/bioabsorbability ensures they are both body- and environment-friendly. This review summarizes the recent research progress of BMSCs as wearable and implantable energy storage devices, including the basic requirements and the selection of the components. Additionally, the advanced applications of BMSCs in multifunctional integration systems for real-time health monitoring and medical treatment are introduced, along with the associated challenges and prospects.

Keywords: Miniature supercapacitor, biocompatible, wearable, implantable, health monitoring and medical treatment

INTRODUCTION

Wearable and implantable electronics (WIEs) that could track, analyze, and transmit medical, biological and exercise data of organisms[1-5] are widely applied in the field of health monitoring, physiological diagnosing, and medical treatment[6,7], to improve the health quality, which have received great attention in recent years. Various WIEs have been developed to monitor physiological parameters such as glucose levels, pH value, heart rate, blood pressure, and neurological activity, realizing quickly and accurately diagnosing and implementing treatment and evaluating the efficiency of treatments.

In general, WIEs are mainly composed of sensors or working electrodes, power units, and circuits. Since they are usually attached externally or internally (implanted) on the human body[8], each component is expected to be miniature, flexible, thin, safe, and comfortable. Among these components, a soft and biocompatible energy storage device as a constant power source is indispensable. Unfortunately, nearly all commercially available energy storage devices are planar and rigid, making them a significant drawback for WIEs.

Given this, considerable efforts have been made to develop matching energy storage devices. Besides the ability to provide continuous, stable, and sufficient power, biocompatibility is increasingly important. Biocompatibility here not only refers to the non-toxicity and bio-safety of materials or devices but also involves compatibility with the human body regarding mechanics and geometric forms. For instance, energy storage devices should be flexible and stretchable to conform to the skin or tissue and continuously provide stable power for electronics under deformations caused by human daily activities. Additionally, they should be as small as possible to be portable and comfortable for users, and biodegradable/bioabsorbable to be body- and environment-friendly.

High-performance biocompatible miniature energy storage devices are expected to provide options for WIEs[9-13]. Compared with other energy storage devices, miniature supercapacitors (MSCs) have attracted much attention in recent years due to their long working life (> 100,000 cycles), fast charge/discharge rate, high power density, miniature size, low cost, and low maintenance[14-19]. The high-power density characteristic of MSCs allows for fast remote charging and enables them to provide significant amounts of power much more quickly than rechargeable batteries. This is particularly beneficial for WIEs, where quick response times are crucial, such as in emergencies or when delivering therapies that require exact timing[20]. Recently, the power density of MSCs has been developed to reach approximately ~100 W/cm^{-3}[21,22]. Furthermore, MSCs can be easily designed into various forms, such as stacked, planar, and wire-shaped, depending on their intended use[23-25]. Moreover, most of the materials used for supercapacitor components, including electrodes and electrolytes, are biocompatible. This is crucial for constructing supercapacitors with stable performance and good security, which can come into contact with life systems without any adverse biological effects[26]. Therefore, with stable performance, minimized dimension, and strong selectivity of the biocompatible electrode and electrolyte materials, biocompatible MSCs (BMSCs) have a promising application prospect in wearable and implantable bioelectronic integration systems.

At present, great efforts are being made to design materials and structures of BMSCs for application in bioelectronics. Several reviews have provided in-depth analyses of supercapacitors as energy storage units for powering wearable and implantable bioelectronic devices. For example, Chen *et al.* reviewed stretchable supercapacitors for health monitoring bioelectronics[7], while Keum *et al.* focused on flexible/stretchable supercapacitors with innovative functionalities such as self-healing, shape-memory, and biodegradability[27].

Recently, Chodankar *et al.* reviewed biocompatible supercapacitors used in implantable electronic medical devices, with a particular emphasis on electrode materials[20]. Xu *et al.* also discussed minimally invasive power sources, including supercapacitors, for implantable electronics[28]. However, there is still a need for systematic summaries regarding the development of various types of BMSCs and their integration systems for health monitoring and medical applications. Such summaries would inspire application-oriented designs of BMSCs, which are essential for bridging the gap between academic research and practical applications.

This review provides an overview of the state-of-the-art BMSCs and their applications in health monitoring and medical treatment. It begins with a brief introduction to the basic requirements of BMSCs used for bioelectronics, including biocompatibility, mechanical properties, miniature size, and biodegradability/absorbability, followed by the selection of adequate materials. Then, the recent advancements in BMSCs are discussed in detail, categorizing them primarily into wearable and implantable types. Wearable BMSCs are further divided into non-contact and skin-contact types, whereas implantable BMSCs are classified as general and biodegradable/bioabsorbable. Additionally, multifunctional integrated systems using BMSCs as power units for health monitoring and medical treatment are introduced, along with the associated challenges and prospects.

REQUIREMENTS FOR BMSCS

Compared with traditional energy storage devices, BMSCs are usually applied externally or internally on biological organisms. Biological organisms are soft, flexible individuals made up of various skin, muscle, connective tissue, and functional organs. The specific characteristics of various tissues and organs, the deformation of the living body in daily activities, and the restricted implantation space of the organism bring new requirements for micro-supercapacitors[29]. These requirements include biocompatibility, robust mechanical properties, miniaturization, and even biodegradability/bioabsorbability.

Biocompatibility

Biocompatibility refers to the ability of a material to come into contact with a living system without causing harmful effects, such as inflammation, cellular damage, or other adverse reactions[30]; it is crucial to ensure the bio-safety of materials and devices[20]. As WIEs are usually in direct contact with body tissues, biocompatibility is the primary concern[31]. The biocompatibility can be evaluated by two methods: *in vitro* and *in vivo* assays[32,33]. An *in vitro* assay typically determines the biocompatibility of devices or materials by measuring their cytotoxicity when exposed to mammalian cell cultures *in vitro*[34,35]. An *in vivo* assay involves implanting the materials or devices into the body and observing whether there is an immune response or inflammation. This type of testing can also assess genetic toxicity, reproductive toxicity, and developmental toxicity[36]. Biocompatibility is a key requirement to ensure that the device does not produce harmful reactions after interacting with the organism, ensuring the safety and effectiveness of WIEs and power units[37]. Especially for the implantable electronics that are applied in the human body environment such as tissues or organs, they should have good biocompatibility to avoid unwanted immune responses and adverse effects.

Mechanical properties

Since the BMSCs are designed for the WIE integration system applied on biological surfaces or within the human body, they need to have good mechanical properties to endure sudden and frequent stretch-release cycles under various deformation caused by the motion in daily activities, such as bending, twisting and even stretching, while maintaining satisfactory energy storage performance[38]. Additionally, to facilitate the accommodation of the movements of substrates or supports, such as clothing, skin, and soft tissue, the BMSCs are also required to have matched mechanical properties. The desired mechanical properties of

BMSCs mainly include stretchability, fatigue resistance, and modulus matching. Stretchability is defined as the degree to which a subject is stretched under different loading conditions, not only including stretching and compression, but also bending, twisting, shearing, and compression. For example, the skin's elongation is up to 20% under human motion in daily life, so electronics with stretchability over 20% are essential to be applied on the skin[39]. Fatigue resistance refers to the ability of the subject materials or subjects to resist fracture or cracking failure under repeated loading conditions. It is the guarantee of a BMSC to maintain mechanical and electrochemical performance unchanged or at a high level after repeated bending or twisting for a long time. It is significant to ensure that skin or tissue deformation does not affect the integrity and performance of the device. In particular, implantable MSCs must show excellent mechanical stability because of their difficult-to-replace nature[40]. BMSCs need to adapt to the irregularities in skin or tissue dynamic deformation without applying any mechanical load, which can be achieved through modulus matching[41,42]. By selecting the substrate, electrode, electrolyte, and current collector materials with similar elastic modulus, the local stress at the interface between different materials due to stiffness differences can be reduced, improving the reliability and service life of the structure. Additionally, creating devices with elastic modulus closer to skin and tissues could potentially reduce the possibility of immune responses[43].

Miniature size

In the field of bioelectronics, which are used for health monitoring and medical treatment[44,45], including both wearable and implantable technologies, the trend toward miniaturization without sacrificing functionalities has intensified the focus on the power units. To be easily integrated into the next-generation minimally invasive bioelectronics system, the size and weight of the power units should also be considered[37,46-48]. Especially for implantable devices, the size should be as small as possible, due to the tiny space in the human body. At the same time, a small size can reduce the stress exerted by electronics on the surrounding muscles, tissue and organs, minimizing the burden on the user. In response to this demand, a MSC, a type of energy storage device with a total device area on the scale of square millimeters or centimeters[49], has emerged and continues to develop. Compactness is the key advantage of the miniature energy storage device, which facilitates the fabrication of more comfortable WIEs and less invasive implantable devices while maintaining sufficient power supply. Common microstructural designs of miniature devices include linear (one-dimensional) microdevices[50], two-dimensional stacked microdevices, two-dimensional planar comb-type microdevices[51], and three-dimensional (3D) planar microdevices generated by vertical arrangement[52,53]. The goal is to build a complete miniature biocompatible supercapacitor device, including the substrate (or supporting matrix), current collector, electrode, separator, electrolyte, and package. The minimized size ensures the effective user-friendliness of supercapacitors, satisfying the critical need for reliability and convenience in bioelectronic applications.

Biodegradability/Bioabsorbability

Generally, a substance with biodegradability means that it can be decomposed through several chemical reactions in a biologically active environment, such as enzymatic reactions by microorganisms or hydrolysis in a non-enzymatic environment[54-56]. The property of biodegradability/bioabsorbability contributes to reducing pollution introduced by associated e-waste streams, and the harmful and toxic effects on the human body[57,58]. It is continuously emphasized to achieve biodegradable/bioabsorbable electronic devices, especially for short-term implantation. For implantable BMSCs, in addition to basic biocompatibility, biodegradability/bioabsorbability will give them greater advantages[59,60]. After the biocompatible and biodegradable MSCs are implanted in the body, they can not only supply power energy without adverse effects and causing rejection, but also decompose in the biological environment in the human body within a specified time range according to the designed retention time (usually between weeks and months), reducing the damage and risk of the removing the devices by the second surgery[40]. At present, water-soluble metals such as magnesium (Mg), zinc (Zn), iron (Fe), molybdenum (Mo), and tungsten (W), and biodegradable polymers such as polyvinyl alcohol (PVA), polylactic acid-hydroglycolic acid (PLGA), polylactic acid (PLA), *etc*., have been demonstrated in biodegradable/bioabsorbable MSCs[37,61-64]. BMSCs with biodegradability/bioabsorbability have higher safety and play a more important role in the application of short-term or single-use implanted bioelectronics.

MATERIALS FOR BMSCS

Electrode materials

For BMSCs, safe, non-toxic, and flexible/stretchable electrode materials that possess good energy storage capacity in biological environments are preferred[20]. Carbon-based materials[65-68], such as activated carbon, carbon nanotubes (CNTs), and graphene, are the conventional Electrical Double-Layer Capacitor (EDLC)-based electrode materials. They have the advantages of large specific surface area, ease of modification, good mechanical properties, good stability and superior conductivity[69-71]; the corresponding supercapacitors often show high power density and charging/discharging rate. In this regard, using carbon-based materials in BMSCs needs to pay special attention to biocompatibility and performance requirements. For example, He *et al.* synthesized biocompatible CNT fiber electrodes by chemical vapor depositing and oxygen plasma treatment, not only enhancing their wetting and mechanical properties but also maintaining high conductivity[72]. The newly developed CNT fiber electrodes can work well in physiological fluids such as phosphate buffer solution (PBS), serum, and blood with good cycling and rate performance. Chae *et al.*[73] prepared a supercapacitor using oxidized single-walled CNTs (Ox-SWCNTs) as the electrode material, showing good biocompatibility, flexibility, and strong cycling performance. No inflammation or corrosive lesions were observed in mice after implanting the supercapacitor for six months.

Although carbon-based materials often show fast charging-discharging rates and long cycle life, the inevitable low energy density limits their practical application. To solve this problem, pseudocapacitive-based electrode materials[74-77] with higher energy density such as metal[78], metal oxides[79,80], metal sulfides[81], metal nitriding[82,83] and conjugated polymers[84-86] have been explored. Considering biocompatibility and safety, only some low-toxicity metal-based electrode materials and conjugated polymers can be used, such as gold nanoparticles, silver nanoparticles, zinc nanoparticles and their oxides (such as ZnO), iron nanoparticles and their oxides, titanium and its oxides (such as TiO_2)[87]. Otherwise, safe and reliable packaging is needed. Additionally, conjugate polymers, such as polypyrrole (PPy)[84], polyaniline (PANI)[85], poly (3, 4-ethylenedioxythiophene) (PEDOT)[86], *etc*., have also been demonstrated to be biocompatible pseudocapacitive materials.

The ideal BMSC electrode materials should have high biological adaptability and good electrochemical performance, meeting the requirements of high energy density, good cycle stability, and excellent magnification performance. The composites of carbon materials with good cycle stability and excellent rate performance and metal oxides or conductive polymers with high energy storage capacity are expected to improve the overall electrochemical performance of BMSCs. Zhu *et al.*[88] developed a supercapacitor (SC) by combining the graphite layer with the MnO_2 layer that can be used for skin-mountable efficient energy storage. Kumar *et al.*[89] produced a device by spray-coating the composite of poly (3, 4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS) and reduced graphene oxide (rGO) on carbon cloth (CC), which showed a greatly enhanced capacitance and energy density. Three devices connected in series can power light-emitting diodes (LEDs).

Electrolyte materials

The electrolyte is another essential component of a supercapacitor. The electrolyte transporting the charges between electrodes consists of a solvent and a conducting salt. As for BMSCs, biocompatibility is the first criterion for selecting electrolyte materials[90,91]. Using biocompatible electrolytes can reduce cumbersome encapsulation and have a wider range of applications. Modifying the physic status of the electrolyte with a polymer matrix to a (quasi) solid state is more adaptable to wearable and implantable supercapacitors, as it helps prevent leakage under mechanical deformation. Biocompatible polymer gel materials with stable physical and chemical properties similar to biological tissues, such as excellent flexibility, deformability, and viscoelasticity, are typically the preferred option[92]. Biocompatible polymer matrixes can be divided into two main categories according to their source: natural polymers and synthetic polymers. Natural polymers are derived directly from natural plants or animals, including protein polymers such as collagen, gelatin, silk proteins[93], and polysaccharide polymers such as agarose, chitosan, hyaluronic acid, alginate, and cellulose[94-98]. Synthetic polymers are prepared by chemical synthesis, including polycaprolactone, PLA, poly-citrate diol, polyglycolic acid, and polyurethane[99]. Natural polymers possess excellent properties such as high biocompatibility, low antigenicity, and anti-inflammatory effects, which are widely used as electrolyte matrices for BMSCs[40]. For example, Sheng *et al.* prepared a flexible, biodegradable supercapacitor with a sandwich structure using sodium alginate gel electrolyte. It is also fully biodegradable and absorbed by rats after a period of time[60]. Synthetic polymers have good mechanical strength, adjustable degradation rate, and improved mechanical properties. For example, Lee *et al.* prepared serpentine wire supercapacitors using PVA-based biodegradable gel electrolytes, showing stable performance under repeated cycles and bending deformation[100].

Physiological liquids and body fluids are rich in numerous cations (such as Na^+, K^+, and Ca^{2+}) and anions (such as Cl^- and HCO_3^-), which enables them to support the energy storage of a supercapacitor[73]. Therefore, physiological liquids such as PBS and human body fluids (such as serum, blood, urine, gastric juice, tissue fluid, *etc.*)[40] have been demonstrated to serve as electrolytes, simultaneously minimizing the leakage risks and avoiding toxic issues. For example, Chae *et al.* prepared supercapacitors using body fluids as electrolytes, showing good and stable electrochemical performance[101]. It is effective in avoiding adverse reactions such as immune rejection or inflammation caused by the use of foreign electrolytes, which are more in line with the requirements of biocompatibility and safety. Physiological liquids and body fluids are beneficial for the BMSCs to be applied internally/externally on the human body[40].

Encapsulation materials

The encapsulation layer is a barrier between the supercapacitor system and the human body[102]. It is of significance to protect the human body from infection, irritation, and injury associated with the leakage of device components. Encapsulation is also conducive to isolation from the external environment, reducing mechanical damage and extending the working life of the device[103]. Particularly in the biodegradable supercapacitor, the encapsulation layer dormitory determines the service life of the devices[60]. Biocompatible polymers have excellent biocompatibility, good biosafety, and strong mechanical strength and are ideal encapsulation materials for BMSCs[54]. Although natural polymers (such as cellulose, lignin, starch, *etc.*) have incredible renewability and biodegradability, their mechanical and processing properties are poor, and the degradation time is nonadjustable[92]. In contrast, synthetic biological polymers usually have low expansibility, excellent mechanical properties, and ideal processing properties, so they have greater advantages in encapsulation materials[104]. Among them, PLA and polycaprolactone have been widely used in the encapsulation of implantable BMSCs[92]. Lee *et al.* used a biodegradable material-poly(1,8-octanediol-co-citrate) (POC) as an encapsulation polymer, and the obtained supercapacitor devices showed improved mechanical and electrochemical stability under repeated tensile deformation[100]. Moreover, the degradation time of the encapsulation material can be controlled by adjusting the synthesis method, processing time, thickness and molecular weight of encapsulation polymers, so as to meet different application requirements.

WEARABLE BMSCS

Wearable devices have received much attention due to their important role in the development of real-time health diagnosis, treatment, and monitoring systems. Highly deformable wearable electronic products[105-108] are expected to replace traditional rigid electronic products, making greater progress in the realization of personalized electronic applications. Wearable electronics powered by BMSCs can be integrated into ordinary textiles such as clothing, shoes, and other accessories[16], or directly worn on human skin, to perform various functions, such as monitoring physiological signals (including blood pressure, pulse, temperature, glucose levels, pH values and neurological activity), analyzing sweat and sensing toxins in the environment[7]. Depending on the biocompatibility requirements, the wearable biocompatible micro-capacitors can be classified as non-contact and skin-contact types.

Non-contact type

Non-contact wearable BMSCs are generally not in direct contact with the skin. They are mainly textile-based micro-supercapacitors, which are usually integrated into diverse new wearable products such as clothing, gloves, wristbands, or shoes[9] using fabrication techniques similar to those used in apparel textile technology. There are two main methods for the preparation of BMSCs: one is to load the active materials directly on fabrics by dipping, screen printing, or spraying, which are inherently stretchable, bendable, and foldable. The other is to combine the active material with a stretchable matrix or elastomer to form a stretchable composite fiber or yarn, which can be integrated into the fabric by weaving, sewing or other methods.

Coating electrochemically active materials and even electrolytes directly onto fabrics allows the assembly of non-contact BMSCs for wearable devices. This method can seamlessly combine the supercapacitors with clothing and facilitates the design of various plane geometrics, offering advantages such as fast processing and large-area preparation. As early as 2013, Jost *et al.* prepared textile supercapacitors using custom knitted carbon fiber cloth as current collectors and activated carbon screen printed on the knitted carbon fiber cloth as active materials[109] [Figure 1A]. This is the first report on knitting as the manufacturing method for integrated energy storage devices. Then, Lee *et al.* prepared a wearable supercapacitor that was directly screen-printed on a T-shirt[110]. Conductive stainless steel wire was sewn into the T-shirt as a shape-directing current collector, and then the electrode materials [activated carbons/multiwalled CNTs (MWCNTs)/ionic liquid] and gel electrolytes paste (ionic liquid/thiol-ene polymer network skeleton/SiO_2 nanoparticles) were successively stencil-printed onto it and sealed with a waterproof packaging film. As can be seen from Figure 1B, the supercapacitor printed on T-shirts can be prepared over a large area and effectively withstand various mechanical/thermal stresses encountered in daily activities (including walking, running, washing, ironing and folding). The printed supercapacitor exhibited an areal capacitance of 74.2 mF cm^{-2} at a scanning rate of 1.0 mV s^{-1}, making it a good wearable energy storage device. Further, Guo *et al.* developed MSCs directly on textiles by combining inkjet printing and extrusion printing, specifically by using the polymer-assisted metal deposition method combined with inkjet printing to deposit a uniform copper layer on textiles as a current collector, and extrusion printing activated carbon on the prepared current collector as electrodes[111]. The multi-step printing enables the flexible MSCs to be directly prepared on textiles and easily integrated with textile-based electronics to support wearable electronics systems [Figure 1C]. The prepared interdigital printable MSC has an areal capacitance of 8.8 mF cm^{-2} at a current density of 0.5 mA cm^{-2} while exhibiting a long cycle life (6,000 cycles) and superior mechanical flexibility (2000 cycles@90°).

As indicated above, the micro-supercapacitors printed on fabric substrates typically have low areal capacity, which limits their ability to support a broader range of applications. To obtain higher energy storage at a

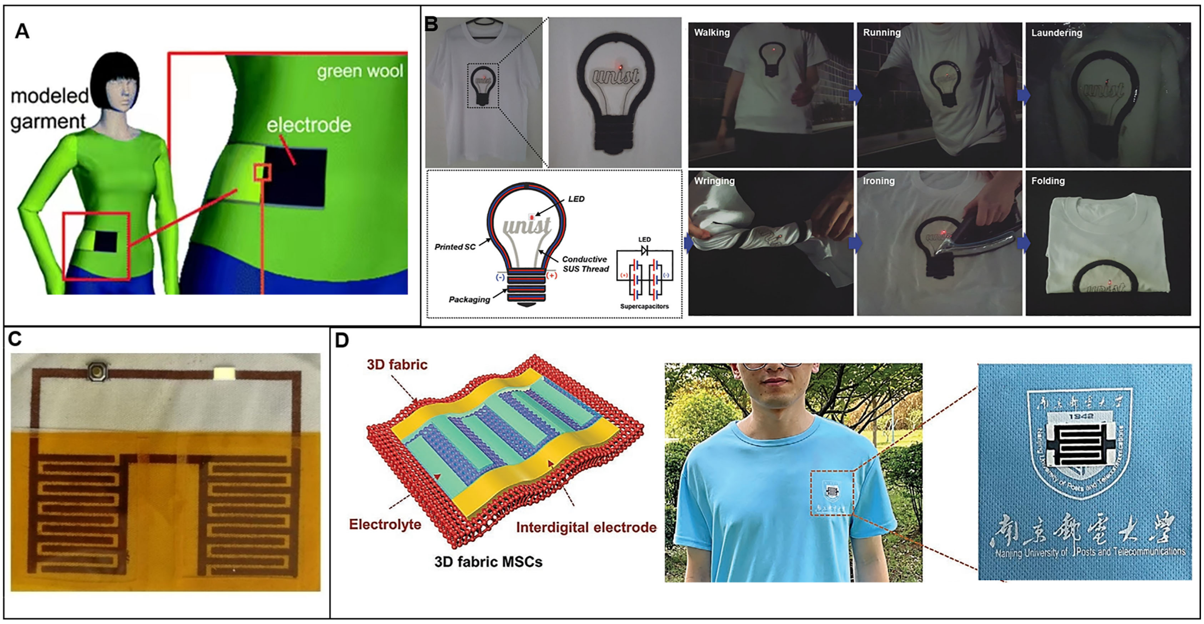

Figure 1. Non-contact wearable BMSCs prepared by dipping, screen printing or spraying. (A) Knitted carbon fiber electrodes[109]; (B) The physical diagram and structure of the SC-printed T-shirts[110]; (C) Textile-based MSCs prepared by combining inkjet printing and extrusion printing[111]; (D) Structure and application of fabric-based 3D MSCs[111]. Reproduced from Ref.[109], Ref.[110], Ref.[111], and Ref.[111] with permission from Energy & Environmental Science, Advanced Functional Materials, ChemElectroChem, and Advanced Functional Materials, respectively. BMSCs: Biocompatible miniature supercapacitors; MSCs: miniature supercapacitors; 3D: three-dimensional; SC: supercapacitor.

limited surface area, printing technology has expanded beyond flat surfaces. The framework of active materials is developed toward a 3D structure by using 3D fabrics as the porous skeleton, which endows a higher loading of active materials without massive collapse and fall-off, and facilitates electrolyte diffusion efficiency, highly improving the areal capacitance. Following this strategy, Li *et al.* constructed a high cross-section fabric-based interdigital MSC with ultra-high areal capacitance[112]. Conducting polymer PEDOT:PSS was screen printed on 3D fabrics to form a continuous conductive network. Then MnO_2 microspheres with pseudocapacitance were epitaxially grown on the PEDOT:PSS. Due to much more active sites in the porous thick electrodes and high electrical conductivity of interpenetrating fiber networks, the fabric-based MSCs exhibit an ultra-high areal capacitance of 135.4 mF cm^{-2} [Figure 1D], which is 3.5 times that of MSCs fabricated on flat polyethylene terephthalate (PET) substrates. Moreover, the unique architecture endows the MSCs with excellent flexibility (94% of capacitance retention after 3,000 bending cycles) and cycle stability (93% of capacitance retention after 3,000 cycles).

Fiber or yarn-like micro-supercapacitors are made from flexible/stretchable liner composites as electrodes, which can be easily connected in series or parallel, knotted, braided, or sewn into almost any desired shape, and eventually integrated into clothing[9,113,114]. The flexibility of the linear supercapacitors can be further enhanced through structural changes, such as pre-strained wavy[115], coiled[116,117], and serpentine-shaped structures[118]. Electric capacity performance can be adjusted by varying their lengths[119]. These special properties extend the application of yarn-like supercapacitors to wearable electronic devices.

Using flexible/stretchable yarn materials as substrates and coating them with electrochemically active materials is one of the most popular methods to obtain yarn-like electrodes. Chen *et al.* developed functionalized stainless steel (FSS) yarns that were good for the growth and adhesion of active material after acidification and annealing, playing the role of a current collector and scaffold simultaneously for supercapacitors[120]. Uniform Ni-Co-S was electrochemically deposited on the FSS yarn as a positive electrode, while graphene oxide (GO) was deposited on the FSS yarn and reduced to function as a negative electrode. After coating the LiOH/PVA gel electrolyte, all-solid asymmetric yarn supercapacitors were prepared. The assembled stretchable fiber supercapacitor shows a high energy density of 0.0487 mWh cm^{-2} at a power density of 0.553 mW cm^{-2}. Through a prestraining-then-releasing method, a stretchable cable-type SC was formed. It can maintain its electrochemical performance well at a high strain of 100%, and be integrated into the clothing and light up an LED [Figure 2A].

Choi *et al.* used CNT yarns as host electrodes and manufactured yarn supercapacitors with asymmetric configurations using liquid-state biscrolling technology[121]. High-load rGO anode guest (90.1 wt%) and MnO_2 cathode guest (70 wt%) were successfully embedded in the CNT yarn hosts. By introducing a poly(vinylidenefluoride-hexafluoropropylene) (PVDF-HFP) gel-based tetraethylammonium tetrafluoroborate ($TEA{\cdot}BF_4$) organic electrolyte, asymmetric yarn-based supercapacitors can be obtained with wide potential window (up to 3.5 V), high capacitance (322.4 mF cm^{-2}@10 mV s^{-1}) and high energy density (43 μWh cm^{-2}). Yarn electrodes have sufficient mechanical strength to be easily woven into textiles. Four asymmetric supercapacitors woven in series can light up a blue LED [Figure 2B], demonstrating the potential to supply power for wearable products.

Lv *et al.* deposited pseudocapacitive PPy on commercial regenerated cellulose (Lyocell) yarns via an improved *in situ* solution polymerization method[122]. PPy endows the Lyocell yarns with excellent electrochemical performance, flame retardancy, and good electrical heating performance, resulting in a simple, low-cost, and highly scalable multifunctional conductive yarn. The areal capacitance of PPy-coated lyocell yarn (PCLY)-based MSCs reaches 663 mF cm^{-2} with an energy density of 21.6 mWh cm^{-2} at a current density of 1 mA cm^{-2}, which is much higher than other yarn/fiber MSCs[24,123,124]. The PCLY can be hand-woven into complete fabrics and even embroidered into various textile patterns. As shown in Figure 2C, the textile MSCs can be sewn into any garment to power wearable electronic devices.

The yarn supercapacitors mentioned above have shown limited electrochemical activities and low energy densities due to the selection of electroactive materials with low electrochemical activity, which is not conducive to their direct application in advanced energy storage devices[125]. To further improve the electrochemical performance of yarn supercapacitors, directly twisting the electrochemically active materials with high capacity into yarn electrodes without current collectors and additives becomes effective. In addition to some commonly used pseudo-capacitor materials (such as metal oxides and conductive polymers mentioned above), transition metal oxides (TMOs) have been gradually used because of their high theoretical specific capacity, structural versatility, and low cost. Ahn *et al.* prepared fiber supercapacitors with high electrochemical activity and rate capability based on dimension-controlled pseudocapacitive TMO yarns, which were obtained by twisting the sandwich-like TMO/Ni/TMO trilayer nanoribbon arrays [Figure 2D][126]. Different TMO-based yarns such as NiOx@Ni (NO), MnOx@Ni (MO), and CoNixOy@Ni (CNO) were prepared, and the electrochemical performance of the constructed fiber supercapacitors have been studied. Notably, the symmetric fiber supercapacitor based on two parallel CNO yarns has an ultra-high specific capacitance of 7.36 F cm^{-3}. The asymmetric fiber supercapacitors using graphene fiber and CNO yarn, respectively, as negative and positive electrodes, exhibited high energy density and power density of 1.04 mWh cm^{-2} and 7.2 mW cm^{-2}, respectively. The specific capacitance can reach 2.93 F cm^{-2}, one order of magnitude higher than previously reported yarn supercapacitors[127,128]. Moreover, these fiber supercapacitors have been demonstrated to retain their specific capacitance after mechanical deformations and electrochemical cycles (10,000 cycles).

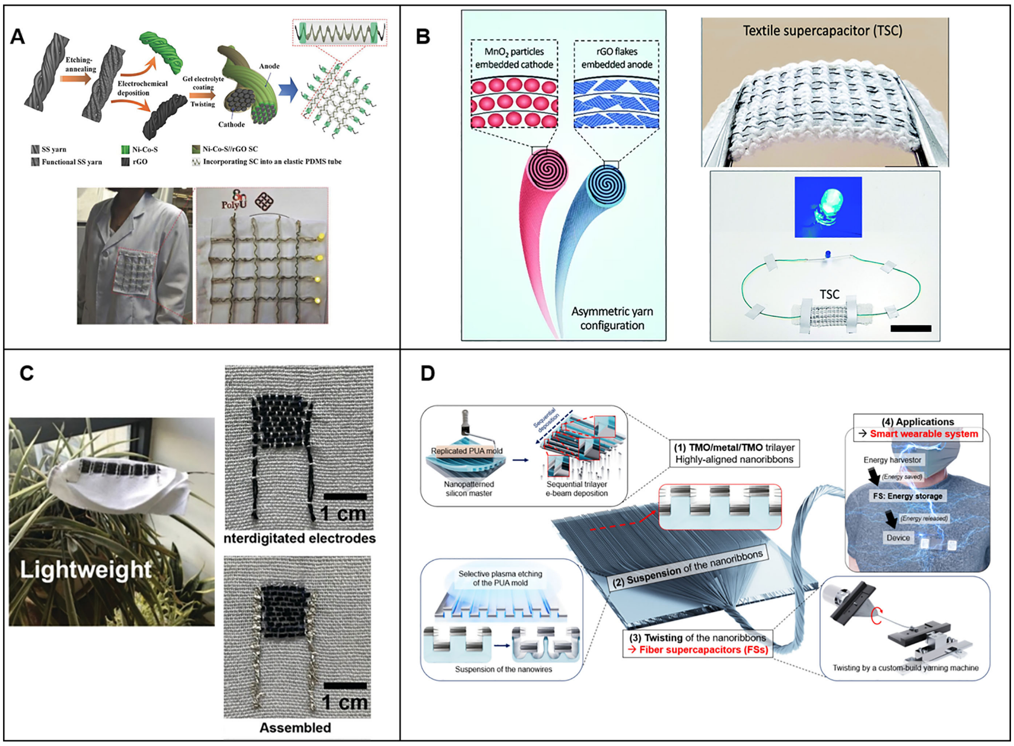

Figure 2. Stretchable non-contact wearable biocompatible fiber supercapacitors. (A) Schematic illustration of woven fiber-based supercapacitors integrated into clothes[120]; (B) Asymmetric yarn supercapacitor fabricated by liquid-state biscrolling technology[121]; (C) Hand-knitted multifunctional conductive PCLY and PCLY-based miniature supercapacitors[122]; (D) Fabrication process and applications of TMO/metal/TMO trilayer nanoribbon yarns[126]. Reproduced from Ref.[120], Ref.[121], Ref.[122], and Ref.[126] with permission from Small, RSC Advances, Journal of Materials Chemistry C, and Springer Nature, respectively. PCLY: PPy-coated lyocell yarn; TMOs: transition metal oxides.

Skin-contact type

Since skin-contact wearable devices attach directly to the skin, they should be highly biocompatible, avoiding biotoxicity, skin irritation, and injury[129,130]. The skin typically undergoes stretching or bending with the motion of the human body. Consequently, it is essential for skin-contact wearable devices to possess adequate stretchability and flexibility[131]. The skin-contact supercapacitors can be divided into two main categories. One is mounted on human skin with the assistance of medical tape or substrates that are soft and compatible with the skin. Another is in a skin-like layout, which is thinner, more lightweight and flexible to allow for adaptability and compliance; thus, it can conformally adhere to the skin and withstand greater tension and bending without losing its performance.

For the first type, Yun *et al.* fabricated a skin-contact all-transparent stretchable electrochromic supercapacitor device with ultra-stable performance under mechanical deformation[132]. The devices are composed of bi-stacked WO_3 nanotube/PEDOT:PSS as electrodes, polydimethylsiloxane (PDMS) substrates embedded with Au/Ag core-shell nanowires as transparent-stretchable current collectors and polyacrylamide (PAAm)-based hydrogel electrolytes [Figure 3A]. Because the electrolyte has high ionic conductivity and stretchability of up to 80%, the resulting wearable supercapacitor patch device showed excellent performance and reliability even under tensile-bending movements, achieving a capacitance retention rate of 98.6% under 20% of total strain. Kil *et al.*[133] deposited Indium Tin Oxides (ITO) on thin PDMS and then coated with GO and electrolyte gel to prepare a patch-type self-charging supercapacitor. All components of the supercapacitor were made of flexible polymer materials suitable for skin attachment and

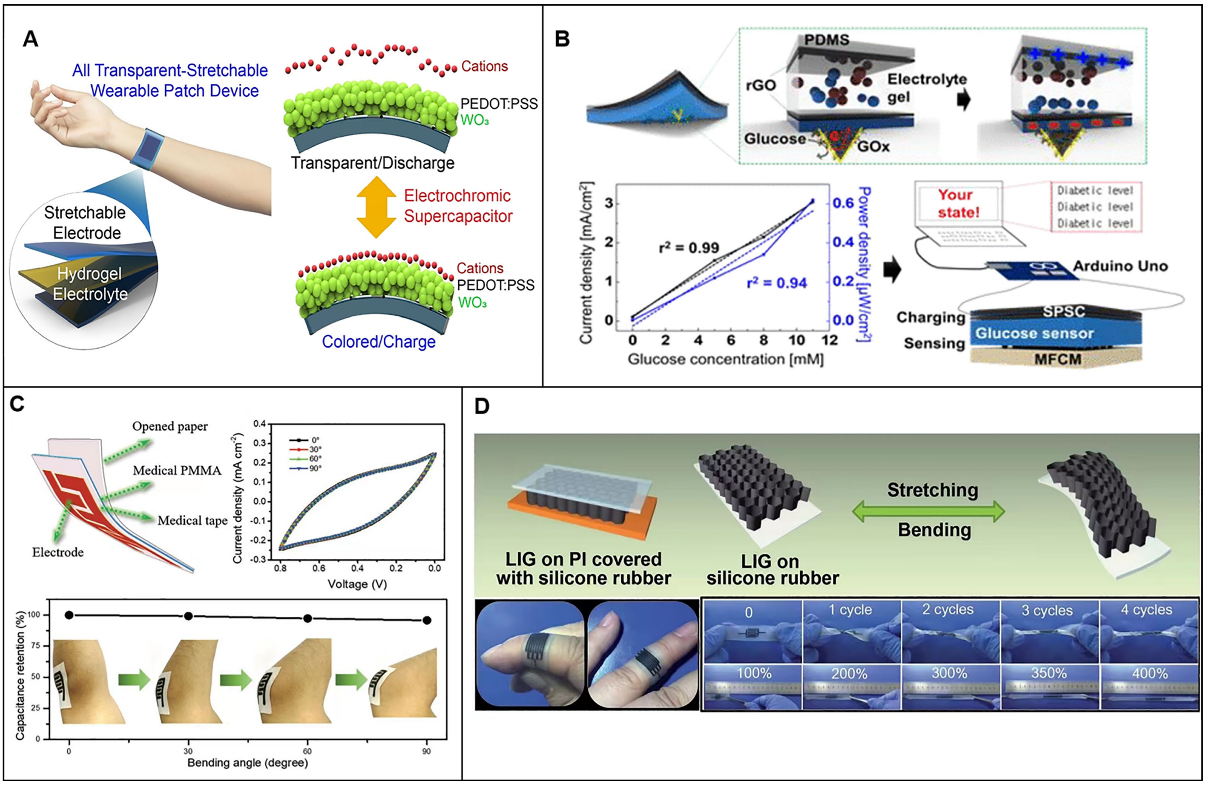

Figure 3. Skin-contact biocompatible wearable miniature supercapacitors prepared on biocompatible substrates. (A) Structure of all-transparent stretchable electrochromic supercapacitor[132]; (B) Patch of self-charging supercapacitor based on thin PDMS[133]; (C) Solid in-plane TFMSCs based on flexible medical tape[88]; (D) Flexible and stretchable supercapacitor based on silicone rubber[134]. Reproduced from Ref.[132], Ref.[133], Ref.[88], and Ref.[134] with permission from ACS Publications, ACS Publications, Small, and Small, respectively. PDMS: Polydimethylsiloxane; TFMSCs: thin-film micro supercapacitors.

can be combined with a microneedle glucose sensor to detect blood glucose signals from skin models [Figure 3B]. Through the design of PDMS films and electrolyte gel layers with a thickness of 700 μm and the deformable physical properties of PDMS micronuclei, the structure of the self-charging supercapacitor patch can withstand deformation without any performance degradation.

Planar supercapacitors with a novel interdigital structure design have a thinner thickness and easier access to flexibility, facilitating the integration and compact package with other electronic devices and applications in portable/wearable devices. Thus, they have witnessed rapid development in recent years. Zhu *et al.* developed stretchable and skin-mountable solid in-plane thin-film MSCs utilizing highly bendable and stretchable medical adhesive tape as substrates[88]. The MSCs were fabricated by coating the graphite layer on the flexible medical tape by a simple pencil drawing process and then depositing the MnO_2 layer by a mild *in-situ* redox method. The solid MnO_2/graphite MSCs showed a maximum areal capacitance of 40.2 mF cm^{-2} at a current density of 0.1 mA cm^{-2}. Additionally, the MSCs exhibited remarkable stretchability, flexibility, and biocompatibility, sustaining nearly consistent electrochemical performance across various stretching conditions ranging from 100% to 130%. With the aid of polymethyl methacrylate (MPMMA) skin bonding layers, the MSCs can adhere to various body parts through a simple uncovering-affixing procedure [Figure 3C], facilitating the rapid integration and use of wearable devices. Song *et al.*[134] developed a highly stretchable planar MSC using silicone rubber as a substrate. The laser-induced graphene with a 3D porous network structure on polyimide was transferred to the silicone rubber substrate and served as active electrodes. After coating potassium polyacrylate-potassium hydroxide (PAAK/KOH) gel electrolyte on the interdigital electrodes, all-solid-state, soft, transparent and stretchable MSC devices were fabricated. Because of the lower elastic modulus of silicone, the MSC can conformally attach to the curved skin of the human finger. In addition, the device can be stretched to up to 400%. After stretching to 300% 1000 times, the average resistance of the device remains unchanged because the planar interdigital structure of the MSC still has high stability and symmetry under severe deformation. Additionally, the silicon substrate can separate the electrode materials and electrolytes from the skin to ensure the biocompatibility of the devices. These all-solid-state MSCs can be easily integrated into wearable devices to meet the energy and power needs of practical applications [Figure 3D].

Compared to the first type, the skin-like energy storage device has the characteristics of conformal attachment/integration, thin, lightweight, and moduli-matching. It can not only sustain greater tension and bending without losing its own performance but also conformally adhere to the skin, providing higher biocompatibility and comfort. Lee *et al.*[135] prepared a skin-like, dynamically stretchable planar supercapacitor through a pre-strain method. Elastomeric porous PDMS/Ecoflex, Cr/Au thin film and Mn/Mo@MWCNT were used as a substrate, current collector and electrode, respectively. Given the strain caused by human joints, the substrate was subjected to a 50% biaxial pre-strain before coating other materials, making the omnidirectional stretchability of the electrodes achieve up to 50%. The resulting supercapacitors exhibit an areal capacitance of 7.5 mF cm^{-2} (0.3 mA cm^{-2}) and an areal energy density of 4.2 μWh cm^{-2} (0.3 mW cm^{-2}). Furthermore, they have static and dynamic tensile properties without performance decay under real-time deformation. The thickness of the whole device is ~270 μm, thus able to be conformally attached to the skin. As shown in Figure 4A, the skin-like, high-performance, dynamically stretchable, planar supercapacitor can conformally adhere to the finger skin and has stable performance during dynamic movement of the finger joints.

An *et al.*[136] prepared a skin-like supercapacitor composed of biocompatible self-assembled vertical gold nanowires (v-AuNWs) and electrodeposited PANI. The v-AuNWs with a thickness of 200 nm offer high conductivity, flexibility, and deformability. Electrodeposited transparent pesuedocapacitive PANI porous network gives the assembled supercapacitor enhanced capacitance and plays the role of charge/discharge level indicator due to the electrochromic property. The devices achieved an areal capacitance of 11.76 mF cm^{-2} at a scan rate of 10 mV s^{-1} and retained 93.6% of its original capacitance after 2,000 galvanostatic charge-discharge (GCD) cycles at a current density of 1.0 mA cm^{-2}. A conformal supercapacitor "tattoo" patch can be formed on soft and dynamic human skin, and the performance degradation under multiple hand movements and skin deformation is negligible [Figure 4B].

Wang *et al.*[137] developed a skin-like supercapacitor using a conformable elastic photopolymer as the substrate, embedded microwave-welded silver nanowires (AgNWs) as conducting electrodes [Figure 4C], PEDOT:PSS as active material and PVA/H_3PO_4 as gel electrolyte. The selected elastic photopolymer (Norland optical adhesive 63, NOA63) substrate has appropriate modulus and adhesion. Meanwhile, the microwave-welded technique effectively reduced the contact resistance of AgNWs at junctions, resulting in highly conductive, robust, and stable embedded-structure AgNW electrodes. Based on the electrodes, skin-like supercapacitors were achieved with high areal capacitance (2.09 mF cm^{-2}) and excellent flexibility (2,000 bending cycles). The device also exhibited good mechanical properties and stability over 2,000 bending cycles, which can be well attached to the wrist and illuminate the LED under bending and stretching [Figure 4C].

In summary, wearable BMSCs have seen significant advancements in recent years, improving both their electrochemical performance and mechanical flexibility/stretchability. Table 1 provides an overview of the

Table 1. Comparison of electrochemical parameters and mechanical properties of the state-of-the-art wearable micro-supercapacitors reported in the literature

No.		Substrate	Electrode materials	Specific capacitance	Potential window	Energy density	Power density	Cyclic stability	Flexibility/ Stretchability	Mechanical stability	Ref.
	Non-contact type	(1) Coating active materials on fabrics									
1		Custom knitted carbon fiber cloth	AC	0.51 F cm^{-2} at 10 mV s^{-1}	0-1 V	/	/	/	Bending (angle = 90°, 135°, 180°), stretching (50%)	/	[109]
2		Conductive stainless steel wire	AC/MWCNT	74.2 mF cm^{-2} at 1.0 mV s^{-1}	0-1.5 V	0.117 mWh cm^{-2}	1.73 mW cm^{-2}	10,000 cycles	Bending (angle = 150°), twisting (R_b = 0.5 cm)	/	[110]
3		Uniform copper layer	AC	8.8 mF cm^{-2} at 0.5 mA cm^{-2}	0-1 V	/	/	99% after 6000 cycles	Bending (angle = 90°, 180°)	89 % after 2000 bending cycles@90°	[111]
4		3D fabrics	PEDOT:PSS/ MnO_2	135.4 mF cm^{-2} at 0.08 mA cm^{-2}	0-0.8V	0.01203 mWh cm^{-2}	32 mW cm^{-2}	93% after 3000 cycles	Bending (angle = 0°-180°)	94 % after 3000 bending cycles	[111]
		(2) Combining active materials with flexible/stretchable yarn materials									
5		FSS yarns	Ni-Co-S//rGO	127.2 mF cm^{-2} at 0.4 mA	0-1.7 V	0.0487 mWh cm^{-2}	0.553 mW cm^{-2}	86.2% after 3000 cycles	Bending (angle = 0°-360°), knotting, and stretching (100%)	95% upon different bending angles	[120]
6		Carbon nanotube yarns	MnO_2//rGO	322.4 mF cm^{-2} at 10 mV s^{-1}	0-3.5 V	0.043 mWh cm^{-2}	/	1000 cycles	Bending	100 bending cycles	[121]
7		Lyocell yarns	PPy	663 mF cm^{-2} at 1 mA cm^{-2}	0-0.5 V	0.0216 mWh cm^{-2}	0.3 mW cm^{-2}	2000 cycles	Bending and twisting	/	[122]
8		/	CoNixOy nanoribbon yarns//graphene fibers	2.9 F cm^{-2} at 2.2 mA cm^{-2}	0-1.5 V	1.04 mWh cm^{-2}	7.2 mW cm^{-2}	94.2% after 10,000 cycles	Bending, stretching, winding, knotting	Almost 100% after 1000 bending @90°	[126]
	Skin-contact type	(3) Using soft and compatible substrates									
9		PDMS embedded with Au/Ag core-shell nanowires	Bi-stacked WO_3 nanotube/PEDOT:PSS	471.0 F g^{-1}	-1.5 - -0.1V	52.6 Wh kg^{-1}	19.1 kW kg^{-1}	79.5% after 50000 cycles	Stretching (80%), bending	98.6% under 20% total strain	[132]
10		PDMS	Graphene oxide	800 mF cm^{-3}	0-1 V	/	0.62 mW cm^{-2}	/	/	/	[133]
11		Medical adhesive tapes	MnO_2/Graphite layers	40.2 mF cm^{-2} at 0.1 mA cm^{-2}	0-0.8 V	/	/	85.8% after 2000 cycles	Stretching (100%-130%), bending (angle = 0°-90°)	> 90% after 200 bending @90°	[88]
12		Silicone rubbers	Laser-induced graphene/PEDOT:PSS	0.79 mF cm^{-2} at 0.05 mA cm^{-2}	0-0.8 V	/	/	96% after 10000 cycles	Stretching (400%), bending (angle = 0°-180°)	> 90% after 1,000 twisting times	[134]
		(4) Using elastomeric substrates and in ultra-thin layout									
13		Porous PDMS/Ecoflex	MWCNT and buckled Mn//Mo mixed oxide	7.5 mF cm^{-2} at 0.3 mA cm^{-2}	0-2 V	4.2 µWh cm^{-2}	0.3 mW cm^{-2}	88% after 5000 cycles	Biaxially stretching (50%)	90% after 1000 stretching cycles	[135]
14		Preservative membrane substrates	PANI	11.76 mF cm^{-2} at 10 mV s^{-1}	0-0.8 V	0.71 µWh cm^{-2}	40 µW cm^{-2}	93.6% after 2000 cycles	Bending (angle = 0°-180°)	95% after 5000 bending cycles@180°	[136]

15	NOA 63/AgNWs	PEDOT:PSS	2.09 mF cm^{-2} at 5 mV s^{-1}	0-1 V	/	/	/	Bending and stretching	2000 bending cycles@radius = 8 mm	[137]

AC: Activated carbon; R_b: bending radius; PEDOT:PSS: poly(3,4-ethylenedioxythiophene):poly(styrenesulfonate); FSS: functionalized stainless steel; rGO: reduced graphene oxide; PDMS: poly(dimethylsiloxane); PPy: polypyrrole; Ecoflex: ecological flexibility; Mn/Mo: manganese/molybdenum; MWCNT: multiwalled carbon nanotube; v-AuNWs: vertical gold nanowires; PANI: polyaniline; AgNWs: silver nanowires; NOA 63: norland optical adhesive 63.

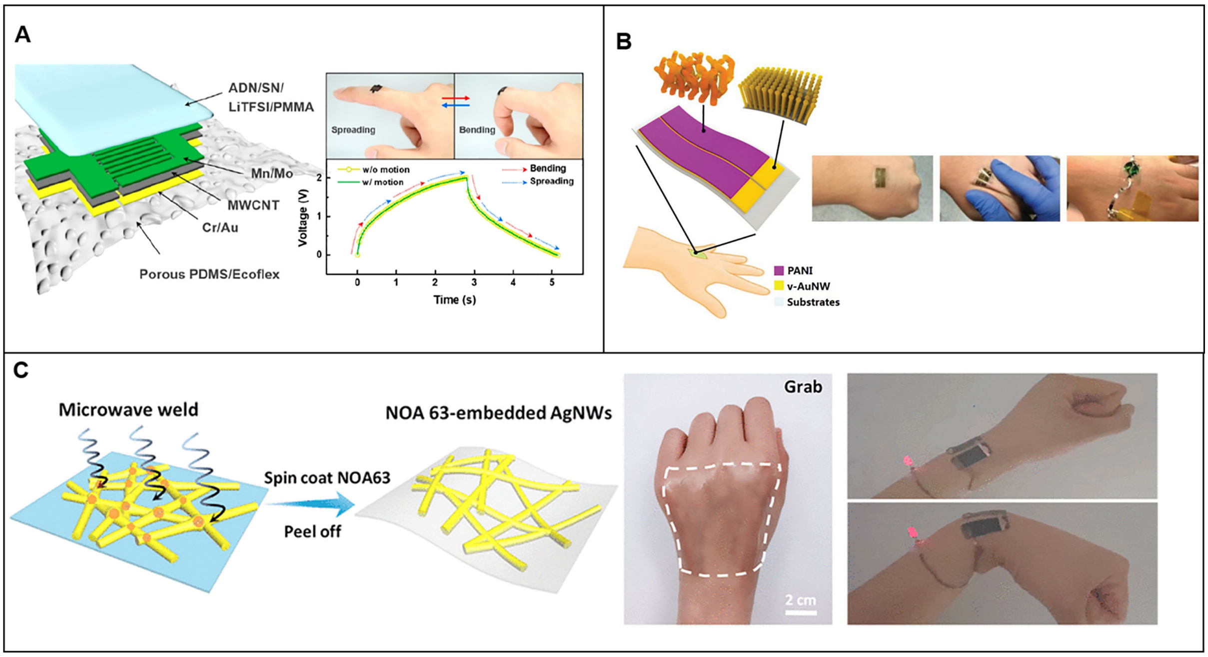

Figure 4. Skin-like biocompatible wearable miniature supercapacitors. (A) Structure and performance of a planar supercapacitor conformable for skin[135]; (B) Structure and application of skin-like electrochromic supercapacitor[136]; (C) skin-like supercapacitor composed of PEDOT:PSS/AgNW electrodes[137]. Reproduced from Ref.[135], Ref.[136], and Ref.[137] with permission from ACS Publications, Advanced Materials Technologies, and ACS Publications, respectively. AgNW: Silver nanowires; PEDOT:PSS: poly(3,4-ethylenedioxythiophene):poly(styrenesulfonate).

methods used to create wearable BMSCs and their associated performance. Non-contact devices are typically made by coating active materials on fabrics or combining the active materials on yarns. They are intrinsically flexible and convenient to incorporate into clothing. Skin-contact type BMSCs are constructed on flexible/elastic substrates, characterized by their thin, soft, and lightweight properties.

IMPLANTABLE BMSCS

In recent years, advancements in contemporary medicine have led to the rapid development and widespread use of implantable electronic medical devices, such as pacemakers, cochlear implants and brain neurostimulation systems[8,138]. Implantable biomedical electronic devices can provide treatment that cannot be done externally, have the potential to address various clinical problems, including real-time health monitoring and accurate treatment[139]. With the growing demand for implantable electronic medical devices, implantable energy supply devices have become a research hotspot in the field of energy. Compared with traditional batteries and fuel cells, supercapacitors have greater potential in energy storage devices for implantable electronic medical devices[140-142]. The strong selectivity of biocompatible materials enables them to avoid issues related to immune rejection, inflammation and biocompatibility problems, which are often caused by corrosion and leakage of batteries or fuel cells[101].

Implantable BMSCs have been rapidly developed and still show great potential for evolution. They can be divided into ordinary implantable and biodegradable/bioabsorbable supercapacitors, depending on whether they need to be removed after implantation in the human body. Compared to wearable BMSCs, biocompatible materials, miniature size, mechanical flexibility, and bio-degradability are more critical for implantable devices. A comprehensive comparison of the properties and electrochemical performance of implantable BMSCs is present in Table 2. Implantable BMSCs are typically designed in the form of fiber or thin film with small size due to the spatial limitations in the human body. For ordinary implantable BMSCs, biocompatible carbon materials are mainly used as electrodes, with body fluids serving as electrolytes. They often show high capacitance and long cycle life, allowing for stable long-term operation within the body without adverse effects. Biodegradable/bioabsorbable BMSCs are designed to operate for a prescribed time and then decompose in the human body, ideal for short-term implantation. Biodegradable, water-soluble metals such as Fe, Zn, and Mo are preferable electrode materials, and biodegradable polymers are used as gel electrolyte matrices. Proper encapsulation is essential to regulate the degradation time, ranging from a few days to several months.

Ordinary implantable BMSCs

Developing biocompatible electrode materials has attracted great attention from researchers due to its importance in determining the electrochemical performance of implantable BMSCs[14,143]. Various natural organic compounds (ferritin, methylcellulose, sodium alginate[60], gelatin, *etc.*) and synthetic polymers (PEDOT:PSS[86], PVA[85,86,100,144], PANI[85], *etc.*) have been proved to be biocompatible materials. Sim *et al.* attached PEDOT:PSS/ferritin nanoclusters to CNT sheets, and then prepared biocompatible fiber supercapacitors by biscrolling method [Figure 5A][6]. The fiber-type micro-supercapacitor made by this method has high flexibility and mechanical strength, which can not only be used as a suture material but also maintain its performance after being implanted into the blood vessels of mice for a week.

Moreover, the electrolytes used in many traditional supercapacitors, such as propylene carbonate[145] and lithium perchlorate[146], are unstable and toxic. Using these electrolytes, which easily cause adverse reactions such as immune rejection or inflammation, is necessary to protect the human body from harm through complex and strict packaging[102]. In this case, the volume of the devices is too large to meet the requirements of miniaturization, limiting the application of supercapacitors in living bodies. To solve this problem, physiological liquids such as PBS and body fluids (such as serum, blood, gastric juice, tissue fluid, *etc.*) were used as electrolytes to enhance the biocompatibility and safety of BMSCs for implantation[44,73]. For example, Chae *et al.* constructed BMSCs utilizing MnO_2 nanoparticles-embedded MWCNTs as the positive electrode and phosphide-activated carbon as the negative electrode[101]. Natural ions (Na^+ and Cl^-, *etc.*) in body fluids were used as electrolytes, thereby enhancing the biocompatibility of the whole device [Figure 5B]. *In vitro* cytotoxicity tests were performed to evaluate the bio-safety of electrodes using two types of fibroblasts (human-derived fibroblast cells and African green monkey kidney COS-7 cells). The results showed that the electrodes have no harmful effects on the cells, demonstrating good biocompatibility. After that, the two biocompatible electrodes were successfully implanted into the subcutaneous layer of rat skin. The implanted devices showed stable electrochemical performance and good biocompatibility, promoting the development of implantable BMSCs and giving them greater application prospects.

Similarly, He *et al.* have prepared a fibrous biocompatible supercapacitor that can operate in physiological fluids such as PBS, serum, and blood [Figure 5C][72]. CNT arrays were modified by oxygen microwave plasma and twisted to prepare hydrophilic CNT fiber electrodes with good biocompatibility. Fibrous BMSCs assembled by the fiber electrodes work with physiological liquids such as PBS, serum and blood as electrolytes and show good capacitive performance of 20.8 F g^{-1}, 11.4 F g^{-1} and 13 F g^{-1}, respectively. The

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Table 2. Comparison of properties of the state-of-the-art implantable BMSCs reported in the literature

No.	Electrode materials	Electrolytes	Size	Biocompatibility test cell culture	Specific capacitance	Energy density	Power density	Cyclic stability	Mechanical properties	Biodegradability /Bioabsorbability	Ref.
1	PEDOT:PSS/ferritin/MWNT fiber electrodes	PBS solution	80 µm in diameter	/	32.9 mF cm^{-2} at 10 mV s^{-1}	0.82 µWh cm^{-2}	150 µW cm^{-2}	/	Strain of 9% (dry) and 20% (immersed in PBS solution for 24 h)	/	[6]
2	CNT fiber	PBS solution	/	NIH-3T3 fibroblast cells	10.4 F cm^{-3} or 20.8 F g^{-1}	/	/	98.3% after 10,000 cycles	/	/	[72]
3	Oxidized SWCNTs	Simulated body fluid	/	Human fibroblast cells	51.3 mF cm^{-2} (13.15 F g^{-1}) at 0.025 A g^{-1}	7.12 mW h cm^{-2}	500 mW cm^{-2}	100% after 50000 cycles	Bending angle (0-180°)	/	[73]
4	PDA/CNT yarn	Body fluids (PBS, HBSS, saline, and horse serum)	2 mm wide and 1 cm long	MOVAS cells	503.91 mF cm^{-2}	274 µWh cm^{-2}	25.52 mW cm^{-2}	98.17% after 10,000 cycles	Bending at 150° for 1,000 cycles	/	[149]
5	Mo interdigitated thin film electrodes	NaCl/Agarose gel electrolyte	Thickness ≈ 160 µm	/	1.6 mF cm^{-2} at 0.15 mA cm^{-2}	0.14 µWh cm^{-2} (at 61 µW cm^{-2})	1.0 mW cm^{-2} (at 0.0083 µWh cm^{-2})	/	Bending with radius of 2.5 mm	Degradation began after 6 h in PBS	[61]
6	Anodized Mo wire	0.05 M NaCl/PVA electrolyte	0.24 cm^2 (one electrode)	/	4.15 mF cm^{-2} at 0.05 mA cm^{-2}	0.37 µWh cm^{-2} (at 20 µW cm^{-2})	0.8 mW cm^{-2} (at 0.14 µWh cm^{-2})	82% after 5,000 cycles	50% strain.	Degradation began after 11 days of stable operation in DI water at 37 °C	[100]
7	ZnO on Fe electrode	PVA/PBS hydrogel	1.5 cm × 1.5 cm × 1 mm.	L929 cells	0.9 mF cm^{-2}	0.153 µWh cm^{-2} at 27 µW cm^{-2}	0.526 mW cm^{-2} (at 0.013 µWh cm^{-2})	70% after 3,000 cycles	/	Stable for 50 days and began to degrade and be absorbed by rats in the next few months.	[156]
8	MoO_x flakes	Alg-Na gel electrolyte	1 cm × 1 cm ×0.1cm	HEC-1-A cells	112.5 mF cm^{-2} at 1 mA cm^{-2}	15.64 µWh cm^{-2}	2.53 mW cm^{-2}	86.7% after 2000 cycles	Bending at 60°	Completely dissolved and absorbed by rats after 6 months	[60]

PEDOT:PSS: Poly(3,4-ethylenedioxythiophene):poly(styrenesulfonate); MWNT: multiwalled carbon nanotube; PBS: phosphate buffered saline; CNT: carbon nanotube; SWCNTs: single-walled carbon nanotubes; PDA: polydopamine; HBSS: Hanks' balanced salt solution; PVA: polyvinyl alcohol; Alg-Na: sodium alginate.

BMSCs have higher energy storage capacity over many of the reported CNT-based fibrous supercapacitors, such as 1.58 F cm^{-3} for those with a spring-like structure[147] or 4.5 F g^{-1} with a twisted structure[148]. The biocompatible fibrous micro-supercapacitor is also lightweight, soft, and small, showing great potential as an implantable energy storage device.

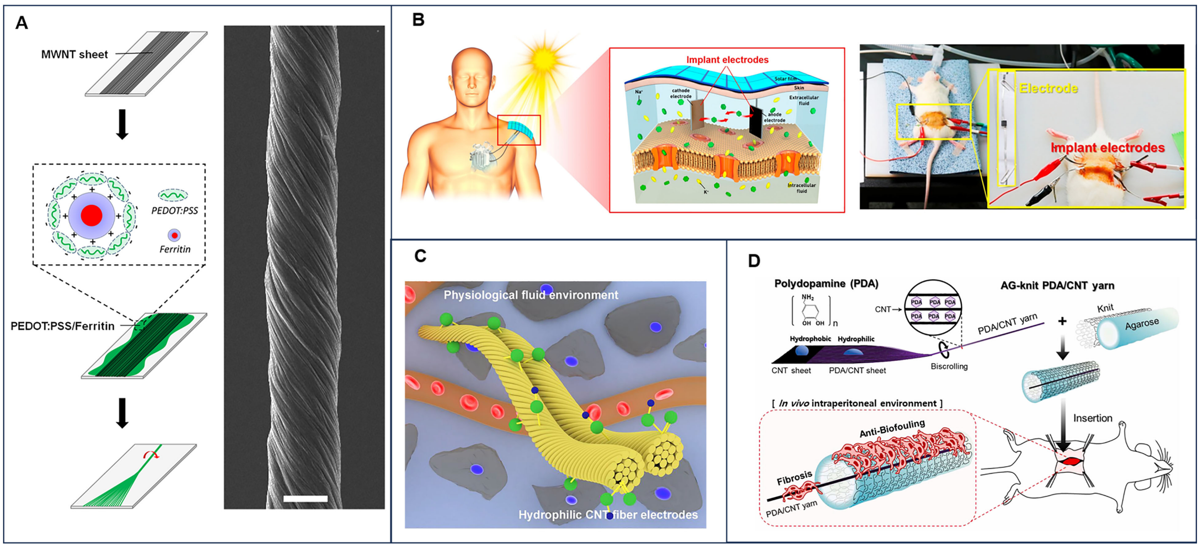

Figure 5. Ordinary implantable micro-supercapacitors. (A) Schematic diagram of the fiber-type biocompatible micro-supercapacitor[6]; (B) Structure and application diagram of the biocompatible micro-supercapacitor using body fluid as electrolyte[101]; (C) Schematic diagram of the flexible biocompatible micro-supercapacitor using body fluid as electrolyte[72]; (D) Fabrication scheme of anti-biofouling PDA/CNT supercapacitor and fabricating agarose-coated circular knit structure with PDA/CNT electrode[149]. Reproduced from Ref.[6]. ,Ref.[101], Ref.[72], and Ref.[149] with permission from Nano Energy, Nano Energy, Small, Biosensors and Bioelectronics, respectively. PDA: Polydopamine; CNT: carbon nanotube.

Utilizing body fluid as an electrolyte offers significant advantages to supercapacitors in implantable electronics and the cumbersome encapsulation can be avoided. However, the consequent performance degradation due to electrode biofouling remains challenging and hinders practical application. Based on it, an anti-biofouling implantable supercapacitor with high energy performance was developed by Park *et al.*[149]. By infiltrating highly biocompatible and hydrophilic polydopamine (PDA) into CNTs, they successfully changed the CNT surface from hydrophobic (contact angle 140°) to hydrophilic (contact angle 25°). And then, a fiber-type supercapacitor was created using the scrolling method [Figure 5D]. In different *in vitro* biological fluids, including PBS, Hanks' Balanced Salt solution (HBSS), normal saline, and horse serum (HS), the PDA/CNT supercapacitor shows excellent capacitive performance of up to 503.91 mF cm^{-2}, about 250 times higher than that of the original CNT supercapacitor (2 mF cm^{-2}). In addition, the PDA/CNT supercapacitor is encapsulated in an agarose-coated circular knit before implantation into the organism, which allows the free movement of biological fluids yet prevents the penetration of near cells and the undesirable adsorption of cell debris, inhibiting the formation of the immune system fiber sac, achieving the purpose of anti-biological contamination. After the encapsulated PDA/CNT supercapacitor was implanted into the rat's abdominal cavity, stable energy storage performance was maintained for 21 days.

In conclusion, implantable micro-supercapacitors have been in multifaceted, stable, and sustainable development. To meet the safety and stability requirements of devices implanted in human bodies, researchers are making efforts to improve the biocompatibility of micro-supercapacitors in terms of electrode materials and electrolytes. Plentiful achievements have been obtained, greatly broadening the application of BMSCs in the field of implantable medical electronic devices.

Bio-absorbable (or -degradable) micro-supercapacitors

For short-term or medium-term implantable electronic applications, such as bone growth stimulation, wound healing, muscle stimulation and neurostimulation, the power source is required to operate only for a prescribed time[150]. In this case, biodegradable and bioabsorbable BMSCs provide a unique opportunity[63,151-153]. Biodegradable materials are materials that can be chemically, biologically or physically degraded or decomposed in physiological or environmental aqueous solutions through the action of microorganisms such as bacteria and fungi[154]. According to the European Committee for Standardization (CEN) (no. EN 13432), substances dissolved by more than 90% within six months can be defined as biodegradable materials[37]. Bio-degradable (or - absorbable) devices can play a therapeutic role for a defined time and then undergo decomposition, absorption or metabolism within the biological environment of the organism at a certain time or rate[57,155]. Consequently, a second surgery to remove the device can be avoided, reducing the possibility of potential risks such as tissue lesions and inflammation[156]. Meanwhile, negative effects caused by long-term implantation on the organism can also be reduced[152].

Lee *et al.* first reported fully biodegradable MSCs and studied the dissolution kinetics in PBS at physiological temperatures [Figure 6A][61]. They prepared MSCs using biodegradable water-soluble (i.e., physically transient) metals (W, Fe, and Mo) as electrode materials, which can also be used as current collectors, and biodegradable agarose gels containing NaCl salts as electrolytes. It is worth noting that during the charge-discharge cycle, redox reactions occur at the interface of water-soluble metal electrodes and hydrogel electrolytes, forming a metal oxide layer and generating additional pseudocapacitance. It significantly enhanced the electrochemical performance of MSCs, which was comparable to that of non-transient supercapacitors. The biodegradable MSCs with Mo interdigital electrodes show an areal capacitance of 1.6 mF cm^{-2}, an energy density of 0.14 μWh cm^{-2} and a power density of 1.0 mW cm^{-2}. At physiological temperature, the prepared interdigital Mo electrodes (with a gap of 150 μm) were completely degraded and disappeared in PBS solution after nine days. The degradation rate can be adjusted by changing the size of the interfinger gap, pH values and temperature of the solution, and the thickness and composition of the electrode film.

Then, Lee *et al.* reported a serpentine-shaped wire supercapacitor that is easy to manufacture and completely biodegradable[100]. The supercapacitors were constructed using biodegradable materials such as water-soluble molybdenum wire, molybdenum oxide (MoO_x) film, and ionic salts (Na^+ and Cl^-) containing PVA. Biodegradable material POC was used as encapsulation polymer. The POC membrane enhanced the water resistance of MSCs; they could run stably in deionized water at 37 °C for 11 days. Then, the degradation of POC led to the infiltration of the surrounding water, resulting in the degradation of the whole MSC. The MSCs can be made into different lengths and have a constant length capacitance of about 0.37 mF cm^{-1}, regardless of the total length [Figure 6B]. It still has stable performance under repeated cycles and bending deformation, showing potential to be an energy storage device for implantable equipment.

As the energy storage units of implantable electronic systems, it is better for the BMSCs to be bio-absorbable. Li *et al.* constructed bio-absorbable BMSCs with symmetrical multilayer structures[156], as shown in Figure 6C. They comprise PLA with nanopillars, iron films, zinc oxide layers, and PVA/PBS hydrogels. The polylactic acid nanopillar arrays protect the whole device from the external environment, ensuring stable electrochemical performance both *in vivo* and *in vitro*. Consequently, the BMSCs can work well with good capacitance performance not only in the air environment, but also in the liquid environment of PBS and animals. The capacitance of BMSCs can reach about 0.15 mF cm^{-2} in PBS at 37 °C and in rats. Furthermore, the BMSCs can work in PBS and rats for 30 days and 50 days, respectively. Most importantly, after completing the task in the rat body, the BMSCs will be completely degraded and absorbed. By varying the encapsulation polymer (PVA and PLA), the working time of the bio-absorbable (or -degradable) BMSCs can be regulated from a few days to a few weeks. This micro-supercapacitor is expected to play a role in implantable medical electronic devices for short-term treatment.

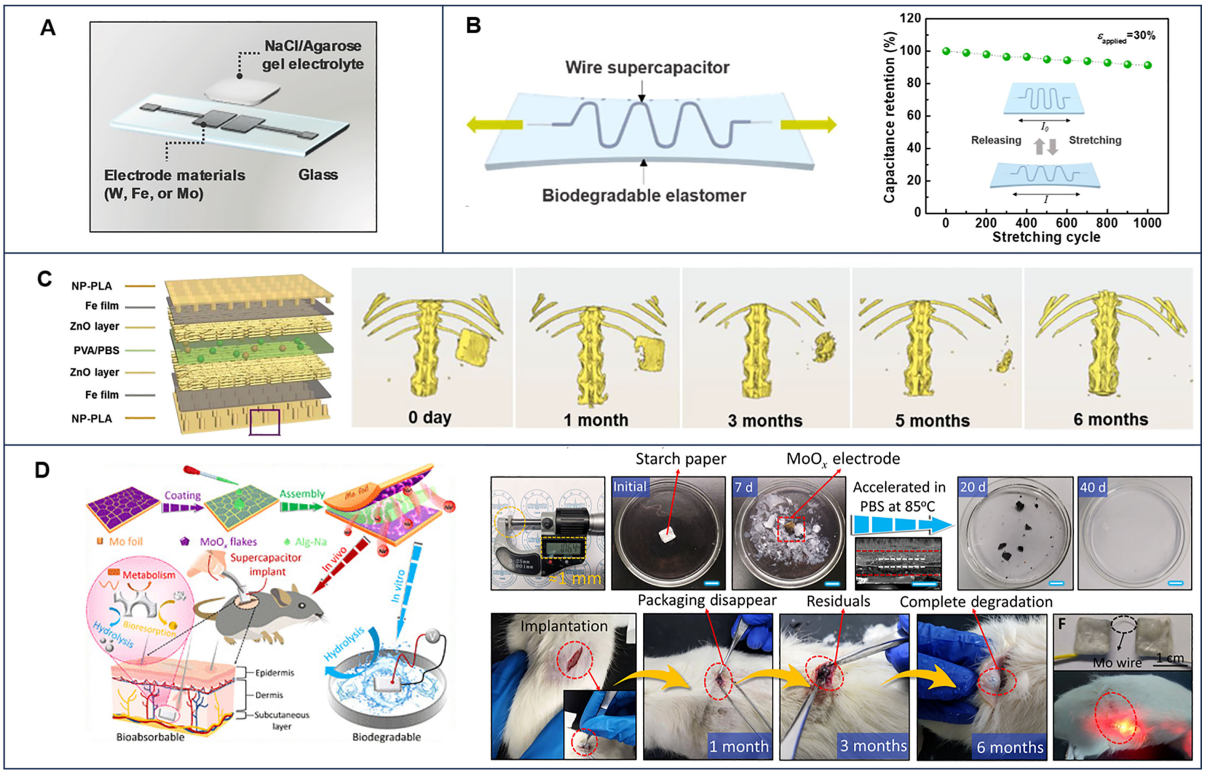

Figure 6. Bio-absorbable (or -degradable) BMSCs. (A) Schematic illustration of a planar-type supercapacitor consisting of biodegradable metal thin-film (W, Fe, or Mo) electrodes and a NaCl/Agarose gel electrolyte on a glass substrate[61]; (B) Diagram of the biodegradable serpentine-shaped wire supercapacitor and cycle stability during bending deformation tests[100]; (C) Structure and degradation absorption diagram of the bio-degradable and bio-absorbable micro-supercapacitor[156]; (D) Schematic illustration of the fabrication and degradation tests of the thin, high-performance bio-degradable and bio-absorbable MSC, and the results of degradation/absorption *in vitro* and *in vivo*[60]. Reproduced from Ref.[61], Ref.[100], Ref.[156], and Ref.[60] with permission from Advanced Energy Materials, Chemical Engineering Journal, Advanced Science, and Science Advances, respectively. BMSCs: Biocompatible miniature supercapacitors; MSCs: miniature supercapacitors.

In general, the thinner the thickness of the implantable device, the less interference and impact it will have on the human body. Therefore, under the condition of maintaining sufficient performance and biocompatibility, it is very promising to develop devices with low thickness and lightweight[42]. Based on this, Sheng *et al.* reported a thin, deformable high-performance supercapacitor and demonstrated that it is biodegradable and bioabsorbable within animal bodies[60]. Amorphous MoO_x sheets were grown on molybdenum foil by one-step electrochemical oxidation and used as electrodes. This MoO_x sheet electrode, together with molybdenum foil (current collector) and sodium alginate gel electrolyte, forms a flexible supercapacitor with a sandwich structure [Figure 6D]. This kind of supercapacitor shows high performance, including ultrahigh areal capacitance of 112.5 mF cm^{-2} (at 1 mA cm^{-2}) and energy density of 15.64 μWh cm^{-2}. The encapsulated supercapacitors using PLA and starch paper as packaging materials have a small size (dimension, 1.0 cm × 1.0 cm × 0.1 cm) and are lightweight (100 mg), which is desirable for the implanted devices. The compatibility and biodegradation/bioabsorbability have been demonstrated via *in vitro* and *in vivo* methods. The *in vitro* testing was conducted using a PBS solution and it showed that the supercapacitor could be entirely degraded. Within ten days, the PLA/starch packaging paper of the supercapacitor was degraded. Over time, the supercapacitor device begins to disintegrate along with the partially dissolving of the MoO_x electrode and Alg-Na electrolyte. When the experiment was accelerated at 85 °C, it took an additional 30 days for the remaining material to completely decompose. When the packaged supercapacitor was implanted subcutaneously into the back of Sprague-Dawley rats, it could be completely degraded and absorbed by the rats after six months.

APPLICATIONS

As safe and reliable energy storage devices, the applications of BMSCs are extended by integration with innovative bioelectronic devices designed for biological health monitoring and medical treatment, such as human motion detection[157], non-invasive blood glucose monitoring[133] and wirelessly controlled disease treatment[157]. Certain implantable integrated electronic products can act as nutrients[158]. Through the integration systems, people can conduct real-time analysis of physiological parameters, closely monitor health status and make timely intervention recommendations. Furthermore, they possess the capability to conduct both *in vivo* and *in vitro* medical treatment, making real-time health monitoring, prevention, and personalized medicine of various chronic and acute diseases possible[159].

Health monitoring

The health of living organisms encompasses not only the stability of vital signs (such as heart rate, pulse, and body temperature), but also metabolic states (such as blood glucose and blood pH). BMSCs-based integration systems for health monitoring can be classified into physical characteristic monitoring and chemical/biochemical analysis. In terms of physical characteristic monitoring, BMSCs are usually integrated with wearable sensing units (such as pressure sensors, temperature sensors, *etc.*) for real-time monitoring and analysis of an individual's vital signs. Teng *et al.* used cellulose nanofibril-graphene conjugated polymers to assemble a core-sheath microfiber electrode that showed electrochemical activity, mechanical stability, photothermal conversion effect and thermal sensitivity, thereby constructing a solar and thermal multi-sensing all-solid-state microfiber supercapacitor (ASSMFSC)[160]. The prepared ASSMFSC exhibited excellent electrochemical performance with a volume capacitance of 85.8 mF cm^{-3} and a volume energy density of 11.9 mWh cm^{-3}. Regarding monitoring human body temperature, ASSMFSC has a sensitive perception of subtle temperature changes with a current sensitivity of 0.47437 ± 0.00549 °C. For example, the real-time simulation of body temperature changes (from 37 °C to 42 °C) showed current curves corresponding to average body temperature, low fever, and high fever. Furthermore, when an ASSMFSC was installed on different parts of the volunteers' body (forehead, arm and index finger), it captured current fluctuation signals with different body temperatures [Figure 7A]. This demonstrates its potential to evaluate the body's ability to regulate temperature and assist patients in self-diagnosis.

Based on the designed vanadium nitride-graphene (VN-G) architectures, Yu *et al.*[161] developed an innovative supercapacitor/pressure sensor integrated wearable device with dual advantages of strain-stable electrochemical performance of flexible supercapacitors and ultra-high sensitivity of electronic skin sensors. This ultra-sensitive health monitoring device can fit well with human skin (such as on the wrist and throat) and show different current changes under varied applied pressures and deformations, demonstrating excellent sensing performance. With the assistance of ordinary medical tape, it can be attached to different parts of the human body and exhibit the functions of monitoring the human pulse (wrist), recognizing the voice of different people and different words (throat), and detecting other physiological movements (finger joint movements and frowning movements), as shown in Figure 7B.

Yuan *et al.* designed smart wearable band-aids integrated with energy storage, humidity sensing and pressure sensing units by using a facile laser-scribing and drop-casting strategy[44]. Using sodium lignin sulfonate (SLS) coated on the woven fabric of band-aids as raw materials, laser-induced S-doped porous graphene (LISG) electrodes with different patterns were fabricated on the surface of the band-aids by laser scribing. The LISG-based MSCs have excellent areal capacitance (68.6 mF cm^{-2}) and good cycling performance. The GO-coated LISG electrode has high humidity detection sensitivity to work effectively

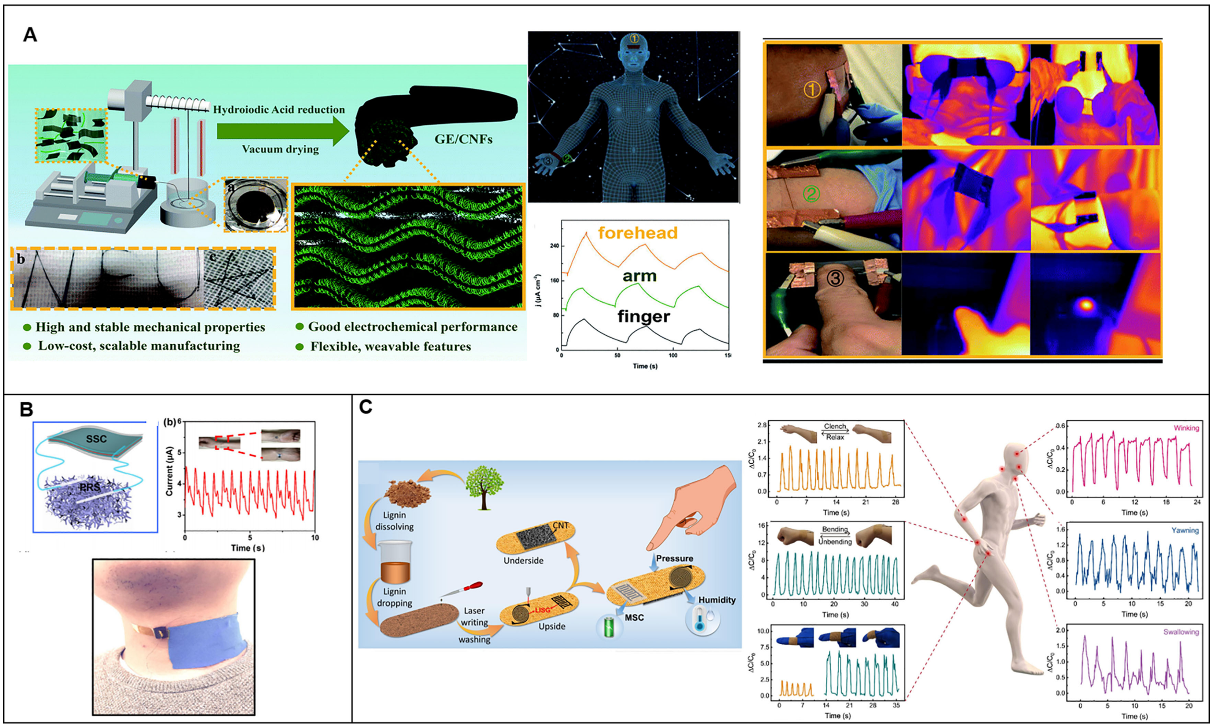

Figure 7. Application of BMSCs integrated system in monitoring physical parameters of organisms. (A) Schematic illustration of the fabrication of the GE/CNFs@PANI microfiber and application of ASSMFSC as a temperature monitoring device for different parts of the body[160]; (B) Schematic diagram of the supercapacitor/pressure sensor-integrated wearable device that can be used to monitor human physiological movement[159]; (C) Schematic diagram of the multifunctional band-aid and applications for various human activity detection[44]. Reproduced from Ref.[160], Ref.[159], and Ref.[44] with permission from Journal of Materials Chemistry A, Nano Research, and Chemical Engineering Journal, respectively. BMSCs: Biocompatible miniature supercapacitors; ASSMFSC: all-solid-state microfiber supercapacitor; GE/CNFs@PANI: graphene/cellulose nanofibrils@polyaniline.

across a wide range of humidity detection [11%-97% relative humidity (RH)]. By dropping CNTs on the cotton pad on the back of the band-aid, a conductive CNT sponge electrode was prepared, capable of functioning as an electrode of the capacitive pressure sensor. The CNT sponge-based flexible capacitive pressure sensor on the band-aid can be attached to various locations on the skin to detect physiological signals generated by the human body, such as muscle contraction, joint bending, finger bending, *etc.* At the same time, capacitance changes caused by the pulse can be obviously observed. The characteristic waves contained in the representative pulse waveform are closely related to diastolic pressure and heart rate [Figure 7C], indicating that the integrated smart wearable band-aid can play an important role in disease prevention and medical diagnosis.

Chemical/biochemical analysis, such as the concentration and composition change of a particular biochemical constituent in the body fluid (sweat, tears, blood, *etc.*), plays a crucial role in the diagnosis and prognosis of diseases. Wearable and implantable BMSCs will significantly enhance the convenience and speed of monitoring. Zha *et al.* pioneered a non-invasive blood glucose monitoring system [Figure 8A] consisting of wearable BMSCs and glucose detection units[162]. NiCo metal-organic frameworks (NiCo-MOFs) were used as the active material. The resulting micro-supercapacitors have an energy density of up to 11.5 mWh cm^{-2}, and the glucose sensors have an excellent sensitivity of 0.31 μA $μM^{-1}$. The integration system can monitor the concentration of human glucose in sweat in real time, preventing patients from increasing pain and infection by puncturing the skin during invasive procedures.

 Luo *et al. Energy Mater.* **2025**, *5*, 500070 | https://dx.doi.org/10.20517/energymater.2024.239

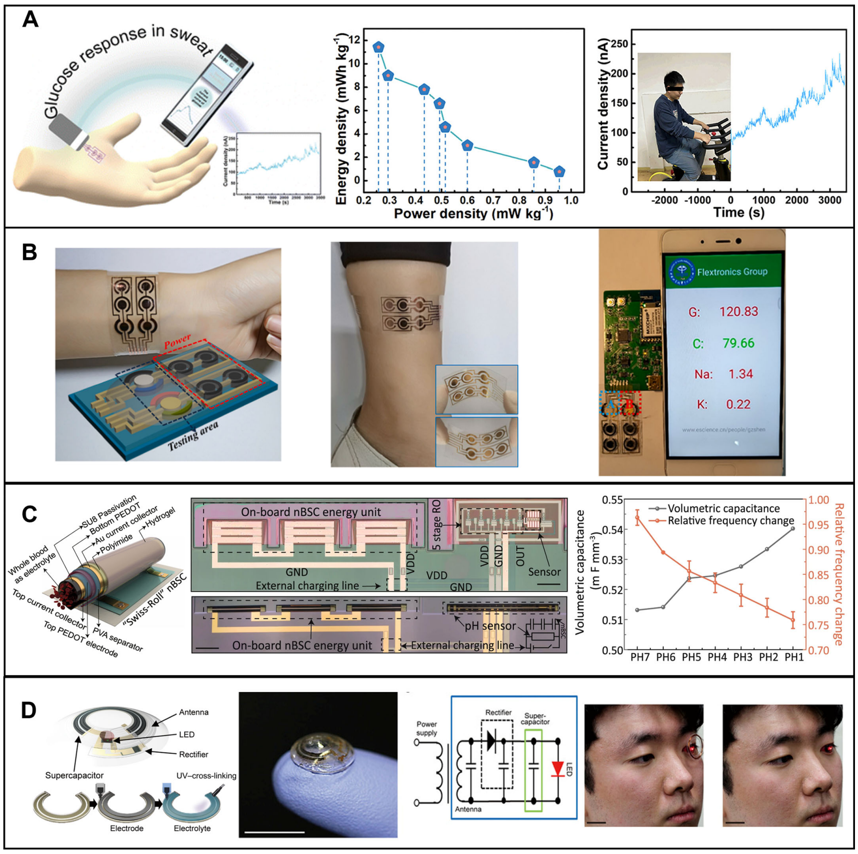

Figure 8. Application of BMSCs integrated system in chemical/biochemical analysis of organisms. (A) A non-invasive blood glucose monitoring system consisting of wearable BMSCs and glucose detection units[162]; (B) Preparation strategy and application of wearable self-powered sweat monitoring system[163]; (C) Tubular biocompatible supercapacitors that can be implanted in a blood vessel for blood pH analysis[45]; (D) The flexible intelligent contact lens that can operate in human eyes[165]. Reproduced from Ref.[162], Ref.[163], Ref.[45], and Ref.[165] with permission from Dalton Transactions, Nano Energy, Springer Nature, and Science Advances, respectively. BMSCs: Biocompatible miniature supercapacitors.

Furthermore, Lu *et al.* established a wearable self-powered multifunctional sweat monitoring system integrated by $NiCo_2O_4$/chitosan-based glucose sensors, ion-selective membrane-based [Na^+] and [K^+] sensors, and $NiCo_2O_4$-based MSCs on flexible PET substrates[163]. The prepared MSCs exhibited a high energy density of 0.64 μW cm^{-2} (at a power density of 0.09 mW cm^{-2}) and were series-connected to sensor arrays for power supply. The self-powered wearable sweat monitoring system can be easily worn on various body parts to analyze the concentrations of glucose, [Na^+] and [K^+] in the metabolic sweat excreted to the skin surface. By designing an in-situ concentration analysis/display system, the real-time monitoring data of volunteers after strenuous exercise can be displayed [Figure 8B], showing the physical conditions and indicating whether hydration is needed.

Lee *et al.* have created a fully microsystem-integrated nano-biosupercapacitor (nBSC) which can be implanted in blood vessels for blood pH analysis[45]. The nBSC is only 1/1,000 mm^3 in size, which is achieved by self-assembling planar structures into a 3D compact tubular geometry. The compact tubular structure makes it strong and durable in the body environment under the external force of blood and muscle contraction, showing stable performance in energy storage and power output. The supercapacitor can directly use blood as an electrolyte and its capacitance varies in relation to the blood pH [Figure 8C]. By integrating three-series-connected nBSC with a ring oscillator, changes in capacitance can be converted to frequency modulation. In this way, the pH value in the blood can be monitored and potentially reveal the formation of cancer cells. This provides an opportunity for the next generation of intravascular implants, which are expected to operate in small spaces deep within the human body that are difficult to reach and for health monitoring purposes.

The biomarkers related to various diseases in tears are of great significance to the health of organisms. Smart contact lenses are regarded as a new platform for continuous monitoring of vital signs (multiple physiological signals) in eyes and tears. Chiou *et al.* used 3D packaging technology to package 130 μm supercapacitors into standard hydrogel contact lenses with great stability and flexibility[164]. This is the first report of smart contact lenses using thin film supercapacitors as energy storage units. The prepared thin film supercapacitor can work in salt water and help radio frequency identification (RFID)-based smart contact lens system become semi-passive, which is expected to play a role in vision and ophthalmopathy in the future. Park *et al.* further developed a flexible intelligent contact lens, as shown in Figure 8D, which integrated with a retractable antenna, rectifier circuit, LED, and supercapacitor to achieve wireless charging and discharging processes[165]. The integrated LED indicates the charging and discharging status of the smart contact lens when it is driven wirelessly. When the biocompatible smart contact lens is worn on the eyes of living rabbits or humans, they operate reliably without obvious adverse effects.

Medical treatment

Traditional disease diagnosis and treatment commonly used in hospitals need the assistance of professionals, making them time-consuming and expensive. This approach is not suitable for the development of personalized medical treatment. The progress of BMSCs as energy storage devices has promoted the development of wearable and implantable medical devices, which play an important role in enabling targeted and convenient medical treatment[42]. The current medical treatment can be simply divided into *in vitro* and *in vivo* treatment. *In vitro* treatment is mostly adjuvant therapy to promote skin wound healing or biomarker monitoring[166], while *in vivo* treatment can go deep into the interior of the brain, blood vessels, heart and other parts[167].

The healing of skin wounds is a long process[168]. Common treatment methods (compression bandage therapy[169], negative pressure therapy[170], *etc.*) have some problems, such as high treatment costs, poor treatment effects, long wound healing time, and so on. Electrical stimulation therapy has attracted wide attention as a kind of skin wound healing method with high safety, ease of use and low cost. Wang *et al.* developed a special all-in-one wound dressing which integrates supercapacitor and wound dressing[86]. The integrated wound dressing with good biocompatibility and excellent flexibility can be fixed in different parts of the body with the help of medical bandages and its size can flexibly adjust to meet clinical requirements [Figure 9A]. On the one hand, the upper supercapacitor can provide electric energy for electrical stimulation therapy to meet the needs of patients anytime and anywhere. On the other hand, sodium hyaluronate in the wound dressing, as an active substance and a new biopolymer electrolyte, not only promotes the proliferation of fiber cells and accelerates wound healing, but also improves the electrochemical performance of supercapacitors and prolongs the time of power supply. Figure 9A shows the process of treating mice skin wounds using the all-in-one wound dressing. The wound is almost closed after 16 days of continuous treatment.

Compared to wearable devices, devices implanted in blood vessels have higher requirements for supercapacitors[171]. Sim *et al.* reported a flexible fiber supercapacitor that can be implanted into blood vessels, showing great potential in implantable medical devices [Figure 9B][6]. Due to the high flexibility, it can be used to suture wounds, and maintain its performance through mechanical deformation with the

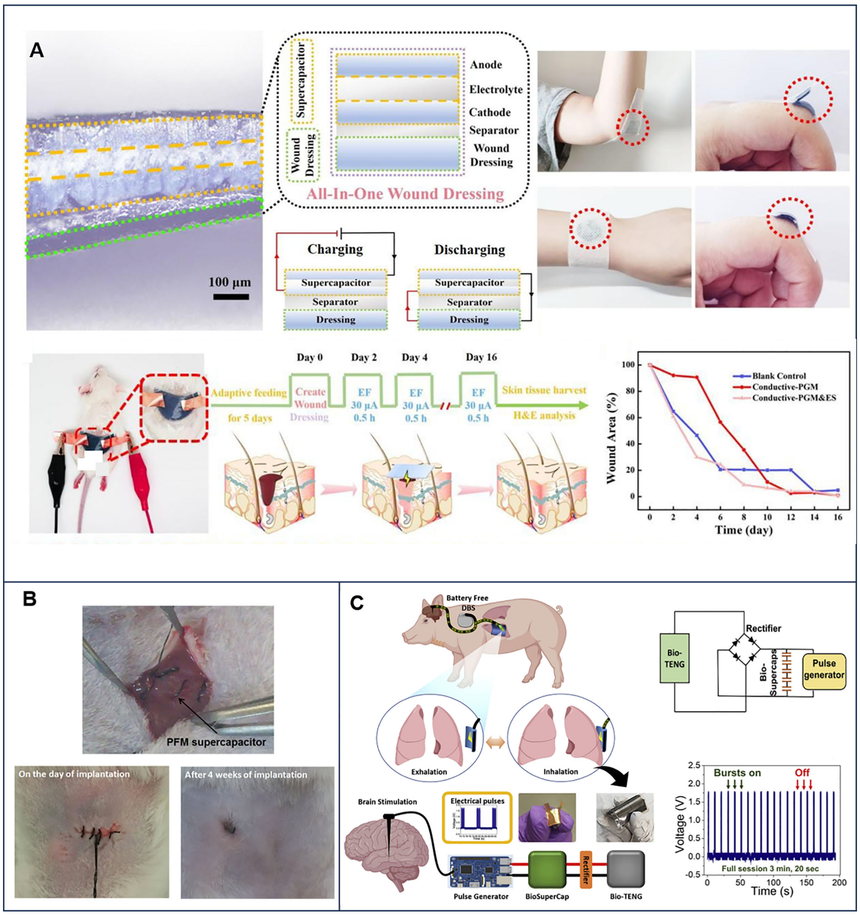

Figure 9. Application of BMSCs integrated system in medical treatment of organisms. (A) BMSCs for wound dressings[86]; (B) Implantation of the flexible fiber optic miniature supercapacitors in mice[6]; (C) The Bio-Teng acts as an energy collector to power the biocompatible micro-supercapacitor through the respiratory movement of the pig's lungs[173]. Reproduced from Ref.[86], Ref.[6], and Ref.[173] with permission from Chemical Engineering Journal, Nano Energy, and Cell Reports Physical Science, respectively. BMSCs: Biocompatible miniature supercapacitors.

normal activity of the human body. This kind of fiber supercapacitor is small in size, flexible and can be implanted into narrow areas such as organs, tissues and blood vessels.

Now, people are increasingly paying attention to mental diseases, leading to a growing demand for treatment. Stimulators implanted into the brain are bringing revolutionary changes to the treatment of many mental disorders[90,172]. Elsanadidy *et al*. developed a self-sustainable, implantable deep brain stimulation (DBS) system based on supercapacitors, which provides a strategy for future implantable devices[173]. Biocompatible supercapacitors were used to store energy to drive the pulse generator to intermittently stimulate neurons in the hippocampus of the brain to achieve the purpose of treatment. It is worth noting that the energy was collected by a high-performance bio-triboelectric nano-generator (Bio-Teng) which powered through the respiratory movement of pig lungs [Figure 9C]. The voltage and current from Bio-TENG are processed by a full-wave rectifier and then stored in five biological supercapacitors in series to supply power to the DBS pulse generator. Moreover, this self-sustainable intermittent DBS can provide a stimulation mode similar to electrical theta burst stimulation, which provides a strategy for developing nerve stimulation in treating human brain diseases.

CONCLUSION AND OUTLOOK

Remarkable advancements have been made in the development of wearable and implantable BMSCs with high biocompatibility, miniature size, excellent flexibility/stretchability, stability, biodegradability/bioabsorbability and high performance have been developed. For wearable BMSCs, non-contact types are mainly deposited or knitted on flexible fabrics, whereas skin-contact types, fabricated on elastomeric substrates, have low modulus and dynamic high tensile properties. These skin-contact types can easily adhere to the epidermis and accurately adapt to the movement of the skin, ensuring high comfort and showing irreplaceable advantages in future wearable electronic products. Implantable BMSCs can greatly reduce the harmful effects on organisms while maintaining excellent capacitive performance and have great potential as energy storage devices for implantable medical electronic devices. For short-term implants, bio-absorbable (or -degradable) BMSCs are more favorable as they eliminate the need for secondary surgery to remove the device, reducing harm to the body. Various integration systems of wearable and implantable BMSCs with bioelectronics have been demonstrated to enable convenient and intelligent health monitoring and precision medical treatment of the human body, promoting the process of modern healthcare.

However, a few challenges still need to be addressed for the improvement of BMSCs and their practical applications in wearable and implantable bioelectronic systems:

(1) More efforts should be made to overcome the limitations of BMSCs, with the most important being their low energy density. BMSCs are constructed by biocompatible electrodes and biocompatible electrolyte materials, which are safe but usually possess poorer electrochemical performance compared to conventional materials. It is still in high demand to develop new materials and optimize device construction, improving the energy storage capacity of the devices.

(2) The issues involving size, flexibility, safety, stability and flexibility need to be resolved to minimize the harm and disturbance of biological functions.

(3) Complex integrated systems with power management, biomedical functions and wireless communication capabilities that can operate independently and stably in the human body remain to be further explored.

Although considerable challenges remain in fully realizing BMSC-based WIEs, recent progress in advanced materials and devices has made this goal more attainable. By addressing the challenges discussed in this review, it is promising to achieve compact and multifunctional BMSC-powered WIE systems that realize real-time health monitoring and medical treatment with high accuracy and fidelity in the near future.

DECLARATIONS

Authors' contributions

Reviewed literature extensively, wrote and modified articles, drew the figures, and set the layout: Luo, P.; Liu, Q.
Contributed numerous ideas for the article, polished and modified the text, and designed the figures: Chen, R.
Polished the article and designed the figures: Shao, H.; Ma, Y.
Revised the article and provided the research direction and funding support: Zhao, Y.

Availability of data and materials
Not applicable.

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Conflicts of interest
All authors declared that there are no conflicts of interest.

Ethical approval and consent to participate
Not applicable.

Consent for publication
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