Architecture of E-Textiles

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E-textiles are the traditional textiles of different hierarchies embedded with multifunctional nanomaterials to be utilized in different areas, for instance, human motion monitoring, i.e., joints bending, walking, running, facial expression, vocal vibration, pulse, breathing, laughing, etc., healthcare applications, i.e., EMG, ECG, EEG, sleep monitoring, drug delivery, cell culture, etc., thermal heating, electromagnetic shielding, antimicrobial protection, self-cleaning, energy storage/harvesting, fire alarm, electronic display, color-changing, etc. with a wide spectrum of functions by mitigating the wear complexities associated with non-flexible and bulky wearable electronics.

Keywords: e-textiles ; architechture ; stability ; washability

1. Fiber Shaped Durable E-Textiles

Fiber is the first phase of the textile hierarchy which serves as the basic construction block of e-textiles, conductivity at the fiber level facilitates seamless integration of electronic function for the next generation of miniature devices. Nanomaterials with fiber components are expected to exhibit strong adhesion at the molecular level with improved electrical properties, mechanical properties (strength, flexibility, stretchability), durability (stability, washability), comfort, etc. Fiber materials can be made of natural (cellulose, protein) or synthetic resources. Synthetic fibers (the filament, i.e., continuous fibrous strand or nanofiber) are manufactured from polymer solution following different electrospinning processes. Traditional cellulosic textile fiber can be functionalized in the typical yarn manufacturing phase (sliver/roving) and subsequently spun into yarn.

Yang et al. demonstrated that the incorporation of nanomaterials at the roving level gives the ring-spun yarn improved stability and washability compared to the cotton yarn coated with carbon nanotube (CNT) via the dip-coating technique. The roving modified ring-spun yarn can withstand repeated bending (180°) of 100 cycles with nominal resistance change (<10%), optimum stability for abrasion (up to 400 cycles), and displayed washability with minimal changes ($R/R_0 < 1.3$) in resistance for 8 consecutive wash cycles while the CNT-coated cotton yarn was vulnerable and could barely satisfy such circumstances [1]. Alternatively, Jia et al. constructed a conductive core yarn wrapped with cotton fiber (roving) where a CNT yarn was introduced prior to the twisting zone. The multifunctional cotton fiber-wrapped CNT yarn retained its electrical properties without change in subsequent folding-releasing (~100 cycles) and washing (~5 cycles) [2].

The functional protein fibers (i.e., silk) are mostly produced by electrospinning (dry/wet/bio-mimetic) processes, which are accused of damaging the micro and nanostructures of the fiber. Thus, directly modified silkworm spinning is admired for keeping the inherent properties of the fiber intact. Wang et al. developed a functional native silk fiber via the continuous force-reeling and dip-coating technique (with CNT, Ag, and thermochromic paint) directly from Antheraea pernyi (A. pernyi) silkworms (known as Chinese Oak Tussah silkworms and having a similar primary structure to spider silk [3]). The functional fiber was highly stable and could withstand 48 h of washing without affecting the surface morphology [4]. Natural fiber in the form of liquid suspension is often prepared and utilized for improved electrochemical performance. Zhang et al. developed a thermally reduced graphene oxide (GO) cellulose composite paper-based pressure sensor (TRG-PS) from cotton pulp dispersion which displayed great cyclic stability (~8% changes in resistance for 300 bending-releasing) and washability up to 20 washing cycles with minimal resistance changes [5].

Fibrous materials are highly flexible to retain any shape as desired at the pre-stage of e-textiles development. Distinctive fiber architecture often offers better performance than regular configuration. A recent study reported a 3D helical fiber-shaped sensor with improved sensing performance (<1% detection limit), superior stability (no obvious change in >20,000 stretching cycles), and washability (no decay of electrical output in ten washing cycles) than regular fiber-shaped triboelectric nanogenerators (TENG). The helical fiber was obtained from the multiaxial winding of two core-shell braided fibers (Ag core in both fibers, whereas the shells were polytetrafluoroethylene-PTFE and nylon, respectively) followed by alternative winding on a stretchable fiber substrate [6]. The Helical fiber produced in a different but facile way, that is, pre-stretched (100–400%) polyurethane (PU) fiber with adhered copper fiber wrapped with glue, also showed satisfactory durability (stable against 500 stretching cycles and 100 min ultrasonic washing [7].

Fibers of all categories in the form of aqueous suspension synchronized with nanomaterials are of great interest and are produced through electrospinning, printing, and other solution-based methods for the development of e-textiles with long-lasting stability and durability. Liao et al. developed large-scale continuous fiber (~1500 km) lithium-ion batteries using the solution-extrusion method that displayed excellent stability (withstands up to 10,000 bending cycles with negligible decay) and durability (<10% loss of capacity) against different hostile events, i.e., water immersion, heavy pressure, washing, and hammer strike [8]. Conductive fiber materials are the fundamental building block of wearable e-textiles but are usually converted into the shape of yarn (continuous length) to enhance cohesion between them and make them suitable for subsequent transformation as required.

2. Yarn Shaped Durable E-Textiles

In general, yarn is a continuous assembly of fibers or filaments twisted/bonded together for improved mechanical properties, i.e., strength, flexibility, etc. Electronically active yarn can be constructed in different ways, i.e., by converting conductive fibers/filaments into yarn, imparting functionality at the yarn stage, and synthetic spinning of polymeric solution with conductive filler. The conductive yarn plays an important role in the architecture of the wearable system by interconnecting different units within the system and facilitates the fabrication of mass-scale electronic devices in the form of fabric or garments. The conductive yarn must be robust enough to withstand different physical, chemical, mechanical, and other hostile stimuli involved in daily use. The combination of nanomaterials at the yarn level expedites functionality-induced performance enhancement because of the increased contact surface area.

Gunawardhana et al. developed wearable triboelectric nanogenerators (TENGs) made of textiles (fabric made of Ag-coated nylon yarn) with differently coated triboelectric material (Polydimethylsiloxane-PDMS). It was observed that yarn-coated TENG outperforms other TENGs (i.e., screen printed and dip-coated fabric made of the same conductive yarn) in output due to higher triboelectric contact surface area. The electrical output of the yarn-coated TENG (i.e., open circuit voltage (V_{OC}) ~ 34.5 V, short circuit current (I_{SC}) ~ 60 nA, short circuit charge (Q_{SC}) ~ 12 nC) was superior to that of other TENGs (screen printed; V_{OC} ~ 17.3 V, I_{SC} ~ 43 nA, Q_{SC} ~ 5 nC and dip-coated; V_{OC} ~ 4.9 V, I_{SC} ~ 11 nA, Q_{SC} ~ 2 nC) and showed better cyclic stability up to 3000 contact separation cycles [9]. Xiao et al. developed cotton yarn-based sweat-activated batteries (CYSAB) by drop coating black carbon (cathode, 4 cm), a bare portion (salt bridge, 0.5 cm), and subsequently wrapped with Zn foil (anode, 1.0 cm) of the same pristine cotton yarn. The device could withstand 2000 bending cycles and 16 washing cycles of 10 min each without a significant change in voltage output of the battery activated with 100 mL of salt solution (NaCl). The higher durability of the device was further verified by the unaffected surface morphology of the cathode portion against washing [10]. Electroactive regenerated cellulose yarn produced via roll-to-roll coating with poly(3,4-ethylenedioxythiophene):poly(styrene sulfonate) (PEDOT: PSS)/Ethylene glycol (EG) showed high conductivity (36 Scm^{-1}) and durability. A thermoelectric energy harvester was designed by sewing the electronic yarn into a multilayered fabric. No resistance changes were observed for the device after repeated bending (1000 cycles) and machine washing (insignificant changes in the first five cycles, while further washing (<10) leads to notable changes) [11].

The core-sheath yarn structure holds great promise toward durability by combining nanoparticles in the core securely and preventing it from decay. Zeng et al. developed a highly durable wearable strain sensor based on a spandex dip-coated CNT core and cotton fiber sheath yarn. The sensor showed promising stability under 20% cyclic stress and ultrasonic washability (<5% deviation in resistance, five cycles) against water, acid, and alkali solution [12]. The self-powered sensor made of commercially available nylon/spandex yarn dip-coated with multi-walled carbon nanotubes (MWCNT) followed by spray coating with silver nanoflakes (AgNFs) and covered with silicone rubber showed good durability (~10,000 cycles of repeated operations) and washability (no significant decrease in performance against five repeated washing cycles) [13]. Zhou et al. demonstrated a polyester yarn twisted around a steel rod (10 µm dia.) covered with ultrathin silicon and weaved into a back textile substrate with the serpentine structure for sleep monitoring. The substrate was consistent under the repetitive pressure test up to 20,000 cycles and with insignificant variation in the electrical output after 8 weeks (20 min per week) of repetitive washing [14]. In the case of core-sheath yarn, where the conductive fiber is wrapped around a textile core, the twist count (number of twists per inch/cm) also plays an important role in enhancing conductivity and robustness. Higher twist counts (over twisting) tend to exert more stability in larger deformation and repeated washing actions [15].

Pre-stretching of the yarn (in case of stretchable substrate) prior to nanomaterial incorporation leads to the formation of a wrinkled surface, which allows the electroconductive properties to be more stable against mechanical deformation by a gradual release of the surface wrinkles upon stretching. Zhang et al. developed an underwater wireless charging patch made of pre-stretched polyurethane filament spray-coated with multi-walled carbon nanotubes (MWCNT), silver nanowire (AgNW), and styrene-(ethylene-butylene)-styrene (SEB), respectively. The device could withstand more than 100,000 stretching cycles under 50% strain and displayed good washability (up to ten cycles without significant resistance change) [16].

Electrospinning is widely being used for yarn-based washable e-textile development, which enables nanomaterial integration at the molecular level in the form of polymeric suspension (which contains both substrate and nanoparticles) spun into a continuous filament directly or the spinning of functional nanofiber around a conductive filament. A unique triboelectric yarn was manufactured via electrospinning of Poly(vinylidene fluoride) (PVDF) nanofiber around a CNT filament. The device showed phenomenal stability (~200,000 fatigue cycles) without a decrease in RMS (root mean square) power output; instead, a 33% increase in energy harvesting capability was observed with a peak power density of 20.7 μW cm^{-2}. Furthermore, the yarn could withstand ten repeated washing cycles without a significant change in RMS power output. The slight resistance change observed in between five and ten washing cycles may be due to the small amount of water residue inside or slight damage due to washing. However, the morphological analysis of the yarn after repeated tapping and washing showed no significant damage, apart from slight tearing of the PVDF fiber surface while the core was completely intact [17]. Medeiros et al. developed omniphobic silk-based coils (OSCs) made of electrospun yarn composed of silk fibroin, multi-walled carbon nanotubes (MWCNTs), and chitin carbon (ChCs) to power the wearable electronics remotely via magnetic resonance coupling. The device possessed great stability upon the repeated strain of 100% for 2500 cycles without a significant drop in performance. Furthermore, no performance degradation was observed even after 50 washing cycles [18].

Different yarn-shaped e-textiles and their endurance properties are presented in **Table 1**.

Table 1. Summary of different yarn-shaped durable wearable electronic textiles.

Substrate	Nano Materials	Fabrication	Initial Output	Durability		Application	Ref.
				Stability	Washability		
Pu/PAN core-sheath yarn	**GO/CNT ink**	**Dip Coating**	**Conductivity, 14.8 S m^{-1}**	**~100,000 operation cycles, 99.3% capacitance retention**	**5 cycles, no significant deterioration of capacitance**	**Pressure sensor, motion sensing**	[15]
Cotton/Lycra yarn	**CNT**	**Dip coating**	**Resistance, 2.39 kΩ cm^{-1}**	**~Cyclic stretching-releasing for 2000 s, high stability**	**10 cycles, slight increase of resistance ($\Delta R/R_0$ ~ 1.6)**	**Strain sensing, thermal heating**	[19]
Pu/PET braided yarn	**CNT**	**Dip Coating**	**Conductivity, 0.12 kΩ cm^{-1}**	**~1000 stretch-release cycles, no obvious change in resistance**	**5 cycles, slight increase ($\Delta R/R_0$ ~ 10%) of resistance**	**Wearable strain sensor**	[20]
PET yarn	**Cu**	**Electroless deposition**	**Resistance, 0.34 Ω cm^{-1}**	**~1000 tapping cycles, no change of voltage output**	**20 cycles, negligible change (<0.6 Ω cm^{-1}) of yarn resistance**	**Respiratory Monitoring**	[21]
SS/terylene yarn	**SS filament**	**Spinning**	**Output voltage, 28 V**	**~100,000 loading-unloading cycles, excellent stability**	**40 cycles, no change of output voltage**	**Physiological signal monitoring**	[22]
Nylon yarn	**Silver**	**Nano coating**	**Resistance, 53 Ω m^{-1}**	**-**	**50 cycles, notable resistance change (108%)**	**Biomedical textile computing**	[23]

Substrate	Nano Materials	Fabrication	Initial Output	Durability		Application	Ref.
				Stability	Washability		
Lyocell yarn	PPy	Polymerization	Conductivity, 21.6 Ω Sq^{-1}	~2000 cyclic operations, 90% capacitance retention	20 cycles, minor variations in electrical response	Wearable electronics	[24]
Cotton yarn	RGO	Dip Coating	Conductance (2.60 ± 0.1 μS)	~1000 bending cycles, slight variation (2.42%) in conductance	5 cycles, minimal (2.96% variation) conductance change	Gas sensing	[25]
CNT yarn	CNT, PEI, $FeCl_3$	CVD, Doping	Conductivity, 3695 S cm^{-1}	~5000 bending cycles, retained 90% PCE	10 cycles, slight change of PCE	Solar cell	[26]
Silk yarn	PEDOT:PSS, EG	Roll to roll dyeing	Conductivity, 70 S cm^{-1}	~1000 bending cycles, stable resistance profile	15 cycles, slight change after 1st wash than resistance kept constant	Wearable keyboard	[27]
Cotton yarn	RGO	Dip Coating	Resistance, 42.7 kΩ cm^{-1}	~1000 bending and compression cycles, stable resistance variance	10 cycles, resistance increased initially then kept constant	Temperature sensor	[28]
Silver-plated nylon yarn	CNTs, TPU	Electrospinning	Sensitivity, 84.5 N^{-1}	~5000 pressure (5 N) cycles, stable current signal obtained	2.5 h of washing, constant order of magnitude (only 1.4% variation)	Pressure sensor	[29]

Abbreviation: Pu—Polyurethane, PAN—Polyacrylonitrile, GO—Graphene oxide, RGO—Reduced graphene oxide, CNT—Carbon nanotube, PET—Polyethylene terephthalate, SS—Stainless steel, PPy—Polypyrrole, PEI—Polyethyleneimine, CVD—Chemical vapor deposition, PCE—Power conversion efficiency, PEDOT: PSS—Poly (3,4-ethylenedioxythiophene) polystyrene sulfonate, EG—Ethylene glycol, TPU—Thermoplastic polyurethane.

3. Fabric Shaped Durable E-Textiles

Fabric is the final phase of the textile hierarchy that enables mass-scale development of the e-textile component by either integrating it as an individual functional unit in the clothing or converting it into a complete wearable garment. Washable electronic fabrics can be obtained in many ways, such as by knitting or weaving the electroconductive yarn, by electrospinning an electronic nanofiber mat/film (nonwoven), or by direct incorporation of nanomaterials with them, etc. Satharasinghe et al. revealed that the washability assessment of photodiode-embedded yarns in both the e-yarn and the fabric form showed distinctive performance. For the e-yarn, the first failure was observed after 5 washing cycles and only 20% of them survived 25 washing cycles, while the fabric remained unaffected up to 15 cycles and 60% of them fully functioned after 25 cycles [30]. The e-yarns in the fabric form performed much better than in the yarn form and can be ascribed to the structural stability and compactness offered by the woven fabric.

The type, structure, and composition of the fabric affect not only the mechanical performance but also its operational longevity when combined with nanoparticles. Salavagione et al. demonstrated that different types of woven fabrics (regenerated cellulose, cotton, nylon, polyester, acrylic, and wool) have variant washability when coated with graphene/elastomer composite ink via hand printing. Although all samples showed stable performance (no change in resistance) against repeated folding (1000 cycles), in the case of washing, surprisingly, nylon and acrylic fabric had superiority (retained their initial resistance even after ten machine wash cycles) over others (significant loss of resistance) [31]. In a different study, polyester fabrics of different architectures, i.e., knit, woven, and nonwoven, demonstrated variable washing performance when coated with silver ink through the inkjet printing process. The woven fabric showed superior wash durability (insignificant resistance change after 15 machine washing cycles), while the knit fabric's resistance doubled (>1 kΩ) after the same amount of wash cycles and 50 times higher resistance (2.3 Ω to >100 Ω) was observed for the nonwoven fabric only after a single wash. The poor resistance to washing of the nonwoven fabric may be ascribed to the looseness of the structure. Compact nonporous fabric structures (i.e., woven and knit) ensured better integration of conductive ink in the inkjet printing process, leading to better durability [32].

Kim et al. prepared a wearable supercapacitor made of supersonically sprayed cotton fabric with reduced graphene oxide (rGO)/silver nanowires (AgNWs) that revealed long-term cyclic stability (86% capacitance retention) under 10,000 operation cycles and exceptional aqueous wash durability (100 times) within acceptable relative resistance change (40% increase) up to 80 cycles and remained stable afterward [33]. Feng et al. developed a self-healing and self-cleaning triboelectric nanogenerator through the liquid-phase fluorination technique via dip-coating of silk and nylon fabric with urethane perfluorooctyl silane (NHCOO-PFOTS). The device showed superior durability. The water contact angle of various liquids (tea, coffee, juice, milk) experienced an insignificant decrease (5.02–8.21%) and the output voltage of the silk/nylon pair remained constant (maintained 96.77% of its original 465 V) even after 70 h of repeated washing. Furthermore, the device exhibited remarkable stability against 45,000 repeated contact/separation cycles with stable electrical output (power density 2.08 $W.m^{-2}$ at 10 MΩ load). Such outstanding durability of the device was attributed to the strong bonding force between the hydroxyl and ethoxy groups of the fabric and the NHCOO-PFOTS molecules, respectively [34]. In a different study, He et al. developed a water-assisted self-healing polymer (WASHP) film based on covalent imine bonds crosslinked with hydrogen bonds with excellent mechanical flexibility (9050% strain) and self-healing capability (95%) in a shorter time (1 h). Later, the WASHP-based light-emitting touch-responsive device exhibited high stability (up to 72 cycles) under cyclic stretching at 30% strain and excellent reproducibility against cyclic switching (on/off) for 515 cycles under pressure. The application of such self-healing polymers together with nanoparticles can be applied to textiles for designing highly flexible, durable, waterproof, wearable soft electronics [35].

Qi et al. developed a wearable e-textiles pressure sensor by plain weaving of CNT embedded electrospun nanofiber yarn. The device had superior stability with insignifcant resistance change against 10,000 operation cycles under 0.1 N pressure. Besides, no obvious change in electrical response was observed after 1 h of continuous water washing [36]. The functional nonwoven fabric made of electrospun cellulose/polyaniline (PANI) nanofiber showed excellent electromagnetic interference (EMI) shielding efficiency even under cyclic twisting (1000 times) with no decay (99.68% of the wave dissipated) and ultrasonic washing (99% of the incident EM wave attenuated) for 10 min. Morphological analysis of the fabric revealed substantial damage to the surface fiber even in a quick wash (10 min) indicating the vulnerability of such a porous nonwoven structure and ineffective integration of PANI molecules in the dip-coating process [37]. Jin et al. demonstrated that an electrospun nonwoven photothermal fabric made of nylon and carbon is capable of absorbing 94% solar spectrum with 83% solar energy utilization efficiency. The fabric was highly washable (100 hand wash cycles) and could withstand different harsh environments for a longer period (3 weeks) [38].

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