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Actuator Materials: Review on Recent Advances and Future Outlook for Smart Textiles

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Abstract
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Review

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Abstract: Smart textiles based on actuator materials are of practical interest, but few types have been commercially exploited. The challenge for researchers has been to bring the concept out of the laboratory by working out how to build these smart materials on an industrial scale and permanently incorporate them into textiles. Smart textiles are considered as the next frontline for electronics. Recent developments in advance technologies have led to the appearance of wearable electronics by fabricating, miniaturizing and embedding flexible conductive materials into textiles. The combination of textiles and smart materials have contributed to the development of new capabilities in fabrics with the potential to change how athletes, patients, soldiers, first responders, and everyday consumers interact with their clothes and other textile products. Actuating textiles in particular, have the potential to provide a breakthrough to the area of smart textiles in many ways. The incorporation of actuating materials in to textiles is a striking approach as a small change in material anisotropy properties can be converted into significant performance enhancements, due to the densely interconnected structures. Herein, the most recent advances in smart materials based on actuating textiles are reviewed. The use of novel emerging twisted synthetic yarns, conducting polymers, hybrid carbon nanotube and spandex yarn actuators, as well as most of the cutting–edge polymeric actuators which are deployed as smart textiles are discussed.

Keywords: smart textiles; actuator; wearable technology; carbon nanotubes; conducting polymers; polymer actuators

1. Introduction

Smart textiles research represents an innovative model for integrating advanced engineering materials into textiles which will result in new discoveries. Smart textiles are defined as the "textiles that can sense or react to environmental conditions or stimuli, from mechanical, thermal, magnetic, chemical, electrical, or other sources in a predetermined way" [1–3]. As a more straightforward definition, textiles which can perform additional functionalities than the conventional textiles are described as smart textiles. Smart textiles have been used in numerous applications in the healthcare industry, military, and as wearable electronics [4–7]. Moreover, smart textiles can be divided in to three categories; passive, active and very smart textiles [1,8–10]. The passive smart textile is the first category of smart textiles that can provide additional features in a passive mode, irrespective of the change in the environment. As examples, anti-microbial, anti-odor, anti-static and bullet proof textiles are considered to be passive smart textiles [1]. Active smart textiles are a group that can sense and react to stimuli from the environment. These materials may also be used as sensors and actuators [1]. Very smart textiles are the third category that consists of a unit for recognizing, reasoning and actuating. This type of textiles sense, react and adapt themselves to environmental conditions or stimuli, such as space suits and health monitoring systems [11]. Textiles which can find prospective applications in

energy conversion are important to smart textiles in many ways. Actuators are considered as a group which can accomplish the conversion of energy to mechanical form with the capability of moving or controlling a mechanism or a system. Actuators can reversibly contract, expand, or rotate themselves, due to the presence of an external stimulus, such as voltage, current, temperature, pressure and many more. These materials can be divided into four major groups depending on their mode of actuation which are electric field, ion based, pneumatic and thermal actuation, and then further into two major groups on whether volume or order change dominates [12]. There are several frontier actuating materials being introduced by researchers, such as carbon nanotubes, conducting polymers, and shape memory alloys [13–18]. Using actuating materials in smart textiles is an impressive approach as a small change in material properties can be converted into significant movements, due to the densely interconnected structures.

The research reported to date on actuating textiles has attempted in force/strain amplifications and to incorporate smart functionalities into fabrics. Some of the polymer actuators exhibit properties, such as the long length, high tensile strength, flexibility and durability which are essential parameters for textile yarns [17]. In addition, polymer fibers have already been used in the textile fabrication process. Therefore, the feasibility of a textile structure can be established with polymer fiber actuators. Integration of actuators into the textiles was performed in most studies using traditional textile fabrication methods, such as weaving, knitting and braiding [13,17,19]. Consequently, materials and fabrication processes for an actuating textile should be selected with careful consideration for optimum performance. This paper is mostly focused on critically reviewing and appraising the materials and processes required to fabricate a high-performance actuating textile. This review further discusses fundamental actuation mechanisms in brief, material fabrication, properties and actuating materials already being trailed in textiles.

2. Overview of Different Actuation Mechanisms

Actuator designers have introduced criteria to allow the optimal selection of actuators for a given application. Power output per mass, per volume and actuator efficiency are the three fundamental characterizing properties of actuators [20]. Furthermore, stress, strain, strain rate, cycle life and elastic modulus are some of the other general characteristics considered in the evaluation criteria [20,21]. In addition to the above technical parameters, user friendliness, ease of fabrication and maintenance, cost and availability of the raw materials are some of the additional requirements to be considered in selecting actuators for an application. It is also necessary to consider the actuation mechanism which is as important as the other performance characteristics. Most of the actuators which are being reported in the literature actuate with one of four different methods—electric field, pneumatic, ionic and thermal. This section will provide an overview of the actuation mechanisms, and their characteristics.

2.1. Electric Field Actuation.

Electric field actuation is a result of electrostatic interactions between electrodes or molecular re-organisation within the actuator material structure. These are commonly known as electronic artificial muscles and are one type of electroactive polymers (EAPs). The electric field actuation is present in low modulus polymers, such as dielectric elastomers (DEAs) and electrostrictive polymers where the electric dipoles are arranged by the electric field which result in displacement [22,23]. DEAs are simple in mechanism, construction and able to produce large strains 10% to 100% but can reach up to 380% with high electric fields [24,25]. These actuators can yield stress up to 7.7 MPa and 3.2 MPa in silicone and acrylic based actuators, respectively [26]. Due to the large strains these actuators produce high work per unit volume per cycle with a maximum of 3.4 MJ/m^3 [23].

During the actuation of DEAs, electrostatic attraction between two surfaces of elastomer films induces compressive strains, as shown in Figure 1. Since the elastomer maintains constant volume contraction in one direction will cause expansion in the other two. Most mechanisms use expansion perpendicular to the applied field because it will result in large displacements. The electrostrictive

relaxor ferroelectric polymer actuators have high work density of 1 MJ/m^3 and strain up to 7–10%. These actuators generate high stress, around 45 MPa and frequency up to 100 Hz [27]. In electrostrictive relaxor ferroelectric actuators, the application of an electric field aligns polarized domains within the material. When the applied field is removed, the permanent polarization remains. Ferroelectrics are characterized by a curie point, a temperature above which thermal energy disrupts the permanent polarization. Field-driven alignment of polar groups produces reversible conformational changes that are used for actuation. The application of a field perpendicular to the chains leads to a transition between the non-polar and polar forms. The result is a contraction in the direction of polarization and an expansion perpendicular to it.

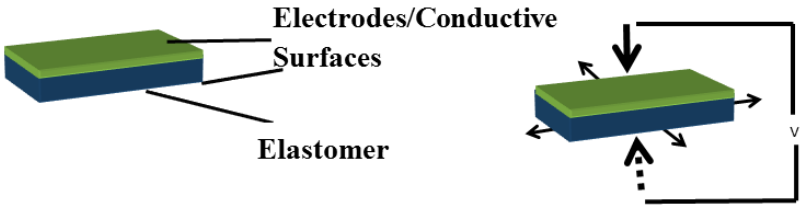

Figure 1. Schematic of dielectric elastomer mechanism with two electrodes: When a high electric field is applied to the electrodes the opposite charges attract squeezing the polymer into a different geometry causing an actuation of the device. "Reproduced with permission from [24], SPIE publications, 2000".

2.2. Ion Based Actuation

In these material's actuation is caused by the ion transport within the polymer material and exchange of ions between the actuator and an electrolyte solution. In common, the ionic EAPs need relatively low voltage for actuation (1–7 V) but the energies associated with these actuators are high because of the large amount of charge that needs to be transferred. Ion based actuators are most commonly fabricated with, conducting polymers (Conjugated polymers) and ionic polymer-metal composites (IPMC) [28].

Furthermore, IPMC contain an ion-exchange polymer film coated with metal electrodes. These metal electrodes are composed of platinum or silver nanoparticles. When the voltage is applied between two electrodes, the mobile cations move toward the oppositely charged electrode. This action results in swelling near the negative electrode, shrinkage near the positive electrode and bending of the actuator as can be seen in Figure 2.

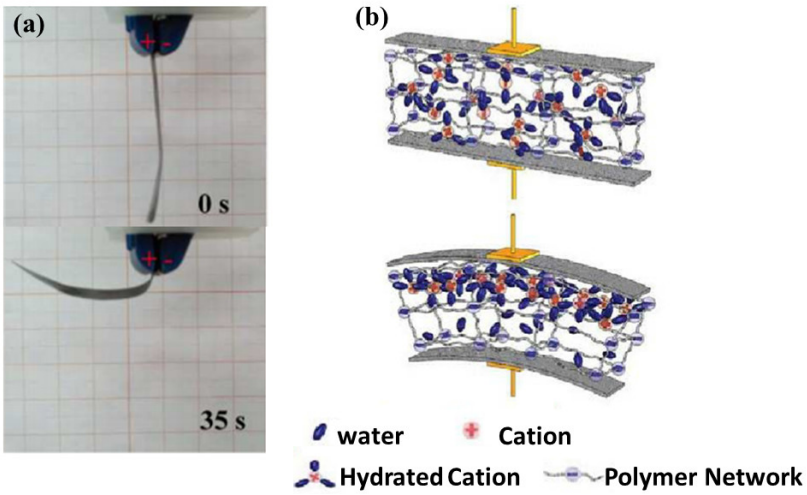

Figure 2. (**a**) The actuation of IPMC (**b**) the applied force cause the cation migration "Reproduced with permission from [29], Royal Society of Chemistry and Cambridge University Press [30]".

These actuators were reported with maximum actuation strains of 3.3% [26,31], and the stress of 30 MPa [25,32]. These actuators are actuated up to a frequency of 100 Hz [31]. The actuation mechanism of conducting polymers will be described in more detail in Section 3.1.1.

2.3. Pneumatic Actuation

The pneumatic artificial muscles (PAMs) are operated by air pressure and contract with inflation. These actuators consist of a soft membrane covered with a braided or fibrous filament structure. As the soft membrane is pressurized the volume is increased while expanding in the radial direction and contracting in the axial direction. The operating mechanism of PAMs can be described in two categories which are, (1) under a constant load and with varying pressure, and (2) with a constant gauge pressure and a varying load. As can be seen in Figure 3a the pressure is increased from P0 to P under constant weight of M which results in increasing the volume and decrease in length as demonstrated in Figure 3b. Actuation under the constant pressure is presented in Figure 3c,d. In this mode of operation weight is decreased from M to M0 under the constant pressure of P, which an actuator exhibits the maximum volume with the minimum length. The most widely used type of PAMs reported to date are the McKibben muscles [33,34]. These pneumatic actuators have high strength, high power-weight ratio, are economical and display high strength. However, the cycle life of these actuators is limited, due to the flexible membrane rupturing with stress. Pneumatic actuators have been reported with 25–30% actuation stroke and with actuation times of less than one second [35].

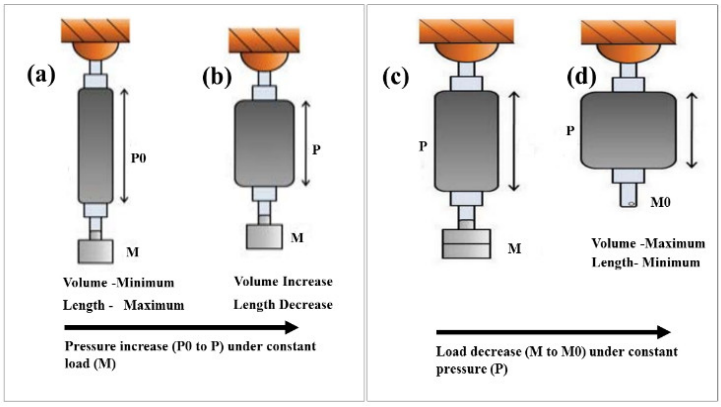

Figure 3. PAMs operation, (**a**) under constant weight (M) the pressure is increased to P, (**b**) volume is increased and length is decreased, (**c**) under constant pressure of P the weight is decreased to M0, (**d**) resulting in maximum volume and minimum length "Reproduced with permission from [36], Institute of Electrical and Electronics Engineers (IEEE), 2011".

2.4. Thermal Actuation

As the name suggests, thermal actuators are operated with the presence of heat. The first generation thermally actuated materials are shape memory alloys (SMAs), that "remember" their original shape and they returned to the original shape after being deformed and exposed to heat. The operating mechanism and fabrication details of SMAs are discussed in Section 3.3. Thermally actuated liquid crystal elastomers have the same working principles as of SMAs. In brief, phase changing and changing order alignment of liquid crystalline side chains generate stresses in the polymer backbone which result in actuation [25]. More importantly, liquid crystal elastomers display low stiffness. Therefore, a small change in the load can cause large displacements. In addition, actuation frequencies and loads on liquid crystal elastomers are limited by the tensile strength of these materials. The latest generation of thermally driven actuators is fabricated from synthetic polymer fibers with many outstanding properties. These actuators exceed natural muscle performance in many aspects and are recognized as one of the latest generations of artificial muscle actuators [17].

The actuation mechanism, fabrication and properties of these actuators are comprehensively described in Section 3.4.

2.5. Other Actuation Mechanisms

In addition to the more common actuator types listed above there are many other actuation mechanisms, such as electrochemical [16,37,38], electrostatic [39,40], optical [41], magnetic [42], hydraulic [43,44] and pH actuation [45,46].

3. Polymer Actuators in Smart Textiles

Some of the actuators described above consist of rigid components, robust operating systems and material properties which render them unsuitable for assembling into smart textiles. This section therefore will describe actuators with different mechanisms which have already been demonstrated in textiles mainly with polymer fiber actuators, such as conducting polymers [47] and shape memory polymers [48,49].

Helically arranged polymer actuators with amplified actuations have already been described in the literature. This encouraged researchers to consider these actuators in many further applications. The researchers employed an ancient technology of twisting which was able to produce highly twisted or coiled polymer fibers with giant actuations. The fiber types that have shown the capability to achieve these high actuation levels extended from twisted carbon nanotube (CNT) yarn to inexpensive commercially available fishing line and sewing threads [16,17,50,51]. This research was able to demonstrate reversible actuation cycles with high work capacity for the actuators. Therefore, actuating textile with helically arranged actuators can be further considered as an important approach for generating optimal force and strain. Hence, this material review is further intended to explore the properties of twisted and helically arranged actuator configurations, which has been successful with many materials, such as synthetic polymers and CNTs that have found potential applications in the area of smart textiles [14,18,38,52,53].

3.1. Conducting Polymers Actuators

The conducting polymers (CP) are also known as conjugated polymers, due to the altering single or double bonds in the polymer backbone. This is a class of electroactive polymers which are activated by ion transport [54]. CP actuators are normally actuated chemically or electrochemically and need electrolyte for their operation. Most of these semiconducting materials are doped with ions by chemical or electrochemical method.

3.1.1. Actuating Mechanism

The actuation mechanism of CP is very well described in many articles [25,55]. The CP actuators are operated under the mechanism of a dimensional change of the material which is caused by addition or removal of charge from the polymer structure.

The dimensional changes of these materials are achieved through the insertion of ions between polymers. The ion flux which is introduced by an electrolyte can cause swelling or contraction of the material as described below [25].

There are two major types of CP actuators classified as anionic and cationic driven. The CPs are produced by an oxidative polymerization process. During the chemical reaction, electrons are removed, and the monomers are put together by a chemical reaction to form the CP chains. Ionic cross links are formed with the polymer chains, due to insertion of anions (A-) which cause the material to be stiff and swollen, as shown in Figure 4a. Crosslinks formed by the bonding between anions and polarons (caused by the removal of electrons) enhance the inter-polymer bonding. The oxidized state of CP is reduced by applying a negative voltage either by way of Figure 4b or Figure 4d to the states Figure 4c or Figure 4e. When a small anion is used, the reduced state is achieved by way of Figure 4b as the anion is emitted causing the polymer to shrink as indicated in Figure 4c. With the oxidation

the polymer is swollen from Figure 4c to Figure 4a through the process shown in Figure 4b. Thus, the mobile ions are anions in this mechanism, the actuators are named as "anion driven" actuators. The second mechanism takes place with the introduction of large anions during the fabrication of CP actuators. The immovable large anions are neutralized by inserting cations via process Figure 4d. This causes the polymer to further swell and achieve the status of Figure 4e. Due to the moving cations in this mechanism, these types of actuators are defined as "cation driven" actuators [55].

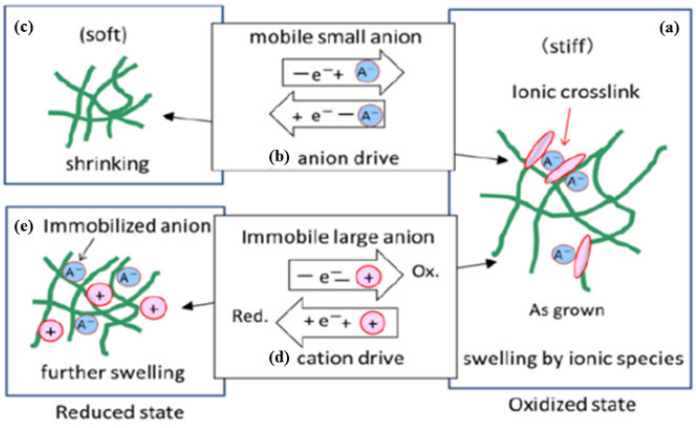

Figure 4. The mechanism of actuation in conducting polymers (**a**) oxidized state, (**b**) anion drive, (**d**) cation drive, (**c**) and (**e**) reduced state. "Reproduced from [55], Journal of physics, 2016".

3.1.2. Fabrication and Properties

CP actuators are typically fabricated through chemical or electrochemical polymerization of conducting materials. The common materials used for CP actuators are Polypyrrole (PPy), Polyaniline (PANi), and Poly (3, 4-ethylenedioxythiophene) (PEDOT)/poly styrene sulfonate (PSS). Due to the aromatic structure of these polymers which are shown in Figure 5, they are stable compared with other linear conducting polymers.

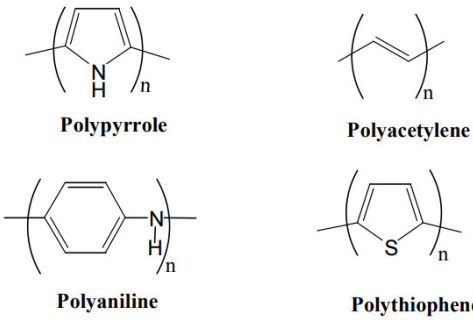

Figure 5. The chemical structure of conjugated CP in undoped form "Reproduced from [56], University of Wollongong Thesis Collection, 2009".

The materials that are used to fabricate these actuators have a strong influence over the actuator performance. PPy is the most popular material used for conducting polymer actuators. Predominantly, PPy is easily electrodeposited and it is feasible to obtain high conductive and tough films which provide high strain, force and long-life cycle [14,55,57]. Alternatively, PANi is prepared chemically by oxidative polymerization in bulk and the strain of actuators made from this material are lower when compared to PPy [58–61]. PEDOT:PSS is another material that has been used as a conductive coating in fabricating CP actuators. The fabrication of PEDOT:PSS actuators has been reported in combination with multi wall carbon nanotube, polyurethane/ionic liquid and Polyvinylidene fluoride [62–64]. CP actuators have been shown to exhibit both bending and linear movement. Linear actuators are fabricated by lamination of anionic and cationic driven actuators on a stretchable film. The fabrication of bi-layer and

tri-layer conducting polymer actuators have also been reported in the literature [65–69]. The solvent and salts used in deposition and the electrolyte employed during actuation are the three major factors that play a significant role in determining the properties of these actuators. These actuators have a high tensile strength which can reach up to 100 MPa and with large stress up to 34 MPa [70]. Moreover, CP actuators are also able to withstand large stresses up to 34 MPa [71]. The strains of these actuators are typically 2–7% and the improvement for the CP actuators has been demonstrated even to reach up to 20% [72]. The strain rates of the CP actuators are low, since they are limited by the internal resistance of polymers, electrolytes and due to ionic diffusion rates [25]. Performance of CP actuators is weakened with the evaporation of the solvent during normal operation in air. As a resolution for evaporation, encapsulation methods were introduced to enhance the life time of these actuators [65,73]. Furthermore, actuators were introduced with internal ion conduction between active polymer layers instead of the external liquid electrolyte as an improvement. This research was demonstrated with PEDOT that shows the only deformation on actuation as can be seen in Figure 6 [74]. Consequently, CPs operated without an external electrolyte may increase their potential for incorporation into practical applications.

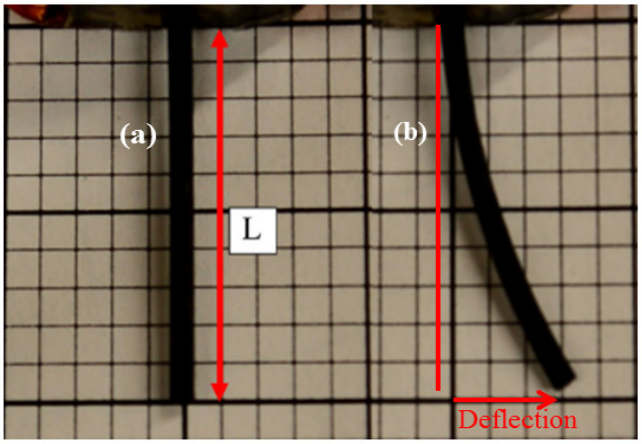

Figure 6. Actuator fabricated with PEDOT to provide deformation, (**a**) before and (**b**) after the application of 2V. The 20 mm length (L) actuator showed 6.5 mm deflection in open air "Reproduced with permission from [74], Elsevier, 2016".

Nevertheless, most of the linear CP actuators reported to date need encapsulation for an electrolyte which is an operational barrier [28]. The efficiency of these actuators is described to be low and their operational stability can be affected by the environmental conditions.

3.1.3. Conducting Polymer Based Actuating Textiles

The commercial availability of conducting polymer coated yarns makes them a practical option for use in actuating textiles [47]. A conducting polymer based actuating textile with different textile structures is presented in Figure 7. In this research a chemically synthesized PEDOT layer was deposited on the yarn/fabric as a "seed layer" to form a highly electrically conductive surface, followed by the deposition of the actuating PPy layer. This research verified the force amplification of actuators assembled into a woven textile structure and the increased strain by using a knitted textile. The research further confirms the mechanical stability of the CP actuators in textile structures [47]. This further outlines the different possibilities of a future improvement to the CP based actuating textile with enhanced features, such as conductivity and anisotropic movements.

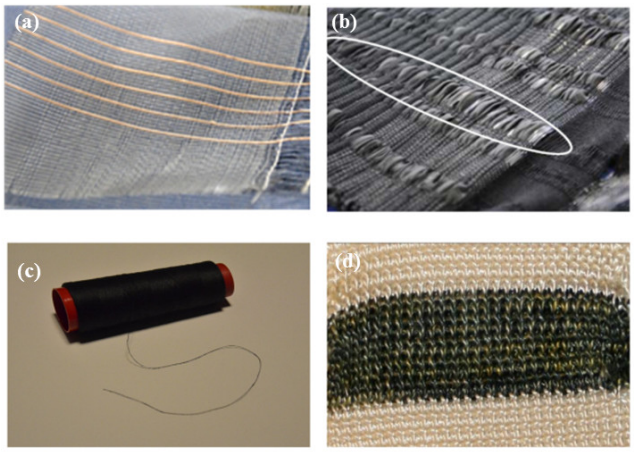

Figure 7. Processing and integration of electroactive textiles, (**a**) Copper monofilaments in weave fabric, (**b**) example of a custom weave with spacing (marked) that enables movements of yarns within the marked area, (**c**) a bobbin with industrially manufactured PEDOT-coated yarn, (**d**) a knitwear structure for respiratory monitoring with CP-coated yarns (black yarn) knitted together with normal (white) yarn "Reproduced from [47], Science Advances, 2017".

3.2. Carbon Nanotube Actuators

Research into Carbon Nanotubes (CNTs) over the last decade has demonstrated that CNTs have the capability to act as an actuating material powered electrochemically, electro thermally, electrostatically and/or optically [16,51,75–77]. The performance of CNT actuators has been increased with the research progress to improve the mechanical properties of CNT sheets and yarns. The following sections cover highlights in CNT actuator research.

3.2.1. Actuating Mechanism

The actuation of CNTs is achieved by mobile ions of a solvent within a polymer. An applied electric field leads to swelling or contraction of the CNT when these ions enter or leave the regions of the polymer. This is accomplished by dipping CNT in an electrolyte and applying a voltage (1–7 V) between the nanotubes. As the CNTs are electronically conductive, the ions are gathered onto the surfaces of the CNTs balancing the electronic charge as the potential has changed. This results in reformation of the electronic structure of the CNT which leads to dimensional changes.

The electrostatic actuation of CNTs is achieved by introducing a high level of charge injection. Electrostatic forces are generated, due to the interaction between the charges introduced into the CNTs instead of two electrodes as for electric field actuation [25]. The actuation of electrochemically powered CNT yarn has been demonstrated with the presence of electrolyte in several publications [16,38]. The actuation mechanism of CNT actuators was extensively studied and explained in the literature with twisted torsional artificial muscles reported by Foroughi et al. [16]. Moreover, CNT actuators with large torsional actuation at a high rotation rate were also demonstrated in this study. The large a scale actuation is achieved by applying a voltage between a counter electrode and a twisted multi wall carbon nanotube (MWNT) in an electrolyte. The contraction of the reported CNT is due to the volume expansion caused by ion insertion which provides a 1% lengthwise contraction with respect to the initial length. A scanning electron microscopic (SEM) image of the twisted MWNT symmetrically twist-spun from an MWNT forest is shown in Figure 8a. The actuation mechanism in brief can be described as a partial untwist of the yarn during the charge injection which is changing the geometrical configuration of the yarn from Figure 8b1 to Figure 8b2. This is associated with the yarn volume expansion after the large positive or negative charge insertion which results in a lengthwise contraction. This research provides further evidence for twist-spun nanotube yarns driven by internal pressure, due to ion insertion [16].

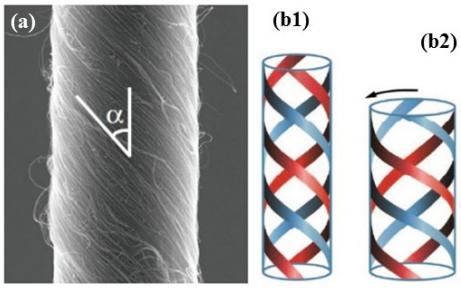

Figure 8. (**a**) SEM of twisted twisted carbon nanotube (CNT) yarn, (**b**) Schematic of the yarn volume expansion during the charge injection "Reproduced with permission from American Association for the Advancement of Science [16], 2011".

Meanwhile, electrothermally driven CNT actuators were reported in the literature overcoming the necessity for the presence of electrolyte for actuation. The electrothermal actuation of CNT was achieved through combining with other polymers which have the ability to thermally expand and contract, such as phase change materials like paraffin wax [78] or with CNT network in silicone polymer elastomer [79]. In general, the electrothermal actuation mechanism of hybrid yarn is driven by volume expansion of the guest polymer materials which are merged with the CNT. Nevertheless, electro thermally driven hybrid CNT actuators need comparatively high applied voltage compared to electrochemically driven actuators [76].

3.2.2. Fabrication and Properties

The electrochemical actuation of CNT was first demonstrated by Baughman et al. for CNT sheets [37]. The research was validated with single-walled nanotube (SWNT) sheets which generated higher stresses and strain than natural muscles. This study opened up possible new dimensions in actuator technology. Thereafter, CNT actuators with un-oriented CNT sheets were demonstrated by a group of researchers. These actuators with low modulus and strength generated around 0.2% stroke and stress 100 times more than skeletal muscle. This study further demonstrated electrostatically driven actuators with 220% stroke [51]. The above research demonstrated actuation for CNT in form of sheets. Meanwhile, a process for the continuous production of CNT yarn fabrication was introduced. The fabrication of CNT yarn evolved by combining the ancient technology of twist insertion during the spinning process. As can be seen in Figure 9a, the CNT yarn is drawn from a vertically aligned MWNT forest. Then the CNT yarn is twisted by a spinning machine as presented in Figure 9b. The schematic Figure 9c shows the magnified view of yarn drawing, twisting and winding during the spinning process. The SEM image in Figure 9d shows the CNT yarn was drawn and twisted simultaneously during the fabrication process. This procedure was able to produce a high strength, multi plied torque stabilized CNT yarn in which the strengths are greater than 460 MPa [50]. Further, the twisted MWNT actuators were demonstrated with high torsional actuation per muscle length with high rotation rates which provided a breakthrough for many types of helically arranged actuators. The twisted CNT actuator was mainly demonstrated for torsional actuation that demonstrated a practical application for a prototype mixer [16].

As mentioned above, the torsional or the tensile actuation of CNTs are achieved as a result of a volume change of the yarn. To accommodate the volume changes, an electrolyte or a guest material should be introduced into the CNT yarn structure. In contrast, the electrolyte used in electrochemically driven actuators adds more volume to the actuator system. Therefore, rather than fabricating these actuators using a sole material, researchers had shown an interest to fabricate CNT hybrid actuators in solid states. As a result, identical anode and cathode yarns were fabricated by permeating the electrolyte and electronically insulating the surface of the yarn to prevent any electrical shorting. The microscopic images of the CNT solid state actuators are presented in Figure 10. As shown in the figure, all solid state actuators were fabricated by plying anode and cathode yarns together [76].

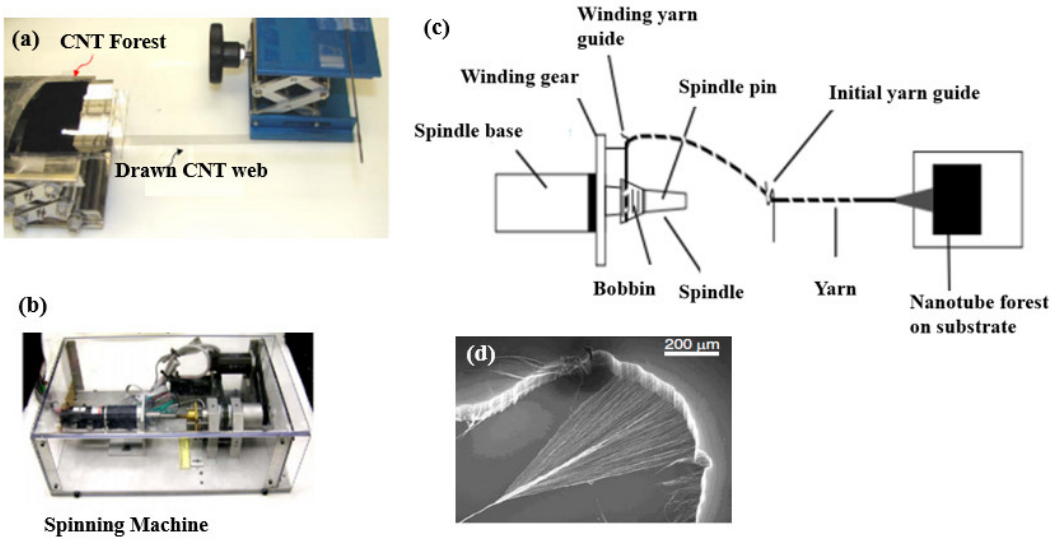

Figure 9. (**a**) The CNT drawn from CNT forest, (**b**) spinning machine, (**c**) the schematic diagram of the CNT spinning "Reproduced from [56], University of Wollongong Thesis Collection, 2009". (**d**) SEM image of CNT yarn being drawn and twisted "Reproduced with permission from [50], American Association for the Advancement of Science 2004".

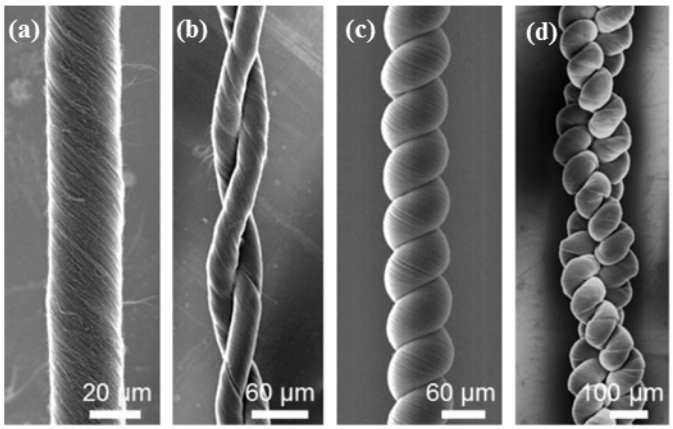

Figure 10. Twisted multi wall carbon nanotube (MWNT) yarn structures, (**a**) Scanning electron microscopic images of single yarn, (**b**) two ply yarns, and (**c**) Single coiled yarn and (**d**) plied coiled yarns "Reproduced with permission from [76]), American Chemical Society2014".

3.2.3. CNT Based Actuating Textile

MWNT yarns largely retain the twist when yarn ends are released compared to conventional textile yarns. Studies have found that these yarns can retain their twist up to the breaking point [50]. Accordingly, highly twisted yarns were demonstrated for plying, knitting and knotting, as well as shown in Figure 11 [50].

Moreover, electrochemically driven plied actuators were reported by Lee et al. [75]. These actuators provided a tensile contraction of 11.6% and 5% for parallel and braided muscles respectively, which were driven electrochemically without a liquid electrolyte. This research further progressed to produce an energy conserving actuator with 16.5% contraction which is the highest reported to date. Theses actuators eliminate the electrolyte bath by replacing it with an ionically conducting gel, as shown in Figure 12b. The gel insulates the anode and cathode yarns while providing ionic conduction [75].

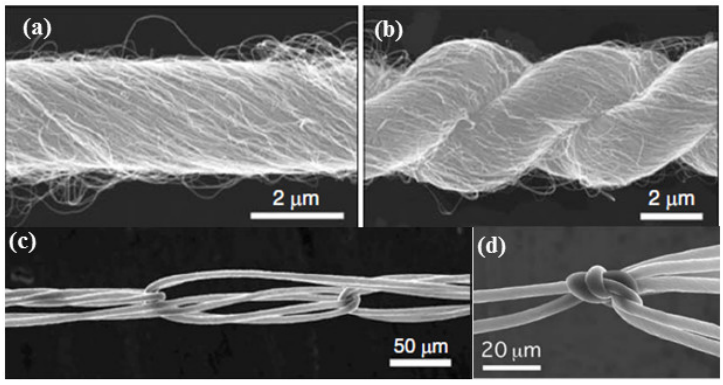

Figure 11. SEM images of (**a**) single twisted, (**b**) two-ply, (**c**) knitted and (**d**) knotted MWNT yarns "Reproduced with permission from [50], American Association for the Advancement of Science, 2004".

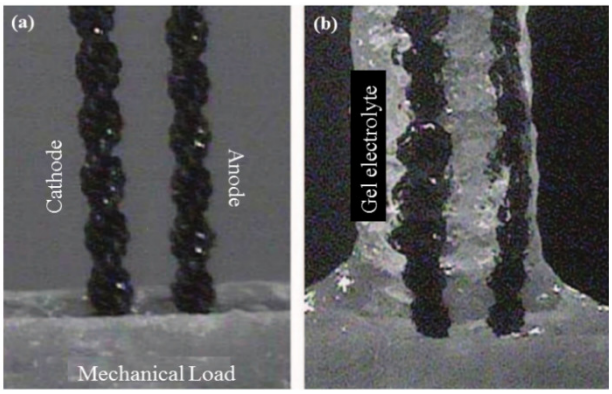

Figure 12. Optical microscopic images of parallel arranged actuators (**a**) before, (**b**) after coating with gel electrolyte to accommodate ion conduction" Reproduced with permission from [75], WILEY-VCH, 2017".

Even though these studies demonstrated technical feasibility, the cost of CNT yarns can be the major drawback in the production of a CNT based actuating textile.

3.3. Shape Memory Alloy (SMA) Actuators

Thermally actuated shape memory alloys (SMAs) are a class of materials that can "remember" their original shape. SMA actuators with both linear or rotary motions are reported in the literature that provided a great impact for thermally driven actuator technology [80].

3.3.1. Actuating Mechanism

The operating mechanism of SMA actuators has not been fully verified, since direct observation of their dynamic behavior in a wide range of temperature is difficult. The actuation of SMA occurs due to a change in the atomic structure between two phases: The low temperature (martensite) and high temperature (austenite), as shown in Figure 13. The actuating mechanism of SMA is achieved by training the material to remember a definite shape at high temperature. Both phases are identical in chemical composition, but when the material is deformed at low temperature the residual strain can be recovered by heating it to the austenite state. This type of SMAs can only remember the parent high temperature phase, and so are referred to as SMAs with one-way shape memory effect. The actuators with two way shape memory effect can perform in two stable phases, i.e., both in high temperature and low temperature [25]. Two way SMAs can provide tensile force much lower than the contraction force and the strain exhibited is half of that can be seen in one way type [81].

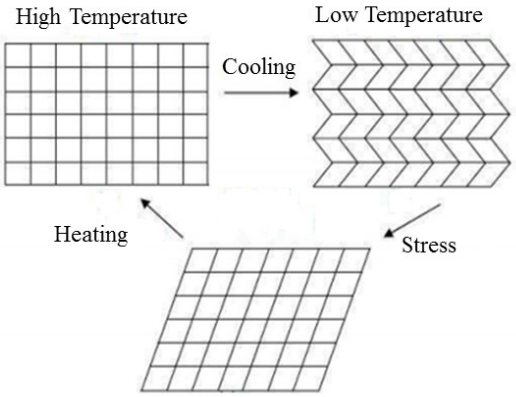

Figure 13. Grid-like representation of shape memory alloys (SMA) structure "Reproduced from [82], InTech., 2010".

3.3.2. Fabrication and Properties

A limited number of raw materials were used to fabricate SMA actuators in the literature. The Nitinol (Ni-Ti) is the most widely used SMA although Copper and iron based SMAs are also employed in some applications. The material selections for SMAs are highly dependent on their transformation temperature. Relatively, Ni-Ti is expensive and copper alloys are less costly but not as widely used, due to the lower fatigue tolerance and thermomechanical instability [83]. The attractive properties of SMA actuators, such as low operating voltage, clean, silent and having a long actuation cycle life have enabled them to be used in many applications [82]. SMAs exhibit a high energy (work) density which is around 1000 KJ/m^3. These actuators operate at very high strain rates (around 300% per second) responsive and exhibit large deformations (around 5%) [26]. Furthermore, SMAs are very responsive and can deliver large strokes. The operating frequencies of these actuators are dependent upon the rate of cooling and heating of SMA to promote phase change. Conversely, exhibiting energy loss during phase transformation can cause a hysteretic behavior to the SMA including nonlinear actuation, parameter uncertainties and their relative costs restrict their use in commercial applications [84].

3.3.3. SMA based Actuating Textiles

An SMA based actuating textile designed for self-recovery by weaving and knitting textile structures with embedded Ni-Ti wires was introduced by Carosio et al. [48]. The fabricated woven textile structure was shown to display self-ironing with the presence of Ni-Ti wires. The fabric was crushed, as shown in Figure 14a, and then was able to exhibit a self-shape recovery as can be seen in Figure 14b. This research further highlights the successful combination of Ni-Ti wires in a woven fabric structure [48].

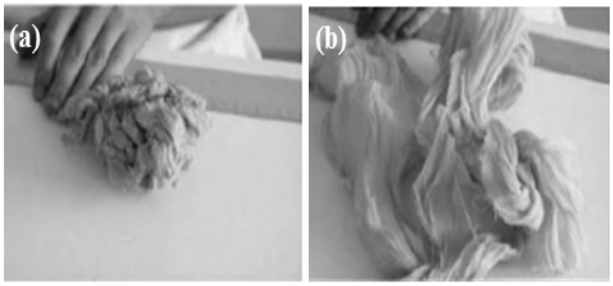

Figure 14. The Ni-Ti embedded fabric (**a**) crushed and (**b**) self-recovered "Reproduced with permission from [48], IOS Press, 2004".

Further, an analytical model using SMA in a garter knit structure was presented by Juliana et al. [51]. A prototype knit textile was fabricated and tested within the range of forces as a characterisation of the textile. The knitted textile fabricated from Flexinol actuators was able to achieve larger strains (around 51%) at moderate forces and usable strains (around 4.1%) at the enhanced force of 12 N, compared to the single actuator alone with 4% strain at 5.8 N [49].

3.4. Twisted and Coiled Synthetic Fibre Actuators

Synthetic fibers are designated as "man-made fibers". These are popular in many practical applications, due to interesting properties, such as high tensile strength, high modulus and shear stability [85]. The precursor fibers used to fabricate coiled actuators are readily being used in high strength applications, such as fishing, apparel and sewing. The high degree of polymer alignment of these fibers provides them with high strength. Moreover, forming these fibers in a twisted fashion and arranging the polymer chains helically provides for a thermally persuaded length change during untwisting. The phenomenon for actuation of these materials will further be described in the section below.

3.4.1. Actuating Mechanism

Synthetic fibers are produced from a process called "polymerization" followed by fiber drawing. Upon drawing, the crystalline blocks of the polymer become increasingly aligned along the draw direction. The drawn polymers will consist of an amorphous region, tie molecules and inter crystalline bridges, as shown in Figure 15. The amorphous region contains floating chains and polymer chains which are attached to the crystalline region at one end and loops, which starts and end at the same crystalline region. The tie molecules joining one crystalline block to another block increases with both number and steadiness by increasing draw ratio. The crystalline regions of polymer fibers have a small degree of negative thermal expansion. Fiber direction aligned polymer chains in non-crystalline regions are less constrained and thus they can cause larger reversible contractions when heated. This reversible contraction is amplified by inserting twists and coiling the yarns.

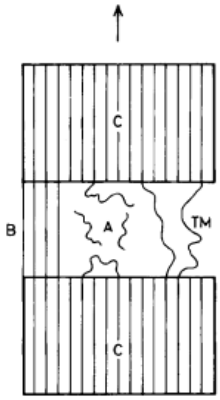

Figure 15. Schematic diagram showing the structure of a highly oriented semi crystalline polymer. (C) crystalline region; (B) bridges; (A) amorphous region; (TM) tie-molecules "Reproduced with permission from [86], John Wiley and Sons, 1981".

The giant actuation of these actuators is achieved through partial untwisting of the twisted fibers [17]. The untwisting of twisted fibers provides an expansion in the radial direction which leads to a contraction in the fiber axis direction.

3.4.2. Fabrication and Properties

High strength polymer fibers, such as nylon, polyester and polyethylene, are anisotropic materials and considered as raw materials for these actuators. The fabrication procedure of these actuators was

fully described in research work by Carter S. Haines et al. [17]. The precursor fibers (Figure 16a) were twisted until they get coiled, as shown in Figure 16b or they can be fabricated by wrapping the twisted fiber around a mandrel as can be seen in Figure 16e. The actuator structure was set using an annealing procedure to retain the helical shape. Furthermore, actuators can be tailor made to achieve the desired actuation based on fundamental studies.

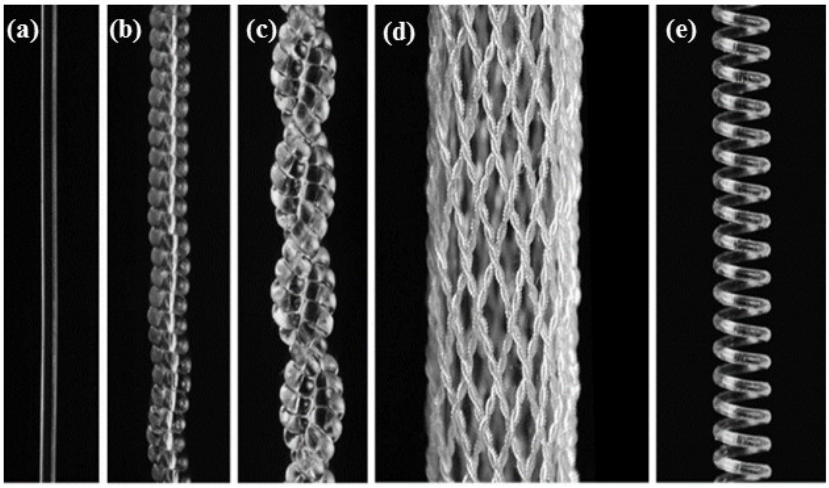

Figure 16. The actuators (**a**) a non-twisted monofilament, (**b**) after coiling the monofilament, (**c**) a two –ply muscle formed from the coil, (**d**) a braid formed from 2-ply muscles, (**e**) a coil formed by inserting a twist "Reproduced with permission from [17], American Association for the Advancement of Science, 2014".

Figure 17 shows the bulk-produced coiled actuators manufactured by a continuous process where (a1) is a spool of the non-conductive actuator and (a2) is a spool of the conductive actuator. The conductive actuator is fabricated by wrapping with insulated copper wire for electrothermal heating. The continuous production possibility of these actuators will further enhance the feasibility of fabricating them into textiles.

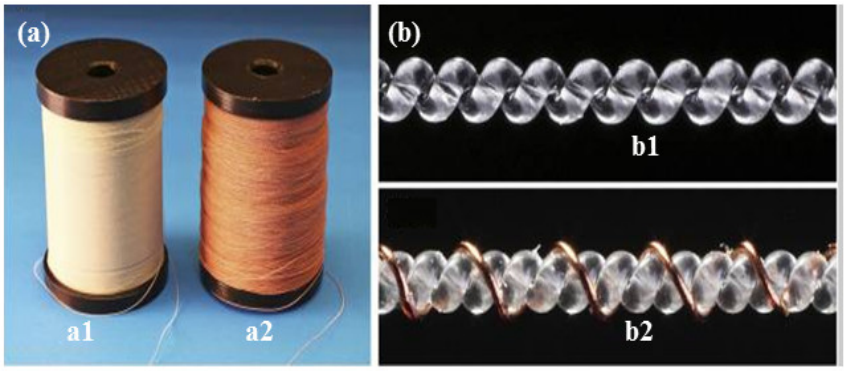

Figure 17. Coiled polymer actuators produced by a continuous process, (**a1**) spool of non-conductive actuator and the optical image of non-conductive actuator is shown in (**b1**), (**a2**) spool of conductive actuators produced by wrapping with an insulated copper wire, as shown in optical image (**b2**) "Reproduced from [19], Proceedings of the National Academy of Sciences, 2016".

These coiled synthetic polymer actuators exhibited a 49% maximum lengthwise contraction. Furthermore, these actuators were able to lift loads over 100 times heavier than a human muscle of the same length and weight. In addition, they can generate 5.3 kW/kg of mechanical work, (similar to that produced by a jet engine) with the highest operating frequency of 7.5 Hz reported to date. The low cost, less-hysteretic behavior, ease of handling, high tensile strength and other exhibited performance

characteristics are some additional favorable properties of these actuators [17]. Further research of synthetic polymer actuators was published by Cater S. Haines et al., which discussed the practical opportunities and challenges of artificial muscles. This research highlights the limiting factors of the tensile actuation and the further improved spiral shape actuator which was fabricated with 200% tensile actuation [19]. Thus, the coiled actuators have been widely investigated by researchers for textile fabrication.

3.4.3. Twisted Polymer based Actuating Textiles

Twisting and coil formation of polymers offer high-performance actuators which provide promising materials in designing a high-performance actuating textile. A model textile has been demonstrated for the first time in the literature from the twisted actuators with nylon fishing line, as shown in Figure 18 [17]. The textile was weaved from silver-plated nylon for electrothermal heating (brown in color) and polyester, cotton yarns (white and yellow in color) in the weft direction and nylon coiled actuators were used as the warp yarn.

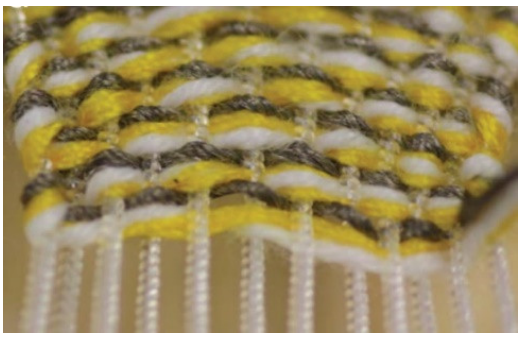

Figure 18. An actuating textile woven from conventional polyester, cotton, and silver-plated nylon yarn (to drive electrothermal actuation) in the weft direction "Reproduced with permission from [17], American Association for the Advancement of Science, 2014".

The textile actuation was achieved via heating the textile electrically which provides a gateway for fabricating novel actuating textiles. Thereafter, actuating textiles were formed using traditional textile fabrication methods with the recent research of Hanes et al., as shown in Figure 19 [19].

This research successfully combined the actuators in woven, stitched and knitted textile structures. These textiles were fabricated with non-electrically conductive actuators. The researchers have recommended these textiles in applications, such as porosity changing textiles and breathable curtains.

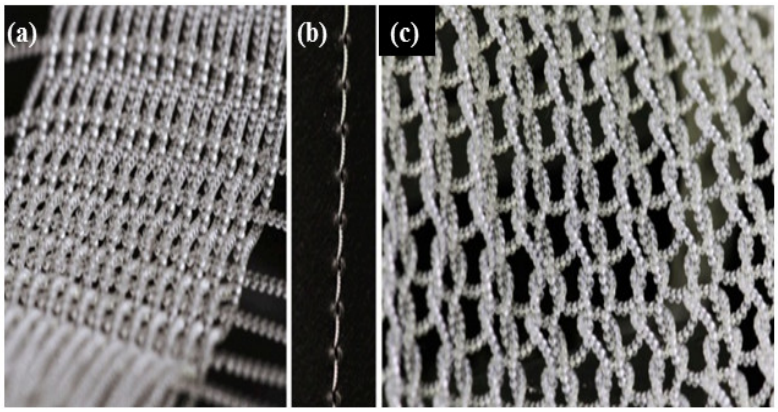

Figure 19. (**a**) Woven fabric made from coiled, 225-µm-diameter nylon sewing thread coils, (**b**) stitches made by sewing the coiled fiber in into a polymer sheet using a conventional sewing machine, (**c**) machine-knitted textile made from a coiled 225-µm-diameter nylon sewing thread. "Reproduced from [19], Proceedings of the National Academy of Sciences, 2016".

Furthermore, nylon actuators were recently demonstrated in a bionic bra developed to minimize breast discomfort during exercise [87]. The woven actuators were used as active materials to control the breast movement, as shown in Figure 20.

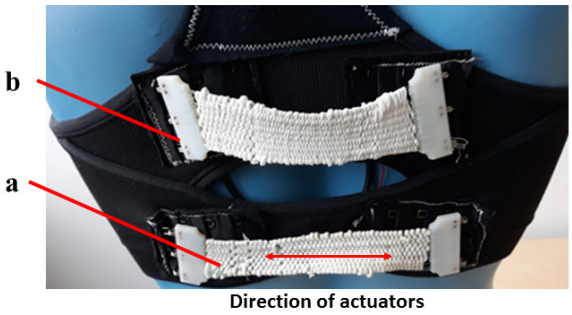

Figure 20. The bionic bra fabricated with woven actuators (**a**) the actuator placement in the bra woven with an electrically conductive yarn for heating (**b**) 3D printed actuator connector.

The actuators were heated by weaving them with a conductive yarn. A single actuating fiber was able to generate around 0.6 N force following heating to 75 °C and a woven textile actuator with the nine, parallel actuating fibers was able to generate around 3 N force heating to the same temperature.

3.5. Knitted CNT/Spandex Yarn as Smart Textiles

More interestingly, an electrothermally activated "clever yarn" was invented by overcoming the technical obstacles by Foroughi et al., as shown in Figure 21 [13]. A highly stretchable, actuatable textile was produced by wrapping spandex filaments (SPX) with CNT yarns to give the actuating performance and conductivity respectively. This knitted textile structure exhibits 33% contraction and mechanical work output of 1.28 kW/kg which exceeds that of skeletal muscle. This research presents adjusted electrical conductivities by changing the SPX/CNT ratio and hysteresis free resistance was obtained by changing the tensile strain. A hybrid SPX/CNT based actuating textile opened a new dimension into manufacturing actuating textiles using an existing textile fabrication method. Further, this was recommended for applications where it was required to apply force or pressure to the wearer [13]. The actuating textile was heated by applying a voltage of 12 V and current of 0.25 A. Further, this research demonstrated the feasibility of using coiled synthetic fiber actuators in smart textiles.

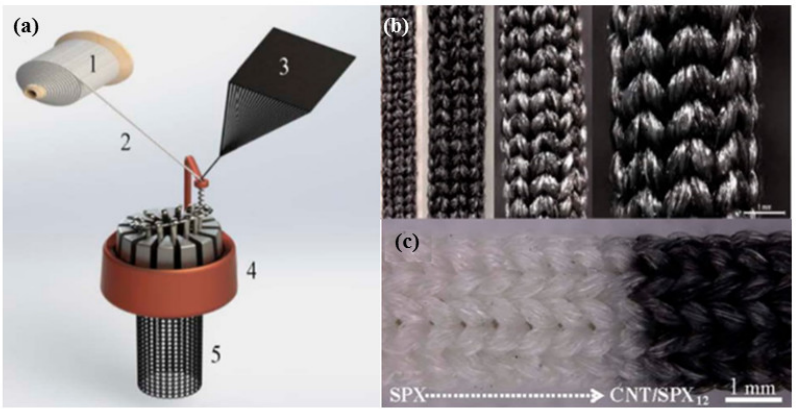

Figure 21. (**a**) Schematic of the process for producing a knitted CNT/SPX (wrapping spandex filaments) textile. The illustrated items are (1) a spool of SPX fibers, (2) an n-fiber SPX yarn, (3) a CNT forest, (4) a circular knitting machine, and (5) a knitted CNT/SPX textile. A CNT ribbon drawn from a CNT forest was wrapped around SPX fibers and knitted in the knitting machine to produce the circular knitted textile, shown in (**b**) and (**c**). "Reproduced with permission from [13], American Chemical Society, 2016".

4. Overview in Different Actuation Mechanism for Smart Textiles

The actuating mechanism should be selected with a major emphasis on end user requirement. This section is focused to discuss the suitability of different actuation mechanisms for an actuating textile for high tech applications including biomedical, soft robotics and apparel. Herein, we are appraising above described popular actuation mechanisms; electric field, ion based, pneumatic and thermal means for a workable textile fabrication.

Electric field actuation is caused by electrostatic attraction. Therefore, it requires two surfaces or alignment of polarized domains which need voltages as high as 1 kV. Generally, there is need of an amplifier to convert line or battery voltages up to kV potentials, which adds cost and consumes volume. Thus, the cost, size and safety measures may prohibit electric field actuators for applications in small portable (e.g., handheld) devices. All these limitations can be a concern in smart textiles, as well as in bio medical and toy applications [25,26].

Ion based actuation requires electrolyte to be presented in the polymer structure. Therefore, assembling them in a smart textile would need a configuration to retain the electrolyte medium. Actuator arrangements described in the literature without the liquid electrolyte need sophisticated manufacturing procedures and actuation mechanisms which add more cost and operating barriers to the system. Moreover, low efficiencies are one of the key disadvantages of these actuator types. The main disadvantages of pneumatic actuators, such as McKibben, are that, they need a compressor or pump and their dynamic behavior is nonlinear. Consequently, they are difficult to make into a textile, and a robust control mechanism is needed to achieve the desired motion [88,89]. Therefore, the feasibility of incorporating actuators with these major actuating mechanisms into smart textile will present many challenges.

In contrast, most of the research has focused on the use of thermally driven actuators in smart textiles [13,17,19,48,49,87]. This may be mainly due to the utilization of electrothermal heating as a reliable and clean source of energy. Many studies have been reported for textiles combined with different types of electrical conductors for smart textiles and electrothermal heating applications [90–95]. Furthermore, the outstanding properties of thermally driven actuators make them an attractive prospect in high end future applications. Thermally driven synthetic coiled actuators show 49% contraction which will enable them to be used in a highly contractible actuating textile. This high contractibility is able to generate a high pressure which makes it an attractive proposition in many applications. Since, it will produce a textile structure which is generating high work output per unit area. The cost of raw materials and cost of processing sets the final price limit for the textile. The use of inexpensive synthetic polymers will be advantages for producing an actuating textile at low cost which will increase affordability and market demand. Moreover, the durability and demonstrated operating consistency will increase the feasibility for their use in applications, such as bio- medical where reliability is paramount. The high tensile strength and the reversible actuation over one million cycles enables the production of a durable textile with less damage to the actuator system during operation. Additionally, the low hysteresis behavior of synthetic polymer coils increases the possibility of producing an easily controllable textile which will exhibit a consistent actuation in heating and cooling cycles. These outstanding properties point to exciting prospects for the use of coiled synthetic actuators in future high-performance actuating textiles. Table 1 provides a summary of the properties of different actuating mechanisms, actuators, their advantages and drawbacks.

Table 1. The summary of different actuators with their actuating mechanisms, actuator properties, advantages and disadvantages.

Actuating Mechanism	Actuator Type	Strain	Stress (Mpa)	Work Capacity	Advantages	Disadvantages	References
Electric Field Actuation	Dielectric elastomeric actuators	10–380%	7.7	150 kJ/m^3	Simple in mechanism and construction	High voltages	-
					Large strains	Cost and consumes volume	-
					High efficiencies (30%)	-	[22,23]
					High bandwidths	-	
					Low current		
					Low cost		
	Electrostrictive polymers	7%	45	320 kJ/m^3	High work density	High voltages cycle life is unclear	[26,27]
					High Stress		
Ion based Actuation	Conducting polymer	12%	34	100 kJ/m^3	Low Voltage	Need encapsulation Low Efficiencies	[25,70,72]
					High Stress		-
					High work density	-	
	Ionic Polymer Metal Composites	3.30%	30	5.5 kJ/m^3	Low Voltage	Need encapsulation	[25,26,31,32]
Pneumatic Actuation	Mckibben	25–30%	-	-	Fast	Difficulty to control	-
					High strain	Bulky operating method	[35]
Thermal Actuation	Shape Memory Alloys	8%	200	1000 kJ/m^3	High stress Low Voltage High work density	Difficult to control Large currents Low efficiencies	[26,84]
	Twisted Synthetic Fibers	49%	-	2.48 kJ/kg	High Strain	Limited Operating temperatures (250 °C)	[17]
					High work output per kg Inexpensive		
					Light weight		
					Flexible	-	
Electrochemical	Carbon Nanotubes Yarns	16%	2	2 kJ/m^3	High Stress	Expensive	-
					Low Voltage	-	[26,75]
					High temperature range	-	

5. Future Outlook

An electrically operated high-performance actuating textile with high strain and force will benefit many future applications. However, the fabrication of conductive textiles is limited by many technical and nontechnical parameters and it is important to analyze the contests associated with fabrication. The processes of weaving or knitting electrically conductive actuators for electrothermal heating are normally associated with several challenges, such as an increase of electrical resistance with tensile strain and changes in the conductive path ways of textile yarns or fabrics. In addition, the weaving of conductive yarns/wires involves high strains, process constrains, and long-term stability of intersection points are some of the other limitations of bulk manufacturing of actuating textiles. Electrical shorting between two yarns at their mechanical intersection is another key limitation

in establishing electrical links [96]. Damaging of electrical connections during washing, and other activities performed by the user are some other challenges in smart textile applications. As a result, some researchers have investigated the used of surface modified conductive textile yarns for their hydrophobicity and electrical encapsulation. As examples, the textile cables can be coated with silicone substrates with improved mechanical properties which will minimize the conductivity and electrical shorting limitations described above [97]. Further, a method of encapsulation for washable, reliable and wearable electronics was demonstrated by Tao et al. which was focused on two types of silicone where the devices were able to perform after washing [98]. Moreover, the actuation frequency can be lowered with cooling in normal air. Therefore, incorporating cooling material is important to maintain a consistent frequency during operation [99]. Heating might be another limiting factor as the human body can only tolerate a certain temperature range. This temperature range will differ with the application type and the area of the body exposed to the textile. Hence, the limiting factors of electro thermally driven textiles need to be well controlled in order to produce a high-performance actuating textile.

6. Conclusions

Development of materials for the preparation of actuating materials is an important enabling step towards their application, particularly in smart textiles. We have summarized the history of the emergence of actuating materials, categories, and preparation and fabrication methods for the recent development of smart textiles, as well as their current/future of applications. Smart textiles based on different actuating mechanisms and a comprehensive study on polymer actuators has been reviewed. The compatibility of diverse actuating mechanisms in actuating textile was showed that the thermally driven actuators can be considered as a potential actuator type to incorporate into actuating textiles. Moreover, thermally driven twisted synthetic fiber actuators with high actuation strain and work capacity will provide extraordinary features to a high-performance actuating textile. Thermally operating actuators are fabricated based on man-made fibers, such as nylon, polyester, and spandex which can be manufactured using conventional textile processing. In addition, the thermal energy for actuation can be harvested from electric power as a reliable method of operation. The electrical Joule heating method for textile can be achieved by incorporating conductive materials to the textile structure. The processes and materials described above need to be evaluated when considering the fabrication of electrically operated actuating textiles. The introduction of guest materials to achieve desired application properties is also a key area to be considered during fabrication. Most importantly, thermally driven actuators should be evaluated for the most efficient and even means of heating. Actuators heated electrically by connecting with a conductive yarn or conductive coatings are some of the technically stable methods which have enormous potential. Furthermore, the possibility of using contractile polymers in an artificial heart has been investigated and there is a high possibility of employing an electrically operated actuating material structure in biomedical applications [100–102]. A well fabricated actuating textile will find multiple applications possibilities, such as biomedical, prosthetics, soft robotics, and smart apparel which can make a significant impact in many areas. Although recent development in smart textiles appears extremely promising, there still remain challenges to improve their properties and performance to become adequate for a practical and commercial application.

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