Functional fibers for robotic fabrics

Multifunctional Materials

TOPICAL REVIEW

Functional fibers for robotic fabrics

Trevor L Buckner and Rebecca Kramer-Bottiglio[1]

School of Engineering & Applied Science, New Haven, CT, 06510, United States of America

[1] Author to whom any correspondence should be addressed.

E-mail: trevor.buckner@yale.edu **and** rebecca.kramer@yale.edu

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Abstract

Fabrics have conventionally been passive materials with static properties, leveraging the mechanical, optical, and thermal properties of networks of fibers. Recently, however, the emergence of functional fibers with dynamic properties has begun to disrupt this conventional definition. Engineers have begun to explore new materials and manufacturing processes for actuating, sensing, and variable-stiffness fibers, and the integration of these functional fibers into dynamic, robotic fabrics. This review discusses recent developments in functional fibers and speculates on their utility in future robotic fabrics.

1. Introduction

A fabric is a thin, flexible assembly of interlacing fibers with adequate mechanical strength to be considered a cohesive structure. Fabrics can be manufactured from a variety of materials, both natural and synthetic, to provide desired properties in terms of durability, weight, comfort, protection, appearance, breathability, and more. In contrast to other sheet materials such as paper or plastic, a fabric can typically recover its shape after bending or crumpling, and has sufficient strength and tear resistance for use in many commonplace and technical applications [1, 2]. As an inactive yet highly customizable material, fabric finds wide-ranging use in applications such as clothing, bedding, and furniture, to more specialized cases such as backpacks, protective flame-resistant garments, resilient canvas in sails, and weather-resistant tarps and tents. Such qualities and use-cases have established fabrics as an effective and adaptable manufacturing material.

Recently, researchers have begun to realize new responsive materials and manufacturing methods that have led to the development of functional fibers with active stimulus response [3–6]. With these resources in reach, we see an opportunity for the emergence of a new class of planar soft robots based on fabrics. These *robotic fabrics* will extend the benefits of conventional fabrics to include intelligent garments and robust adaptive structures that leverage the diverse properties of technical fibers. A robotic fabric, then, is a functionalized network of flexible, responsive fibers, thereby enabling sensing, actuation, and stiffness control embedded in a single conformable substrate. By treating fabric as the foundation of a robot, it can be transformed from passive equipment to active machinery that will positively impact the manufacturability, transportability, and adaptability of complex robotic systems. Robotic fabrics will enable a new method of on-demand machine reconfiguration through adaptable structure (figure 1), as well as enhanced compatibility with wearables. Furthermore, by designing components to be fiber-based, they can be integrated into a fabric structure using well-established fabric manufacturing techniques, such as weaving, knitting, and sewing.

2. Grand challenges and scope of review

The development of robotic fabrics presents many technical challenges, two of which we will highlight in this review. The first challenge is the need to generate adequate forces in thin-body or fiber form. Although some examples do exist [7], fabrics that exhibit active motion are rare. Traditional robot actuators are not so constrained, and hence can make use of heavy electric motors or bulky pressurized fluid reservoirs to generate

Figure 1. Simulation of a hypothetical robotic fabric. The robot transforms from a neutral planar state to a legged 'walking' form.

large, predictable forces. Such components can generally be scaled in size to fit the required load and are readily available. In contrast, a robotic fabric, which by its nature is a thin entity, would be restricted to components which are small and flexible, such as fibers and yarns.

A second challenge is establishing rigidity control to achieve move-and-hold operations or load-bearing structures in a fabric. While the inherent softness of a robotic fabric may allow for extreme conformational adaptability, light weight, and resistance to trauma, these same properties become disadvantageous when attempting to apply forces to other bodies or to directly manipulate the environment in which the robot operates. In order to overcome this challenge, robotic fabrics require a method of selectively adjusting their stiffness to create rigid load paths on demand. Variable-stiffness control of this type has become an important topic in the realm of soft robotics, and a variety of solutions have resulted with varying levels of feasibility. These include using pressurized balloons [8], granular jamming [9], and changing shape to make use of geometric stiffening [10]. However, not all methods are scalable for integration into a fabric.

To demonstrate the progress that has been made toward conquering these two challenges, we will review both geometries and materials as applied to robotic fabric components. First, we will present fiber geometries that are commonly used with fiber-based actuators to enhance the performance of the bulk actuating material. This information will be critical in forming a reasonable comparison between the performances of various fiber actuators. Second, we will expand our discussion from individual fibers to assembled fabric units. We will discuss fabric manufacturing methods and the effect of the resulting fabric structure on performance. Third, we will present the state-of-the-art in responsive, motion-generating materials that have demonstrated feasibility of being manufactured into thin actuating fibers for integration into fabrics. Fourth, we will review some candidate methods of achieving variable structural stiffness in the form of a fiber. As a benchmark, it is convenient to compare actuators and load-bearing structures to human skeletal muscle, due to its well-documented properties and wide relatability. The performance of human muscle can vary somewhat between specimens, but we will provide a general range of properties.

In presenting this information, we build upon the vast amount of work that has been done in 'smart textiles' or 'e-textiles' as they are sometimes referred to [11–13]. E-textiles represent a set of technologies which endeavor to functionalize common fabrics, usually by introducing flexible [14–16] or miniaturized [17, 18] versions of existing electrical components. Several comprehensive reviews have been published which summarize various stationary fabric-based components, including electrically conductive fabric materials [13, 19], energy collectors [2, 20, 21], and several types of sensors [11, 19, 22]. We recognize that many of these precursor technologies will form the basis of robotic fabrics, however we differentiate a robotic fabric from these works by the stipulation that it must also provide active motion control, such as actuation and stiffness tuning. As such, this review will focus specifically on those technologies that contribute to motion generation in a robotic fabric and have been demonstrated as viable responsive fibers. Given the wide variety of potential fabric substrates and integration methods, an evaluation of the performance of each fiber within an assembled fabric unit is beyond the scope of this review. Rather, we intend this work to serve as a reference for future development in this area, both as a showcase of the state-of-the-art in relevant topics as well as to provide collected data to aid researchers in designing robotic fabrics that meet specific design requirements.

Table 1. Direct comparison of fiber geometry effects on actuator performance, assuming comparable fiber diameters (qualitative evaluation scale: ++, +, o, −, − − from the highest to the lowest values). Upward and downward arrows indicate properties that are more favorable when high (▲) or when low (▼).

Geometry	Stroke length ▲	Pulling force ▲	Stiffness ▼	Actuation speed ▲
Monofilament	− −	++	++	− −
Twist	o	−	−	++
Coil	++	− −	− −	o
Writhe	−	o	+	o
Hierarchical	+	+	+	+

3. Fiber morphology

As evident by observing a length of rope or the fabric of modern clothing, a given set of fibers can be joined in a variety of configurations, both functional and stylistic, to achieve an aggregate unit. At the most fundamental level, this includes collecting smaller fibers into bundles, twisting into cords, and coiling into loops. Different fiber arrangements offer different benefits, from stretchability, strength, and thickness, to decoration and texture.

In the context of fiber actuators, single monofilament fibers are often not the most effective way to achieve motion. Similar to how the difficult task of lifting a heavy weight by a rope can be made more manageable by introducing a pulley, actuator filaments can be arranged in favorable configurations that enhance performance, perhaps at the expense of some other property. A simple demonstration of this can be performed with a piece of plain cotton string. By twisting one end and holding the other fixed, the string will become thicker and shorter in length as it begins to coil upon itself; in exchange, the string now has an internal contracting force which will pull back to its shortened state when stretched apart. Here we will cover some of these geometric configurations that prepare inert fibers to generate motion and can be used in combination with active materials to amplify their effects. A qualitative summary is presented in table 1.

3.1. Twisted bundles

Pulling axially on a single linear fiber (figure 2(a)) will cause it to quickly reach a maximum extension, after which point any further extension requires breaking apart atomic bonds. As a result of this, individual fibers formed from bulk material will have a relatively high stiffness in tension, which corresponds to short stroke length if used as an actuator. One method to combat this is to twist a bundle of many smaller fibrils together into a single yarn (figure 2(b)). Now, when pulling on this larger aggregate fiber, the individual fibrils have freedom to release their internal torsion and straighten in the direction of tension to some degree before the tensile limit is reached. This effectively results in an aggregate fiber that is lower in stiffness (has more conformational freedom) than the individual fibrils, thus allowing a larger actuating stroke.

Another benefit of utilizing many small fibrils in composite rather than a solid homogenous fiber is the increase in the surface area to volume ratio. Many of the materials to be mentioned in this review rely heavily on the rate at which an outside stimulus, such as heat, can fully penetrate the structure. In this case, a higher surface area will generally induce actuation more rapidly and aid in activating the full cross-section of the fiber more completely resulting in a higher actuation force.

3.2. Coils

Coils are one of the simplest configurations that can improve the performance of an actuating fiber. Rather than twisting multiple small fibrils together, a coil is generated from a single fiber by wrapping it around a central axis in the shape of a spring (figure 2(c)). When a coiled spring is stretched, it produces radial twist at the cross-section of the fiber, rather than direct prismatic stretching. By distributing this twist along the length of the fiber, a spring takes advantage of the sum of many small atomic displacements to provide a large overall macroscale strain. Thus, a coil can be elongated to many times that of bulk material, at the cost of a moderate reduction in stiffness. Tighter coils will produce a higher pulling stress due to their increased stiffness, while wide coils will produce a larger strain [23].

It should be noted that as an actuator, a coil works best against a pre-strain. An unloaded coil will experience very little contraction when activated and would gain no benefit over bulk material. With pre-strain, however, a

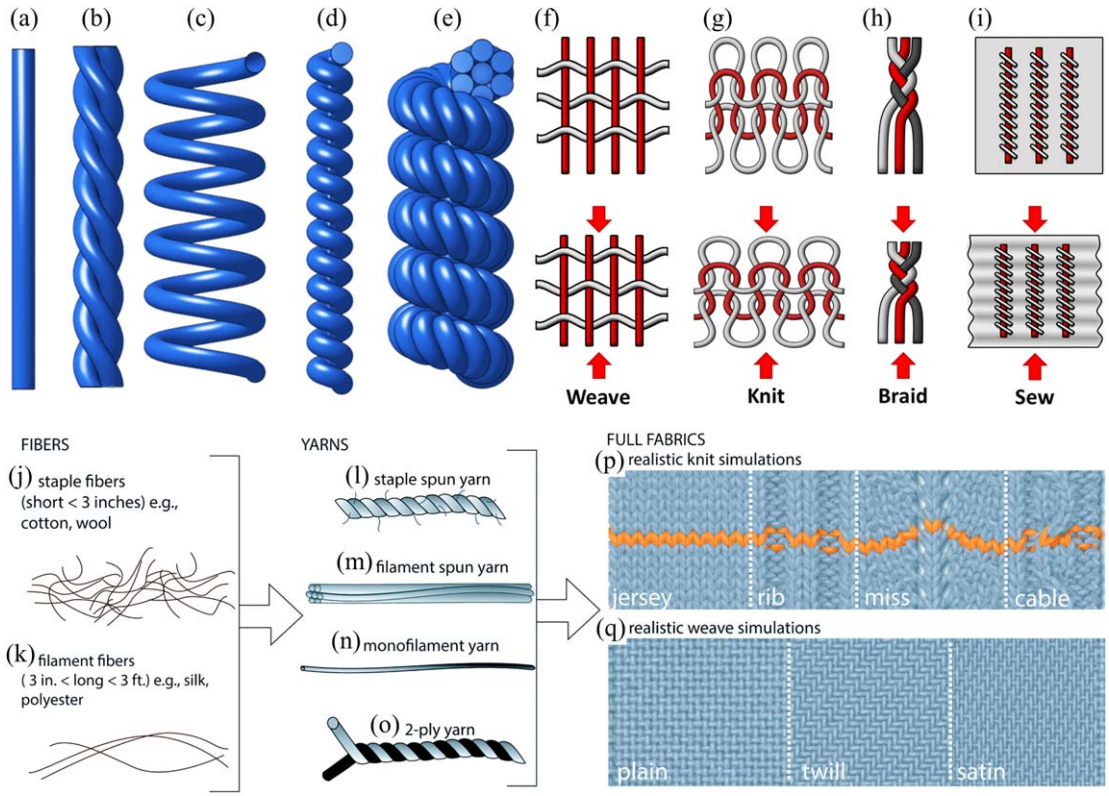

Figure 2. (a)–(e) Geometric configurations used to tune the capabilities of an actuating fiber. (a) Typical unmodified fiber. (b) Twisted bundle of small fibrils. (c) Coil. (e) Writhe. (e) Hierarchical combination of a twisted bundle and writhe. (f)–(i) General methods of combining multiple fibers into a fabric structure. (f) Fibers woven in parallel will enhance the output actuator stress. (g) Fibers knitted together allow a greater range of motion, resulting in enhanced stroke length. (h) Braided fibers will enhance actuator stress as well as fabric strength and stiffness. (i) Fibers sewn directly onto another fabric substrate allows for greater control over load paths. (j)–(q) Illustration depicting fabric component parts and their proper names. (j) Staple fibers. (k) Filament fibers. (l) Illustration of a staple spun yarn. (m) Illustration of a filament spun yarn. (n) Monofilament yarn is a single fiber acting as a whole yarn. (o) Illustration of a 2-ply yarn. (p) Realistic simulations of different knit structures, with a single yarn in orange to depict the path of the yarn. (q) Realistic weave simulations. (j)–(q) Reproduced with permission [2]. Copyright 2014, The Royal Society of Chemistry.

coil can work to pull the load back into to the initial unstretched length, resulting in a larger effective stroke length.

As an example, coils are most often seen used with shape memory alloys (SMA) [24–28]. An SMA spring can far exceed the bulk-material 4% strain limit, reaching strains of 50% or more, at the expense of pulling force, reduced to about 70% of the original [25]. There are a few rare examples of other materials being made into coils to increase actuating strain. Strips of liquid crystal film cut in a particular orientation can be made into a coiled actuator that amplifies the natural curling motion of the film [29]. Similar work has been done with ionic polymer-metal composite (IPMC) actuators [30]. Conductive polymer actuators have been made with the fibers oriented helically in a tube [31].

3.3. Writhes

By fixing one end and turning the other, straight fibers can be overtwisted to the point that coils spontaneously form along the length (figure 2(d)). These internally twisted coils are known as 'writhes' [32]. While they may appear similar to a wrapped coil spring, the additional internal angular strain imparts an improved pulling stress. This can also serve as an alternative geometry to simple coiled structures when the chosen material is too flexible to maintain the spring shape created by wrapping alone. However, this type of inserted-twist actuator can also result in reduced stroke length for materials that expand when activated. This expansion causes some 'untwist' in the coil, which might counteract some of the linear contraction of the writhe, resulting in an overall lower stroke length of the thread [33, 34]. On the other hand, some actuators rely entirely on the strain-augmenting feature of the writhe configuration to achieve any amount of usable stroke and do so with remarkable success. This incredibly useful configuration allows creation of actuators from materials as common as nylon fishing line [23, 32].

Table 2. Direct comparison of whole actuating fabric morphologies, assuming comparable fiber diameters (qualitative evaluation scale: ++, +, −, − − from the highest to the lowest values). Upward and downward arrows indicate properties that are more favorable when high (▲) or when low (▼).

Geometry	Stroke length ▲	Pulling force ▲	Stiffness ▼	Strength ▲	Customizability ▲
Weave	− −	++	+	+	− −
Knit	++	− −	− −	−	−
Braid	−	+	++	++	+
Sew	− −	—	−	− −	++

Table 3. Standard yarn sizes and typical uses.

Size	Name	Diameter (mm)	Uses
0	Lace	0.64–0.85	Lace, thread
1	Super fine	0.85–1.81	Lace, socks
2	Fine	1.41–2.12	Baby clothes
3	Light	1.69–2.31	Normal clothing
4	Medium	2.12–2.82	Blankets, sweaters
5	Bulky	3.18–4.23	Scarves, rugs
6	Super bulky	4.23–5.08	Thick sweaters
7	Jumbo	N/A	Artisan designs

3.4. Hierarchical twist insertion

By progressively introducing additional levels of twist, coils, and writhes, groups of fibers can achieve a hierarchical geometrical structure (figure 2(e)). This results in a compounding effect that can be designed to increase both the effective strain and stress to even higher levels [35, 36]. Lima *et al* [37] explored a series of these hierarchical yarn configurations to maximize either contraction or torsion. As mentioned earlier, to achieve optimal contraction, the fiber must be constrained such that a minimal amount of overall unwinding occurs upon fiber volume expansion. This arrangement is formed by using a consistent winding direction for coils along the entire length of the fiber, as well as clipping both ends in some manner to prevent them from rotating .

4. Assembled fabric morphology

By leveraging existing fabric manufacturing methods, robotic fabrics can be made inexpensively and rapidly, easing the transition from foundational technology to mass-production and commercialization. Here, we present a brief overview of how this process might work (figures 2(j)–(q)). Responsive fibers are created through the appropriate process specific to that material, be it melt extrusion, wet drawing, coating of an inert fiber, or another method. Fibers may be relatively short, known as staple fibers, or may form long, continuous fibers, known as filament fibers [1]. These fibers can then be spun into a thicker thread or yarn; shorter fibers will be more difficult to spin together and result in a more 'hairy' yarn. The resulting yarn may be further spun to take advantage of twist insertion, coiling, writhes, or any combination of these depending on the desired properties, as discussed in section 3. A complete yarn can then be intertwined with other yarns in a particular pattern via weaving, knitting, braiding, or sewing. The manner in which individual actuating fibers are joined together into a fabric will have some impact on the performance of the actuators in aggregate. As with the geometry of a single fiber, different overall fabric structures will have distinct advantages and disadvantages. A qualitative summary is presented in table 2.

The feasibility of a particular pattern will also depend on the diameter of the fiber being used (table 3). Typical yarns are categorized into seven primary size ranges, the thickest of which, labeled 'super bulky', is approximately 4.23–5.08 mm in diameter. Larger fibers ('jumbo') are generally considered novelty yarns that are reserved for artisan textiles and may not be compatible with manufacturing machinery. Minimizing the fiber diameter will generally lead to greater flexibility in manufacturing. For instance, twisted nylon thread fibers [32] or carbon nanotube fibers [38] have been created at the 'lace' or 'super fine' thread size (<1 mm diameter) and could be threaded through a needle for sewing. Somewhat thicker fibers at the 'fine' or 'light' size could easily be woven or knitted, such as low-melting-point-material-core tubes [39]. A 'bulky' or larger fiber, such as a thick strand of acrylonitrile butadiene styrene (ABS) [27] or a jamming tube [40] may not feed properly through available machinery and would instead need to be affixed to a fabric base with a sewing machine.

4.1. Weaving

A weave is a pattern of crossing fibers, the warp and the weft, that alternately pass over and under one another, interlaced row by row as the fabric is created (figure 2(f)). This configuration is easy to produce and has been automated for centuries. The end effect is multiple aligned fibers cooperating in sum to amplify any forces linearly with the width of the section of cloth [41]. Additionally, thermally-responsive woven actuators have been used to increase actuation cycle speed by dissipating heat over a larger surface area than a single large fiber of similar cross-section [23]. The strain of actuation however is limited to that of a single fiber, since all fibers will experience a similar strain as they are pulled in parallel. One other drawback of this configuration is that the actuation is limited to one or two directions unless multiple layers of cloth are stacked upon each other.

More unique patterns can be generated by allowing the weft fibers to skip over a number of warp fibers before interlacing. Weaving demonstrates this in three main construction techniques; plain weaving, twill weaving and satin weaving (figure 2(q)). All other techniques are variations of these main techniques. A plain weave is formed by having each warp fibre pass alternately under and over each weft fiber, and will tend to be of higher strength. A twill weave instead has warp fibers weave over and under two or more weft fibers at a time, resulting in a diagonal pattern and a fabric that is slightly smoother to the touch and more pliable. In a satin weave, the warp fibers pass over four or more weft fibers before weaving under one weft fiber. This gives the fabric a very tight weave and an even, smooth sheen on one side and high pliability [42].

4.2. Knitting

A knit is a teardrop-shaped loop which extends on either side into legs that attach to other adjacent knit loops [43]. The fabric is built one row at a time by feeding new loops through loops in the previous rows, eventually forming a planar chain-like structure (figure 2(g)). This process can be semi- or fully automated by using a knitting machine, of which there are several varieties. Modern knitting machines typically consist of rows of hooks or needles which can be manipulated in sequence to produce knits of varying design. Larger needles can be chosen to handle thicker yarns as needed. Knitted fabrics are loose and highly extensible, thereby drastically increasing the overall stroke length of an actuating fabric. Additionally, a knitted fabric can be made of single continuous strand. In one application using SMA wire, a simple knit pattern produced a strain of 80% when activated [44]. By alternating the direction from which each loop is pulled through the previous one, front-to-back or back-to-front, the actuation response can be further tailored from a curling motion, to a contractile motion, to a buckling motion, or any combination of these.

4.3. Braiding

A braid is an interlacing of multiple fibers in which all strands lie approximately parallel with each other (figure 2(h)). As opposed to weaving, in which fibers cross in perpendicular groups to form a rectangular shape, a braid is generally long and narrow. Braids can be as simple as a flat three-strand ribbon, or become quite complex, involving many intertwining strands to form elegant three-dimensional patterns. A braided rope will generally be thicker but stronger than a simply twisted rope of the same material due to the mechanical interference of interlaced strands. Braiding machines are commonly used to produce fishing lines, rope, and power cable shielding. As such, they can be made to handle a variety of materials including both natural and synthetic yarns, and even metal wire. Modern braiding machines can be designed to produce varying braid styles, and some can be programmed to generate more complex and non-traditional shapes.

The nearly aligned nature of a braided structure benefits from the combined pulling force of multiple fibers in parallel. Without a perpendicular crossweave inhibiting the motion, braids are more flexible than weaves and can produce considerable force in the fiber direction. In thermally activated materials, braided actuators have been shown to have improved heat transfer, and therefore actuate more quickly while consuming less power, than weaves with the same number of parallel strands. By changing the number of fibers and the order of interlace, a braid can be tailored to a particular force and strain requirement as needed [45].

4.4. Sewing

Rather than serving as the base of the fabric structure itself, an active fiber can instead be sewn onto another fabric substrate. Sewing allows a robotic fabric to be manufactured with very specific actuation paths that would otherwise be impossible using weaving or knitting. A thick fiber can simply be placed onto the fabric substrate as desired, and a thinner inert needle thread can be used to sew it in place (figure 2(i)). This process, known as couching, has been used to affix thick actuating fibers by hand onto a commercial cloth [28], and has also been demonstrated with variable-stiffness fibers by first softening and bending them into a desired shape before sewing [27, 46]. However, sewing by hand is a time-consuming and inaccurate process, and is not scalable, particularly if a robotic fabric requires many fibers working together to generate sufficient force.

Table 4. Values for actuator fiber performance as found in the literature. Some values were not reported for every material, and some have been derived by the authors from other reported values. CNT = Carbon Nanotube, Twist = Twisted-bundle configuration, Coil = Untwisted coil configuration, Writhe = Writhe configuration, Knit = Knit of several fibers, X + X = Hierarchical combination of two configurations, * = Not explicitly reported in the literature but calculated or extrapolated by the authors from figures or other reported information. Upward and downward arrows indicate properties that are more favorable when high (▲) or when low (▼).

Material	Fiber geometry	Actuation stress [kPa]▲	Actuation Strain▲	Activation time [s]▼	Relaxation time [s]▼	Work density [J/kg]▲	Energy efficiency[a]▲	Cycle life[a]▲	Sources
Human skeletal muscle		100–500	30%	0.2–0.3	0.2–0.3	9.434	40%	$>10^9$	[3, 50]
Liquid crystal elastomers		280	35%	>60	>60	—	<10%	—	[51, 52]
Liquid crystal elastomers + CNT		280	35%	1	2	—	—	—	[51, 52]
Conductive polymer (polypyrrole)		34 000	2%	25	—	*95 240	<18%	500 000	[3]
Conductive polymer (polypyrrole-coated yarn)		92	0.4%	250	160	—	—	—	[41]
Shape-memory alloy (NiTi)		200 000	4%	2	10	*155	<16%	300 to 10^7	[3, 25, 53]
Shape memory alloy (NiTi)	Coil	46 800	50%	2	10	1226	—	—	[25, 53]
Shape memory alloy (NiTi)	Writhe	*46 800	75%	2	10	*1839	—	—	[25, 53]
Electromechanical CNT	Twist	10 000	2%	0.4	0.4	1100	< 10%	<5000	[54]
Electromechanical CNT	Twist + Twist	19 000	—	0.5	0.2	*4.85	—	—	[55]
Electromechanical CNT	Twist + Writhe	1600	14%	0.2	—	2200	<5.4%	<3000	[56]
Paraffin-infiltrated CNT	Twist	14 500	10%	0.05	2.5	836	—	—	[37]
Nylon		—	4%	—	—	—	<1%	1.2×10^6	[23]
Nylon	Writhe	19 000	34%	2	15	2480	<1%	1.2×10^6	[23]
Polyethylene		—	0.3%	—	—	—	<1%	—	[23]
Polyethylene	Writhe	—	16%	—	—	2630	<1%	—	[23]
PET		2160	8.9%	—	—	—	—	—	[57]
Spandex		—	14%	—	—	—	—	—	[58]
Spandex	Twist + Writhe	1904	45%	—	—	1523	—	—	[58]
Spandex + CNT	Twist + Knit	16 000	25%	1 s	1 s	650	3.2%	>10 000	[59]
Shape-memory polymer (cold-drawn)		2000	600%	10	N/A	—	—	—	[60]
Dielectric elastomer		720	7%	<1	<1	*2800	<90%	10^6	[61]

[a] Values for Energy Efficiency and Cycle Life are gathered from the work by Mirvakili and Hunter [6].

It is also possible to affix a fiber by sewing machine. The thick fiber can be run through the bobbin [47], which will minimize the bending required and allow for 'bulky' fibers (4 mm) or irregularly shaped fibers to be used [48]. This method can easily generate simple straight lines. Alternatively, the fiber can be fed into the machine and used as the needle thread. This does, however, place some limitations on the fiber properties. To feed properly through a normal sewing machine, the fiber must have a consistent diameter, resist elongation, be flexible enough to form small loops, and be torque-free to avoid tangles or kinks [49]. This naturally means that many fibers, particularly those which are easily stretched or are overtwisted may not be suitable.

5. Actuating fibers

A wide variety of materials exist that will respond to a stimulus by changing in shape or size, which can be harnessed to generate motion in a fabric. These materials often have tradeoffs in performance, excelling in certain aspects while another material might perform better in a different area. As such, some key metrics are important when comparing the effectiveness of actuating fibers and will be briefly summarized here. It should be noted that some other important characteristics, including stress relaxation, creep, and density, are not consistently characterized or reported throughout the literature to derive a meaningful comparison, and so will not be included here for compactness of presentation. A summary of these materials is collected in table 4.

Actuation Strain. The majority of actuating fibers operate under a principle of contraction to generate an actuation stroke. In this review, all stroke lengths will be reported in terms of tensile strain as a percentage of the original fiber length.

Actuation Stress. As a fiber contracts, the force of actuation generally is not constant and changes over the duration of the stroke. However, the maximum stress can be assumed to be the smaller of the ultimate tensile strength or the product of the maximum strain and the stiffness. In this review, all actuating forces have been normalized to an actuation stress based on the outer diameter of the actuator to accommodate any unusual fiber surface geometries due to coiling or twisting of filaments. This reported value will be the blocking stress if available, or the highest reported stress otherwise.

Actuation Energy Density. As an addendum to the actuation stress and strain, this value reports the total amount of work performed per actuator unit mass or volume by a typical actuation stroke. This information serves to reveal some less-effective materials that may, for example, pull exceptionally heavy loads but only negligible distances.

Actuation and Relaxation Time. An important factor in actuation is the amount of time not only to actuate, but also to return to the unactuated state. For instance, an actuator may demonstrate a reasonably rapid contraction time, but reliance on thermal sensitivity in the material could result in a long cooling time, often on the order of tens of minutes, rendering the initial burst of speed much less useful. In this review, the relaxation time will be reported for room temperature in air, if available.

Energy Efficiency. In a robotic fabric system, any energy expenditure will require some power source. An on-board battery will have a limited supply, making low-energy systems very attractive. This value will be reported as a ratio of output work to input energy.

Cycle Life. Some materials require intense energy to activate the actuation mechanism, and therefore degrade quickly. As such, we have listed the largest reported number of cycles for each material.

A robotic fabric relies upon very small-scale actuators. In the case of actuating fibers, this size restriction greatly limits the potential force generation, as output force scales positively with actuator cross-section. However, power output, or speed of actuation, increases at smaller dimensions (faster mass/heat transfer, or higher surface area/volume ratios). Below, we list a series of materials which are able to provide motion by exploiting various physical phenomena.

5.1. Human muscle (benchmark)

Human muscle experiences a contracting strain of approximately 25%–30%, with a maximum actuating stress of 350 kPa, although sustained force is about 30% of the peak value [50]. This results in an energy density of about 9.43 J kg^{-1}, or 10 kJ m^{-3}. Human muscle is also extremely fast-acting, allowing both contraction and relaxation times of approximately 0.2–0.3 ms. It is also very robust, allowing on the order of 10^9 cycles before failure due to the live tissue continuously regenerating itself [50, 52, 62, 63]. In general, most artificial actuating fibers are able to greatly surpass human muscle in terms of pulling stress; the limiting factors are stroke length and speed of actuation.

5.2. Aligned amorphous polymers

Some polymer products, such as fishing line, are known for their high strength-to-weight ratio. This is partially due to the polymer chains being highly aligned in the direction of stress. Some polymers of this type have regions

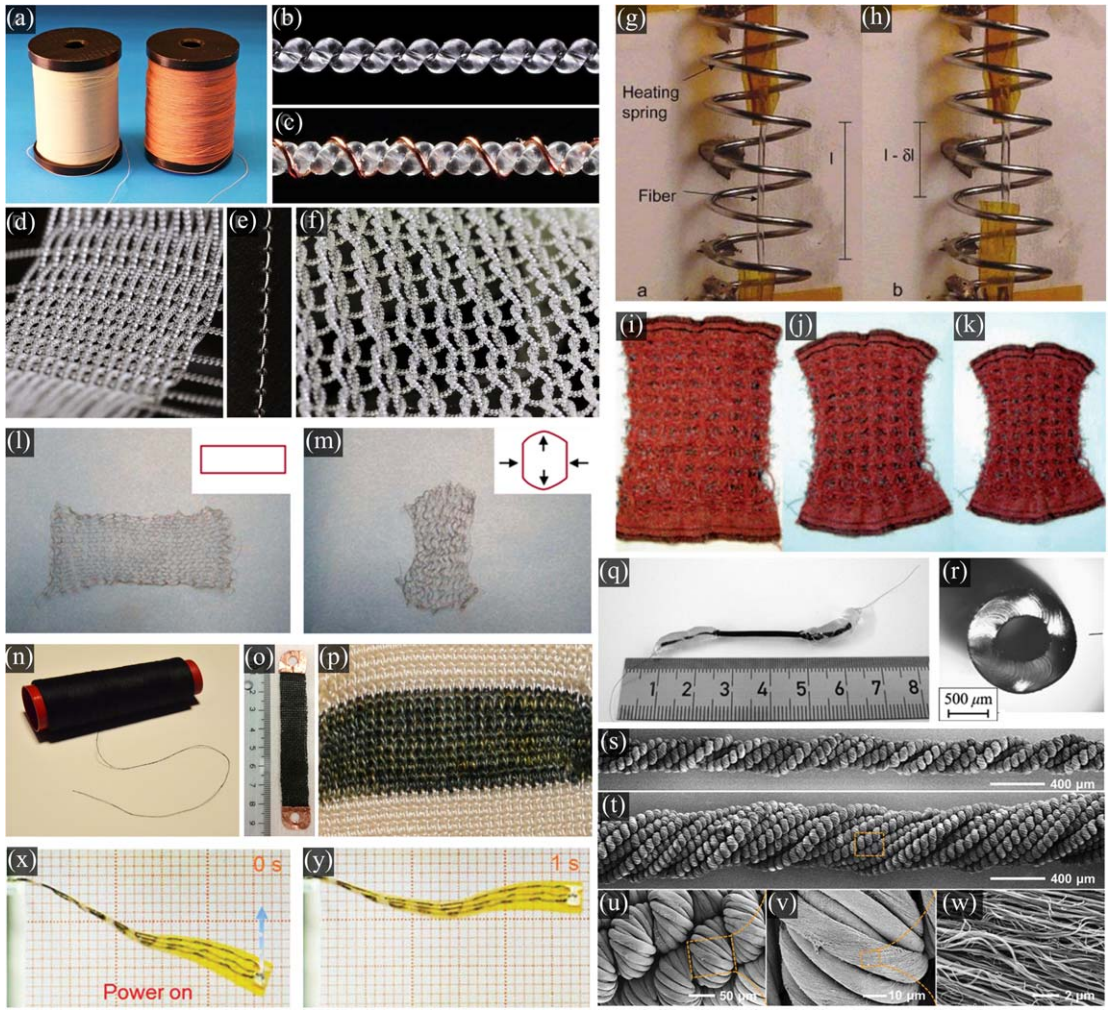

Figure 3. (a)–(f) Aligned amorphous polymer threads coiled into actuators and placed into fabrics. (a) A spool of coiled muscle (235 μm outer diameter) made from 125 μm-diameter nylon 6/6 monofilament sewing thread by a continuous process, which has been prestretched to provide space between coils for actuation, and the same fiber with an insulated copper wire wrap for electrothermal actuation, without prestretch, pictured on the Left and Right, respectively. (b), (c) Closeup photographs of the fibers in A. (d) Woven fabric made from coiled, 225 μm-diameter nylon sewing thread muscle. (e) Stitches made by sewing the coiled fiber into a polymer sheet using a conventional sewing machine. (f) Machine-knitted fabric made from a coiled 225 μm-diameter nylon sewing thread muscle. (g) Liquid crystal elastomer fiber. (h) Fiber contraction due to collapse of mesogen alignment. Fiber warmed with a heating coil to lift a load. (i)–(k) Shape memory recovery of SMP composite loosely woven fabric with SMP yarns at 50 °C with recovery times (i) 0 s, (j) 30 s and (k) 60 s. (l), (m) SMA in a knit pattern. (l) The flat elongated prototype in the cold martensite state and (m) the contracted prototype in the hot austenite state. (n)–(p) Cellulose-based threads coated with CP polypyrrole for actuation. (n) A bobbin with industrially manufactured CP-coated yarn. (o) A knitted actuator unit. (p) A knitwear structure comprising conductive polymer-coated yarns (black yarn) knitted together with normal (white) yarn. (q), (r) Dielectric elastomer fiber created by dip-coating a string. (q) A typical specimen. (r) Cross-section of an actuator with one layer. (s-w) Carbon nanotube fibers joined together by a twist and writhe hierarchical configuration. (s) 5 and (t) 20-ply twisted actuators. (u)–(w) Enlarged images of (t). (x), (y) Electromechanical bending motion generated by sewing carbon nanotube fibers into Kapton ribbon upon applying a pulsed current. (a)–(f) Reproduced with permission [32]. Copyright 2016, National Academy of Sciences. (g), (h) Reproduced with permission [51]. Copyright 2003, American Chemical Society. (i)–(k) Reproduced with permission [65]. Copyright 2007, Sage Publications. (l), (m) Reproduced with permission [44]. Copyright 2013, IOP Publishing. (n)–(p) Reproduced with permission [41]. Copyright 2017 The Authors, some rights reserved; exclusive licensee American Association for the Advancement of Science. Distributed under a Creative Commons Attribution NonCommercial License 4.0 (CC BY-NC). (q-r) Reproduced with permission [61]. Copyright 2010, Springer Nature. (s-y) Reproduced with permission [46]. Copyright 2015, Wiley.

of amorphous structure, allowing individual chains some freedom of movement. When exposed to heat, these 'loose' chains are able to slide past each other into a more entropically favorable conformation, generally resulting in an overall reduction in length in the direction of polymer alignment, with a slight expansion in the perpendicular direction correlated to Poisson's ratio [64]. Several materials exhibit this behavior to differing degrees. In general, high-modulus materials will provide high pulling forces yet experience very little contraction. Drawn polyethelyne, for example, experiences a very small thermal contraction of only 0.3%, yet has been successfully fabricated into an actuating fiber capable of extremely high pulling stresses, up to 190 MPa

when made into a writhe [23]. Twisted polyethylene terephthalate (PET) yarns on the other hand could reach a contraction of 8.9%, but with a pulling stress of only ~2.16 MPa [57].

Nylon is becoming popular as another such material that, in addition to being very inexpensive and readily available as commercial fibers in the form of fishing line or nylon sewing thread, experiences contraction on par with SMA, as high as 4% [23]. By taking advantage of writhe geometry, Haines *et al* developed intertwined fiber actuators with an impressive 34% contraction and 19 MPa pulling stress (based on the coil diameter) with an actuation cycle time of 17 s in air [23]. Increasing the diameter of the coils led to a stroke length of up to 49% at the expense of pulling force (figures 3(a)–(f)).

One new promising fiber actuator uses Spandex as its core material. Spandex fibers experience a contraction of about 14% at approximately 130 °C, compared to the 4% contraction of nylon 6,6 at 240 °C [58]. With the further benefit of a twisted-bundle/writhe configuration, the Spandex actuator was able to reach a maximum of 45% contraction, with 0.758 MPa pulling stress (extrapolated from the data). However, cycle times are upwards of 160 s in air due to long cooling times [58]. An alternative approach involves spinning carbon nanotube thread and Spandex together, and then knitting the resulting twisted fiber into a thin mesh tube only 1.7 mm in diameter, rather than using a monolithic coil. The resulting long knitted tube can be actuated by Joule heating at temperatures as low as 70 °C, and requires only 7.5 s to complete an actuation cycle. This mesh has a blocking force of about 16 MPa, and can contract up to 25% [59].

One difficulty in working with amorphous polymer actuators is the need for precise temperature control. Thermal contraction for nylon 6,6 requires rather high temperatures around 240 °C [23], yet melting occurs at only 265 °C, putting the fiber in danger of rapid degradation. Some more stable methods of temperature control via Joule heating have used a conductive wrapping of carbon nanotube sheets [66], and coating with conductive silver paint [34]. Electroless metal plating of aluminum [67], copper [68], silver [69], or gold [70] could also be options to enable thermal activation by Joule heating.

5.3. Liquid crystal elastomers

Liquid Crystal (LC) materials are so-called because, in addition to a solid and liquid state, they have a unique intermediary phase with behavior somewhere in between. This secondary phase is enabled by the interactions of large, rod- or disk-like monomers, known as mesogens [71], attached to the polymer chains. When cooled to the solid state, these rods are aligned in a regular crystal. With the gradual addition of heat, the material enters the secondary nematic phase, wherein the mesogens become somewhat dislodged from their rigid crystal structure, but are still generally oriented in the same direction. Upon further heating, the mesogens are more and more free to completely reorient themselves, and the material begins to approach something more akin to an isotropic liquid phase. A strand of Liquid Crystal polymer at this stage will experience a contractile force along its length as the unaligned mesogens are able to collapse upon themselves into a tighter conformation. This contractile response can be excited by direct application of heat, or indirectly due to exposure to light [52, 72], electrical fields, pH changes, or other stimuli [73].

Liquid Crystal polymers are classified into three major network topologies. Liquid Crystal Polymers (LCP) contain the mesogens within the polymer chain backbone itself, and have found use as high-performance, high-modulus polymers, such as Kevlar or Vectra, and undergo very little contraction when stimulated. Liquid Crystal Networks (LCN) are highly crosslinked polymers that retain some of the high-performing properties of LCPs, but also experience a moderate amount of thermal expansion when stimulated. Due to the anisotropy of the aligned mesogens in the network, this expansion can be directed along a particular axis or curve, although the degree of crosslinking limits this motion. Liquid Crystal Elastomers (LCE) are a subset of LCNs, where the degree of crosslinking is minimal, allowing the polymer backbone to become more flexible and the bulk material to behave like an elastomer. LCEs exhibit the greatest degree of contraction due to the large changes in mesogen alignment order that are possible. Upon actuation, The loose polymer chain structure will primarily collapse along the single axis of initial mesogen alignment, leading to much larger strains than a typical polymer would experience [73].

Of the Liquid Crystal topologies, only LCEs show real promise as fiber actuators, since they exhibit the greatest amount of strain. LCE material can also easily be formed into a fiber. After combining the necessary polymer components and waiting for the mixture to begin crosslinking, a pair of tweezers are dipped into the mixture and pulled away as quickly as possible, generating a long strand. These strands can then be set aside to finish the curing process [51], after which they can be integrated into a fabric.

A highly deformable LCE fiber has been developed that, when warmed inside of a heating coil, experiences up to 35% strain and 280 kPa of blocking stress [51] (figures 3(g), (h)). The limiting factor for actuation time is efficient dispersion of heat into the fiber from the external source. Doping with conductive particles such as graphite [52] or carbon nanotubes [51] has been shown to decrease this response time from 60 s in some cases to less than 1 or 2 s.

5.4. Shape memory polymers

A shape memory polymer (SMP) contains a high degree of chemical crosslinking. When heated, the polymer reaches a viscoelastic state where it can be easily deformed and if held in place, the polymer will maintain the new configuration upon cooling. The crosslinks then act like stretched springs, ready to pull the polymer back into its original shape once it is heated again and free to move. The recovery stress from this return to the original shape can be employed as an actuation mechanism.

As with other polymers, SMPs can easily be manufactured into long fabric-ready fibers via wet-spinning [74] or extrusion [65], and have already been utilized as a woven fabric component, often as self-unwrinkling mechanism in clothing [75] (figures 3(i)–(k)). SMP fibers have also been woven into fabrics for use as 'smart curtains' that open or close depending on incident heat from the Sun [65]. In some early experiments, polyurethane block copolymers were spun into fibers and found to exhibit a strong shape memory effects. A fiber stretched to 65% elongation strain was able to recover all but 10% strain with a maximum recovery stress of 11 MPa, although recovery time was not provided [74].

Recently, very high-strain SMPs have been developed. Fibers of this material can be stretched to 600% of the initial length and, with enough time, fully recover this length. Furthermore, this recovery can be accomplished using relatively low contact heat from the human body. A fully stretched fiber can pull with a stress of more than 2 MPa, although this stress tapers off approximately linearly toward zero as the fiber returns to its original length [60].

Overall, SMPs seem promising for the amount of strain and recovery stress they deliver. One downside, however, is that the shape memory effect is limited to one stroke until an external force is applied to deform the SMP again; an SMP will not naturally spring back into an 'unactuated' state. This necessitates the use of some other antagonistic actuator which must fight the contraction force to 'reload' the SMP fiber for the next stroke or cold-draw the fiber while it is cooled [60].

5.5. Shape memory alloys

Shape memory alloys (SMA) are metals which experience a change of atomic lattice structure when heated above some transition temperature. In the low-temperature martensite state, the metal is arranged in a face-centered tetragonal lattice. When heated to the austenite state, the lattice rearranges into the slightly more dense body-centered cubic lattice [3]. One of the most popular SMAs, nickel-titanium, also known as Nitinol, experiences a 4% reduction in length during this transition, which can be used as an actuating mechanism [25] (figures 3(l), (m)).

Beyond this base change of length, however, SMA actuators can be made much more effective by coiling SMA wire into a spring. This makes use of the property that an SMA wire in the hot austenitic state has a spring constant that is 2-3 times higher than that of the same spring in the martensitic state [25]. To avoid the coil returning to its original straight wire configuration, the SMA can be annealed at a high temperature, setting a new 'default' shape for the martensite phase.

In a typical actuation cycle, the NiTi coil begins in the cool martensitic state and is stretched with an initial load. The coil is then heated until the austenite transition activates, at which point the spring constant increases, and the actuator retracts until the load and higher internal spring force are balanced. Due to their high electrical resistance, SMA actuators can be heated to the austenite transition state by simple application of electrical current which causes Joule heating. This affords a very easily controlled system since no external heat source is required.

As a straight wire, SMA can provide considerable blocking stress, up to 200 MPa, although with the limitation of only 4% strain. However, when formed into a coil, SMA wire can provide considerable strain in exchange for some pulling force; careful control of the annealing temperature can result in SMA springs with 50% contraction while still pulling with an impressive 46.8 MPa stress [3]. What's more, a coil can be further transformed by pulling it 'inside-out' into a writhe-like formation. The added internal torsional strain in the wire results in not only an increased stroke length and actuation stress, but also helps the actuator pull its load the full stroke length [25].

SMA unfortunately suffers from at least two problems. The first, as typical of any thermally responsive actuator, is the long cooling times. Submersion in water has proven effective, allowing millisecond actuation cycles, however this is not always practical. Other methods have involved lagging the wire with thermally conductive paste with some success, reducing cooling times from 10 s to less than 2 s [53]. The second issue, perhaps more severe, is the rather quick degradation of the actuators. After only hundreds or even tens of actuation cycles, the austenitic 'activated' position can begin to deteriorate, resulting in shorter and shorter strains, until the SMA is re-annealed [3].

5.6. Conductive polymers

Conductive polymers (CP) are an unusual group of materials that have a molecular chain structure and mechanical properties typical of polymers, yet possess surprisingly high electrical conductivity, on par with metals (copper). A conductive polymer is designed such that the backbone consists of alternating sigma and pi bonds, which leaves open orbital positions for electrons to flow from atom to atom along the length of the chain. This conductivity in a polymer is interesting in itself, but it can also be leveraged to produce motion. Given a supply of ions, such as an electrolyte bath [63], a voltage differential can be applied to a strand of CP, which creates either a lack or abundance of electrons at the orbital sites. Ions flow in or out of the polymer matrix to balance the charge, creating a net volume change, and thus motion. There may also be some amount of motion due to absorption of solvent, as well as rearrangement of the polymer chains to accommodate the flux of ions [3].

One major drawback of this system is the need for an ion reservoir. While most demonstrations have taken place in the presence of a liquid electrolyte solution, there have been some more recent attempts to incorporate a layer of electrolyte into a multilayer system, such that the device can perform in open air. These multilayer CP actuators tend to provide only bending motion as one outer layer swells with ions and the opposite side loses them, but some limited progress has been made toward the development of linear, open-air CP actuators [76, 77]. This reliance on ion exchange also means that the actuation times are highly dependent on the surface-area-to-volume ratio of the actuator; a thick fiber can take several minutes to fully actuate, but a film or bundle of thinner fibers may require only a few seconds [78]. CP actuators have been successfully formed into woven and knitted fabrics by taking an existing cloth made from cellulose-based yarns and coating it with an active CP layer. This method allowed the designers to forgo the process of weaving or knitting the CP directly as a fiber [41] (figures 3(n)–(p)).

CP fiber actuators have consistently demonstrated high stress outputs, typically on the order of 5 MPa, and even as high as 35 MPa [3]. The voltages required for actuation are also typically very low, only requiring 1–2 V, although higher voltages will speed actuation times [3, 79]. As a CP actuator approaches equilibrium with its load, it has also been reported the current flow also tapers off toward zero. Thus a catch state is available, with essentially no energy being expended in order to maintain a constant force [3]. Despite these advantages, CP actuators suffer from very small strains, typically on the order of 1%–2% [78]. Some research has reported strains has high as 30% [80], however this capability quickly degrades, losing half its actuation length after only 10 cycles.

5.7. Dielectric elastomers

When a thin, dielectric elastomer film is coated on both sides with a stretchable electrode material such as carbon grease, it can be made to act as a parallel plate capacitor. By applying a high voltage across the two electrodes, the two sides are drawn together, compressing the film in one direction and expanding in the other two, providing an actuation mechanism [81]. Actuation cycles can be extremely rapid for such films since the motion is only dependent on the presence or absence of an electric field. Dielectric elastomers can be rolled up or manufactured directly into a tube to achieve a fiber-like structure [82, 83].

As an extending rather than contracting actuator, dielectric elastomers are often used antagonistically with other mechanisms [84]. While dielectric elastomers in general have demonstrated extremely high extending stroke length (215%), and even respectable actuation pressure (2 MPa) [81], they require extremely high voltages, on the order of kilovolts, which can be difficult to control as well as dangerous. Dielectric actuators also run the risk of self-destruction; if the spacing between electrodes becomes small enough, the dielectric filler can evaporate at that point, causing the opposing electrodes to be shorted together [5].

A few attempts have been made at incorporating dielectric elastomers into a thin fiber-like form factor. One method simply uses a hollow, 0.9 mm-diameter, elastomer tube filled with conductive silver grease, and an outer coating of carbon-black-embedded elastomer, forming inner and outer electrodes. Silicone tubes reached extensions of 7% and blocking stress of 0.24 MPa, while polyurethane tubes reached strains of only 0.6%, but blocking stresses of 0.82 MPa [85]. Another approach involves repeatedly dip-coating the fiber in alternating conducting and non-conducting blends of poly-styrene-ethylene-butylene-styrene (SEBS) and carbon black, resulting in a multilayer, coaxial fiber 0.4 mm in diameter. This approach had similar results as the previously mentioned case, about 7% elongation and reported actuating stress of 0.72 MPa. It was noted that by using many thin layers rather than one large layer, the activation voltage could be lowered, and it is surmised that with layers of 30–40 um, actuators requiring fewer than 1000 volts could be made [61] (figures 3(q), (r)). One group has made use of twist insertion to create a dielectric elastomer actuator that actually generates a contracting stroke, although with electric fields upwards of 10.3 million volts per meter (MV/m) of dielectric thickness, and, with an observed maximum contraction of only 4.3% [86].

5.8. Carbon nanotube fibers

Carbon nanotubes have been the focus of a flurry of innovation in recent years. They exhibit extraordinary tensile strength, as well as high electrical conductivity [55]. Carbon nanotubes can be deposited into other materials to create a composite with enhanced properties, such as increased stiffness, resistance to fracture, and conductivity.

Interestingly, recent developments have provided a method of spinning forests of grown carbon nanotubes into pure carbon nanotube aggregate fibers, similar to how cotton strands are spun into twisted threads. This breakthrough allows the handling of these microscopic particles on a macroscale as a visible yarn. These carbon nanotube yarns are extremely strong in tension and retain electrical conductivity on par with metals, yet can be woven and threaded like any other soft, flexible fabric material [54].

Multiple strategies have been developed to exploit these new carbon nanotube fibers as actuators, the first of which utilizes a guest material infiltrated into the gaps between spun threads. One promising example of this uses paraffin wax, which is chosen for its widely customizable state transition temperature, ability to easily wet the nanotube fibers, and large volume changes at it heated. By Joule heating the fiber with application of electrical current, the infiltrated fiber quickly warms and expands, inducing linear contraction and untwisting. Wax-infiltrated actuators of this type demonstrate strains between 5.1% and 10%, with 16.4 MPa stress and 5.5 MPa stress, respectively. Experiments with microscale threads show very fast heating and cooling cycles, for instance a 20 μm-diameter thread can heat in 15 ms and cool in 25 ms, although any increase in diameter to raise pulling force will increase those times. A 150 μm-diameter thread increased the cooling time to 2.5 s, while heating time remained at only 50 ms [37].

Another strategy uses bare carbon nanotube thread without any guest material. In this case, the actuation is driven by electromagnetic force between individual carbon nanotube strands rather than thermal expansion of an interstitial material. By applying a small amount of current to a twisted carbon nanotube thread composed of many small strands, Ampere's Law states that current flow in parallel wires will cause magnetic attraction between adjacent fibers, resulting in a net torsion and contraction of the fiber. The helical twist angle can be optimized to further amplify the contraction and torsional effects (between 20° and 50°). In general, increasing twist leads to higher contractions, although with bare CNT strands too sharp of an angle forces strands closer to each other, causing current to short between strands rather than flow in parallel and reducing the effect of Ampere's Law. In a simple single-ply fiber (meaning only one level of fibers are twisted together), a linear contraction of about 2% is found, with a pulling stress of about 10 MPa [56]. Winding multiple fibers together in a multi-ply yarn, as well as taking advantage of overtwisting into writhes, can greatly enhance the actuation stroke, reaching up to 14% strain at a reduction to 1.6 MPa of pulling stress [38] (figures 3(s)–(y)). Since this method of actuation does not rely on the transfer of heat as many others do, it has extremely fast actuation times, on the order of 200 ms for both contraction and elongation.

6. Structural stiffness control

Generating motion is only one half of the solution toward effective actuation in flexible robots. A soft robot may be capable of force generation, but the effectiveness of this motion is weakened without a supporting structure to guide and stabilize it. The possibility of decoupling actuation and structure control, then, becomes very intriguing in the context of robotic fabrics. Looking again to the example of human muscle fibers, I W Hunter and S Lafontaine state that stiffness control is one of the most important features of skeletal muscle; since it can effectively only generate tensile forces, it is necessary to have an opposing force to extend the muscle after contraction, usually achieved by having opposing muscles around a joint [50]. The stiffness of the joint can be varied by the nervous system independently of the torque generated by the limb via co-contraction of the opposing muscles. It is the ability of the nervous system to independently set limb force and stiffness that gives rise to much of a limb's mechanical versatility [50]. It should be noted that in a human, this stiffness change occurs on the level of the limb, but not on the single fiber level. A mechanical joint is already in place in the bone structure, about which the antagonistic muscles can contract. In a robotic fabric, this is not the case. Decoupled stiffness and actuation becomes even more critical because a soft robotic fabric may not have defined skeleton or any supporting structure. The capacity to selectively generate joints and bones of varying stiffness not only provides a supportive structure for load handling, but also serves to shape the paths of actuation. Reducing the degrees of freedom in this way can also help to simplify the complicated problem of control of soft robots, which arises due to the nonlinearities of flexible materials.

Below, we present a summary of some key metrics that are important to variable-stiffness materials. A summary of these materials is collected in table 5.

Table 5. Values for variable-stiffness fiber performance as found in the literature. Some values were not reported for every material, and some have been derived by the author from other reported values. ABS = acrylonitrile butadiene styrene, PLA = polylactic acid, LMPA = Low Melting Point Alloy. * = Not explicitly reported in the literature but calculated or extrapolated by the author from figures or other reported information. Upward and downward arrows indicate properties that are more favorable when high (▲) or when low (▼).

Method	Hard modulus [MPa] ▲	Soft modulus [MPa] ▼	Stiffness ratio ▲	Softening yime ▼	Stiffening time ▼	Max strength [MPa] ▲	Sources
Human skeletal muscle (single fibers)	50	10	5	~1 s	~1 s	—	[3, 87]
Phase-change polymers (ABS)	820	160	5.1	15 s	*Minutes	44.8	[27]
Phase-change polymers (PLA)	5100	3800	1.3	15 s	*Minutes	57.8	[27]
LMPA (field's metal)	888	1.2	740	*10 s	*Minutes	*6.5	[39]
Thermally sensitive Elastomer (propylene-ethylene)	37	1.5	24.7	6 s	*Minutes	—	[87]
Coil collision	*1000	*41	24	*2 s	*15 s	—	[23]
Layer jamming (flat polypropylene sheets)	*100 000	*1000	100	<1 s	<1 s	32	[88]
Layer jamming (rolled mylar tube)	*930	—	—	*<1 s	*<1 s	—	[40]
Weave friction	—	—	—	*<1 s	*<1 s	—	[89]
Tendon jamming	*7855	*150	50	*<1 s	*<1 s	—	[90]

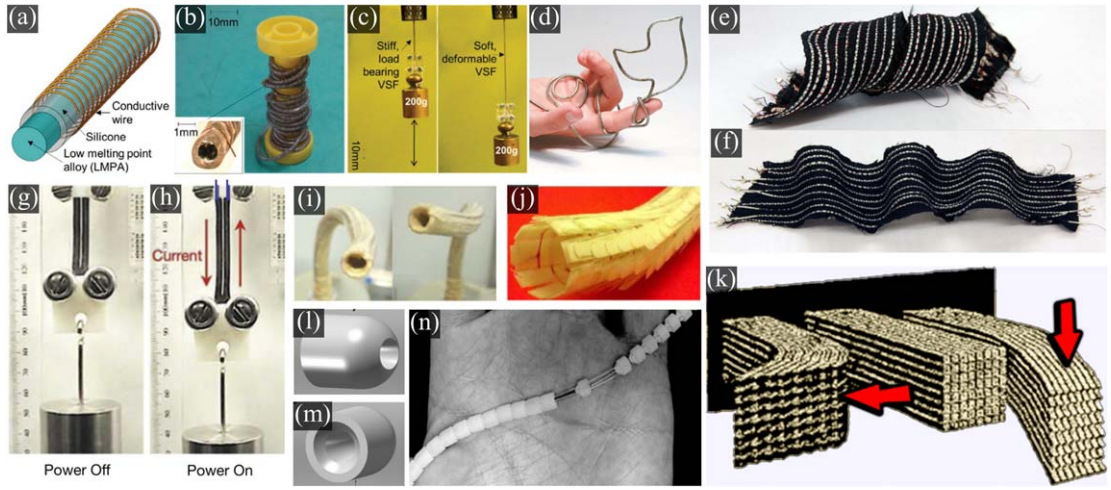

Figure 4. (a)–(d) Variable-stiffness low melting point alloy tube woven into a cotton fabric. (a) Schematic representation of the three components: LMPM core, silicone encapsulation, and conductive heating wire. (b) Manufactured LMPM-core wire with outer diameter of 1 mm. (c) Variable-stiffness fiber loaded with a 200 g load. Left: in the solid state, the fiber sustains the load; right: when current is applied and the metal melts, the fiber deforms under the load. (d) An example custom rigid shape held by the the LMPM fiber. (e), (f) PLA thermoplastic fibers sewn into a section of fabric for stiffness control. (g), (h) A conductive elastomer composite that, when activated with electrical current, rapidly and reversibly softens to 1%–10% of its initial elastic rigidity, shown with power on (g) and off (h). (i), (j) Closeup view of tubular shape of device with a large, central hollow section for tool passage shown on the left side (i), and the layer jamming scales shown on the right side (j). (k) Many wires bound together in an enclosed in an airtight chamber. Because of its structure, this element can bend in two directions and hold its position when vacuum is applied. (l)–(n) Modular tension-bead design prototyped via 3D printing. (l), (m) Body beads are composed of spherical bearing surfaces to enable friction locking and a hole to allow control wires to pass through. (n) A large 6:1 mockup of the assembled tension-bead structure. (a)–(d) Reproduced with permission [39]. Copyright 2016, Wiley. (e), (f) Reproduced with permission [46]. Copyright 2014, IEEE. (g), (h) Reproduced with permission [87]. Copyright 2015, IOP Publishing. (i), (j) Reproduced with permission [94]. Copyright 2013, IEEE. (k) Reproduced and adapted with permission [88]. Copyright 2002, IEEE. (l)–(n) Reproduced with permission [95]. Copyright 2010, IEEE.

Elastic Modulus in Hard and Soft States. The effectiveness of variable-stiffness materials is largely determined by the stiffness ratio between the softened and stiffened states. A larger change means that the material is able to bear a respectable load when rigid without sacrificing the ease of reshaping the device when soft.

Hard-to-Soft Cycle Time. A variable-stiffness material's transition time between hard and soft states is often a concern when working in tandem with actuators. Transition times will be reported for materials and systems operating at room temperature in air, if available.

Maximum Strength. As a structural component, a variable-stiffness material must be able to support some degree of load before failure. A very rigid element is not effective if it is also prone to fracture.

6.1. Human muscle (benchmark)

As individual skeletal muscle fibers contract, they have been recorded to reach a stiffness change of 5–10 times, from approximately 10 MPa to 50 MPa when flexed [50]. However, this value is much smaller than the typical observation of a live subject. Whole muscle may experience some additional stiffening due to pressure from adjacent fibers during contraction as they expand radially. However, the largest stiffness gains are apparent on the level of an entire limb. When placed antagonistically about a common joint, the stiffness of opposing muscles is added together as they contract simultaneously. With this in mind, human skeletal muscle is able to change the stiffness about a joint by a factor of approximately 50, which is used to enhance control and tune force output [91].

6.2. Low melting point materials

Melting is one obvious way to achieve very large stiffness changes in a structure. Several low melting point metallic alloys and polymers have been discovered that, as solids, are extremely rigid at room temperature, but become liquid with only a small application of heat. As such, low melting point materials (LMPM) have already been used in a variety of ways in an attempt to create variable-stiffness components [92].

One drawback is the need to somehow contain the liquid material. When melted, the risk of leaking can be detrimental to the functionality of the device. Another problem is the cooling time; if a material has been melted to allow motion, holding the new position while the material slowly returns to the rigid state requires a continuous expenditure of energy. Without some method of active cooling, such as air or water flow to convectively absorb heat, these materials can take several minutes before becoming solid again [93].

For use as a fiber, molten metal can be inserted into a small-diameter silicone tube by suction. Coils of resistive heating wire are wrapped along the length of the tube, providing a method of electrically heating the metal. This metal-core fiber can be made long and thin, and when heated becomes perfectly flexible so as to be woven into fabric as in one demonstration (figures 4(a)–(d). By pre-stretching the elastomer tube as the metal is inserted, it accumulates a restorative spring force, whereby it can pull any disjointed segments of metal that may have broken apart back together into one solid continuum, self-healing the next time the metal is melted. These devices experienced a 700× change in stiffness from 888 MPa to about 1.2 MPa when melted [39]. Similar core-sheath fibers have been developed using a polymer blend as the phase-change material [96].

LMPMs can also be incorporated into an existing fabric by various means, such as coating via wetting [97], thin film lamination [98], or bonding small microencapsulated particles to the fabric surface [99]. By applying the material to a pre-made fabric, much of the complexity involved in manufacturing directly with variable-stiffness fibers can be avoided, such as maintaining the 'soft' state so as to feed properly through a machine. However, these above applications were designed for uses other than structural control, and so did not report on the stiffness-changing behavior.

6.3. Glass-transition polymers

There are many commercial polymers available that exhibit stiffness change at low temperatures (∼30–100C). Unlike metals which undergo a sharp solid-liquid phase transition, these polymers undergo a glass transition, softening gradually over a wider temperature range from a glassy to a rubbery state due to greater mobility of the constituent polymer chains. In practice, thermoplastic polymers can be used as variable-stiffness materials by heating the polymer slightly beyond the glass transition temperature, stopping the heating process before the material reaches a polymer melt state and flows like a viscous liquid. Alternatively, thermoset polymers can also be exploited for their glass-transition behavior, but will not melt into a liquid-like state due to the crosslinks joining the polymer chains together, keeping the material a solid.

Strands of polymer have already been sewn onto existing cloth for use as a variable-stiffness structure (figures 4(e), (f)). These strands consist of a resistive Nitinol wire coated with polylactic acid (PLA) polymer, which can be softened by Joule heating through the wire. This variable-stiffness fiber experienced a change in stiffness in about 15 s [46]. Later work made use of the Nitinol SMA wire as an integrated actuation element. A combined fiber of PLA or ABS and a Nitinol coil experienced changes in stiffness of about 5.1 GPa to 3.8 GPa, and 820 MPa to 160 MPa respectively. In open air, these fibers required approximately 5 minutes to fully cool to a rigid state [27].

As with low melting point materials, this method suffers from long cooling times. Additionally, since the material does not fully melt, the change in stiffness is comparatively low; either there is still some significant level of flexure occurring even in the rigid state (ABS), or the soft state is perhaps not compliant enough to be used in certain applications (PLA).

6.4. Thermally sensitive elastomers

Expanding on the idea of softening polymers, one variable-stiffness method makes use of carbon-black particle additives to induce conductivity into a propylene-ethylene elastomer. The elastomer can then be cut into narrow strips to be used as a variable-stiffness fiber. By applying 150 volts to the elastomer, it becomes warm by Joule heating and softens from 37 MPa to 1.5 MPa in about 6 s (figures 4(g), (h)). Again, no cooling time is given, but this is assumed to take several minutes. In the stiff state, the material is still rather flexible - on par with leather; in the soft state it is comparable to human skin. Rather than being used as a load-bearing structure, staggered segments of the material can be activated and deactivated to guide the motion of any actuators by promoting bending in one area more than in others [87].

6.5. Jamming

A stack of overlapping thin sheets of material that are normally able to slide over one another freely can become rigidly fixed in place upon application of a pressure differential. This pressure forces the multiple layers together into a high-friction scenario, causing the layers to behave together as a single, thicker sheet. The stiffness of this thick stack can easily be calculated as proportional to the cube of the thickness. This effect of inducing friction to lock a system into position is known as jamming.

Jamming systems of varying approach can be designed to fit different geometries as needed. The most basic jamming structure involves a simple stack of thin flexible films held in an air-tight enclosure to hold vacuum pressure. This structure can be modified into a long, thin tube by simply wrapping the layers in a cylindrical fashion and cutting away slits to prevent buckling of the material when bent. Such an effort has been demonstrated in the context of medical endoscopes [40, 94]. Although the demonstrated product is 22 mm in

diameter, it could be made much smaller by reducing the size of the hollow core, which makes up 15 mm of that measurement (figures 4(i), (j)).

An alternative configuration is to use an air-tight enclosed collection of wires rather than flat sheets. The wires in parallel act as a long fiber, allowing bending motion in any direction rather than being constrained to one dimension (figure 4(k)). Although no performance data was provided on this particular arrangement, it was expected to perform similarly to the basic stacked layer configuration, which can change from 1GPa to 100GPa when vacuum is applied to stack of 15 polypropylene sheets [88]. This method is extremely fast-acting since it can be controlled pneumatically. However, the need for an air supply adds external bulk to the overall product.

Another approach to jamming involves using internal tension in the fiber itself as the source of friction rather than vacuum pressure. For example, when a coiled actuator has contracted to its minimum length, perhaps due to excessive overtwist in the fiber or a very small load, the adjacent coils may begin to come in contact. In the case of a thermally expanding material, further heating at this point will cause the coils to press more firmly against each other. For example, upon coil contact at ~130 °C, nylon 6,6 muscle expands at a rate comparable to the fiber's radial thermal expansion. The coiled structure stiffens with increasing temperature, producing a 24-fold increase in nominal tensile modulus [23], allowing the coiled actuator to serve double-duty as both actuator and stiffening mechanism.

A similar effect can be achieved by using fiber tension to provide the friction pressure. The general design involves threading an actuating fiber through a series of small shaped beads and affixing it to the ends. The actuating core, when contracted, will pull the beads together and lock them in position by friction [90, 95, 100]. This method is capable of changes in stiffness of up to 50× depending on the friction of the materials and bead geometry, and has been validated using beads as narrow as 1 mm in diameter (figures 4(j)–(m)).

The weave of a fabric itself can create enough friction between its fibers that it can become locked in place after being flexed. The locking is continuous, and so requires that the actuator be able to manipulate the fabric with enough force to overcome this friction when motion is desired [89]. In this case, the jamming pressure between fibers being provided by the dense structure of the weave. However, the loading capability of this structure has not been reported.

7. Integrated robotic fabrics and applications

In this section we review some of the assembled fabric systems that have been developed in the context of wearables (figure 5(a)), object manipulation (figure 5(b)), and self-reconfiguration (figure 5(c)).

7.1. Wearables

Robotic fabric technology is highly suited to wearable devices due to its conformable nature, breathability, and ease of integration into traditional fabrics, and consequently has various applications in responsive clothing for both aesthetic and assistive purposes [104]. Smart clothing that uses SMA threads has been shown to adjust garment fit [7] (figure 5(a1)) or roll up sleeves in response to rising temperature [105]. Clothing has also been treated with SMP to recover from wrinkling by applying heat (figure 5(a4–5)) or avoid shrinkage when washed [75] (Figure 5(a3)). Functional fibers have even enhanced fashionable garments with decorative features that self-animate [7, 103] (figure 5(a2)). Variable-stiffness fibers made from PLA or LMPM have been implemented as adjustable splints or casts that easily form to the contours of the body and then lock into place, with the possibility of softening and reshaping as necessary [39, 46] (figure 5(a6-10)). SMA wires programmed to constrict inward can be knitted into dynamic compression stockings [101, 106] (figure 5(a11)) or sewn into a spacesuit to combat orthostatic hypotension [107], and in extreme cases affixed to cuffs to act as an emergency tourniquet [108]. Additionally, active orthotics prototypes have been made by affixing SMA coils to a fabric sleeve and worn about the lower leg, allowing the garment to selectively support different areas of the leg at different points of the gait. However, the result was ultimately too slow for real-world use due to long cooling times [109].

7.2. Object manipulation

A robotic fabric can impart motion onto other objects by interacting with them. However, due to the thin and lightweight nature of fabric, generating sufficient force while maintaining stability and balance to act on a separate body is difficult unless the robotic fabric is affixed to some external rigid support, such as lab stand or a testing rig. Therefore, we designate three categories of object manipulation examples that use robotic fabrics: (1) cases where the robotic fabric is affixed to a rigid support, (2) cases where the robotic fabric is only attached to the manipulation target, and (3) cases demonstrating grasping techniques. There are several examples of fabrics fixed to a support, then contracting to lift a hanging weight. One example used thermally activated Spandex that has been knitted into a long tube [59] to lift a load (figure 5(b1)), and another used SMA wires sewn into muslin

Figure 5. (a) Examples of robotic fabric wearables. (a1) Rising hem line of a dress through the use of hand-stitched Nitinol wires. (a2) Animated flowers that open and close over a 15 s interval. (a3) Wool garment treated with an SMP coating maintains size upon laundering. (a4) Wrinkle-free effect of fabric treated with SMP in comparison with that of the fabric not treated with SMP. (a5) After spraying hot steam, the treated fabric recovers its flat shape. (a6-9) Variable-stiffness low melting point alloy tube woven into a cotton fabric. (a6) Prototype of a variable-stiffness finger splint. (a7) Woven fabric made using the cotton as the weft and the variable-stiffness tube as the warp. (a8-9) Variable-stiffness cast holding two distinct positions. (a10) Variable-stiffness finger cast using thermoplastic fibers. (a11). SMA compression garment. (b) Examples of robotic fabric object manipulation. (b1) Spandex/CNT knitted tube that contracts by 25% while lifting a 25 MPa load as a result of electrothermal actuation. (b2) Characterization of linear force generated by a sewn-SMA actuator unit using a materials testing machine. (b3) A knitted CP actuator unit. (b4) Knitted actuator unit drives a lever arm in a LEGO setup. (b5-6) Knitted actuator unit lifting a 2.0 g load. (b7) Hand-sewn SMA into muslin fabric and wrapped around a foam block, showing initial state, maximum bending position, and the final relaxed state. (b8) Application of the same robotic fabric towards a compression mode, showing initial state, maximum compression, and the final relaxed state. (b9) A knitted SMA ring actuates from the initially compressed state to lift the applied load in the expanded state. (b10) A knitted SMA belt which actuates from the initially expanded cylinder to a contracted cylinder. (b11-14) A mechanical gripper. (b11) A fabric actuator curls to grip a small umbrella. (b12) Lifting up the umbrella. (b13) Dropping the umbrella into a container. (b14) Release of umbrella from the gripper by unrolling the fabric. (c) Examples of robotic fabric self-reconfiguration. (c1-6) Various SMA knit patterns designed to produce different shape tranformations. (c1) An initial flat SMA knit rectangle. (c2) Curling motion. (c3) Arching motion. (c4) Accordion motion. (c5) Folding motion. (c6) Combination of arching and folding. (c7) Shape memory recovery creating a curled shape on one half of a fabric over a period of 20 s. (c8-9) Two knitted SMA fabric patterns that generate a ball (c8) and half-moon (c9) 3D surface texture when activated. (c10) Fabric woven with SMA wires crumples up over a period of 60 s when activated. (c11) A smart partition that opens when activated. (c12) Fabric woven with SMA wires that flattens out over a period of 30 s when activated. (c13-14) Robotic fabric with active variable-stiffness fibers. (c13) Initial stiff state with a hanging 200 g mass. (c14) Actuated and then stiffened fabric holding its new shape. (a1-2) Reproduced with permission [7]. Copyright 2005, IEEE. (a3-5) Reproduced and adapted with permission [75]. Copyright 2012, IOP Publishing. (a6-9) Reproduced with permission [39]. Copyright 2016, Wiley. (a10) Reproduced with permission [46]. Copyright 2014, IEEE. (a11) Reproduced with permission [101]. Copyright 2017, Association for Computing Machinery, Inc. (b1) Reproduced and adapted with permission [59]. Copyright 2016, American Chemical Society. (b2) Reproduced with permission [28]. Copyright 2015, IEEE. (b3-6) Reproduced with permission [41]. Copyright 2017 The Authors, some rights reserved; exclusive licensee American Association for the Advancement of Science. Distributed under a Creative Commons Attribution NonCommercial License 4.0 (CC BY-NC). (b7-8) Reproduced and adapted with permission [28]. Copyright 2015, IEEE. (b9-10) Reproduced and adapted with permission [44]. Copyright 2013, IOP Publishing. (b11-14) Reproduced with permission [36]. Copyright 2017, Wiley. (c1-6) Reproduced and adapted with permission [44]. Copyright 2013, IOP Publishing. (c7, 10-12) Reproduced and adapted with permission [102]. Copyright 2007, Sage Publications. (c8-9) Reproduced with permission [103]. Copyright 2003, Emerald Publishing Limited. (c13-14) Reproduced with permission [27]. Copyright 2016, IEEE.

fabric to pull against a materials testing machine [28] (figure 5(b2)). A more intricate setup used a strip of knitted CP fabric to drive a lever arm in a LEGO setup [41] (figure 5(b3-6)). In contrast, actuating fabrics that do not require a rigid test rig to function are hard to find. One such fabric made from SMA sewn into muslin could be wrapped around a soft structure such as a foam block and used to deform and bend the block into a desired shape [28] (figure 5(b7-8)) and even lock it into position with the addition of stiffness-changing PLA fibers [27]. A knitted ring of SMA was able expand into a tall, free-standing tube, lifting a stack of washers placed atop it [44] (figure 5(b9)). In cases where the manipulation target is not already attached to the fabric, some kind of grasping technique might be needed. By changing the fiber arrangement of the knitted SMA ring mentioned above, the motion was made so it could contract inward upon an object like a belt [44] (figure 5(b10)). Alternatively, a rudimentary gripper has been made by curling an active fabric around small objects [36], although the weight of these objects (cocktail umbrellas) suggests that the gripping strength is extremely small (figure 5(b11-14)).

7.3. Self-reconfiguration

Self-reconfigurable robots are of interest for adaptability in unstructured environments, multi-functionality to increase task performance, and compactability/deployability during transport and use. Robotic fabrics offer a unique solution to these needs, as 3D shapes can be formed out of 2D fabrics, and potential modes of actuation can extend beyond the hinge-like bending utilized by self-folding origami-inspired robots, to include continuum-body bending, twisting, buckling, expanding, and contracting. While a fully integrated robotic fabric of this complexity has not yet been developed, some significant shape-changing demonstrations do exist. With carefully planned knitting arrangements, SMA fabric can be designed to deform in specific patterns, including bending, rolling, arching, contracting, expanding, or any combination of these [44] (figure 5(c1-6)). Woven SMA fabric pieces have been made to curl into tubes (figure 5(c7)), contract in length (figure 5(c10)), and flatten out after being folded [102] (figure 5(c12)). Similarly, a flat piece of fabric with embedded SMA has been made which can alter its surface from a 2D plane to a bumpy 3D texture [103] (figure 5(c8-9)). In a practical application, an SMA woven panel has been made which can act as a smart partition, opening up when activated [102] (figure 5(c11)). By introducing stiffness-changing PLA fibers, a robotic fabric with SMA wires sewn in has been made that can not only crumple into a compact form against an opposing load, but also lock in its new shape after moving [27] (figure 5(c13-14)).

8. Future outlook

The concept of robotic fabrics falls in line with recent trends exploring alternatives to traditional, rigid robot structures. However, the unique approach of using fabrics as the robotic framework introduces a new, exciting dimension of possibility to complementary concepts such as soft robotics, reconfigurable robotics, robotic materials, and origami-inspired robotics. A great deal of preliminary technologies in wearable electronics and e-textiles have paved the way for fabrics that generate force and motion, and we believe a confluence of factors now make it possible to further explore the rich robotic fabric design space: current interest in wearables and human-robot interfaces is high, novel processes are allowing functional materials to be fabricated in fiber form, and well-established textile manufacturing techniques are poised to streamline fiber-based technology breakthroughs into commercial products. While the current state-of-the-art is limited to examples where one or two types of functional fibers are integrated within an existing fabric substrate or comprise the fabric itself, robotic fabrics may include any combination of active and responsive fibers in any number of arrangements, yielding an immense design space for the concept, which is representative of both the promise and challenge of this emerging technology.

In the future, we envision rolls of commercially available robotic fabrics, which could be purchased by the yard and easily programmed to meet the demands of variable tasks and environments. We envision self-reconfigurable 'origami'-inspired machinery that can later be crumpled and stowed for compact storage. We envision consumer clothing that will actively adjust itself and assist the wearer beyond being a simple covering. Such visions call on other challenges such as the development of complex design tools, compact or fiber-form power supplies, distributed computation, and thin-body control. As with most emerging concepts, the architecture of a robotic fabric at its full potential is unknown. The definition of robotic fabrics may very well evolve as new technologies are discovered and new challenges are encountered. Yet, with the 'toolbox' of technologies reviewed herein, we hope to facilitate the transition of commonplace fabrics from passive constructs to a promising new class of active, task-assistive machinery.

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ORCID iDs

Trevor L Buckner https://orcid.org/0000-0002-6602-8511

References

[1] Humphries M 1996 *Fabric Reference* (Prentice Hall)
[2] Jost K, Dion G and Gogotsi Y 2014 *J. Mater. Chem.* A **2** 10776
[3] Madden J D W, Vandesteeg N A, Anquetil P A, Madden P G A, Takshi A, Pytel R Z, Lafontaine S R, Wieringa P A and Hunter I W 2004 *IEEE J. Ocean. Eng.* **29** 706
[4] Stoychev G V and Ionov L 2016 *ACS Appl. Mater. Interfaces* **8** 24281
[5] Hines L, Petersen K, Lum G Z and Sitti M 2017 Soft actuators for small-scale robotics *Adv. Mater.* **29** 1603483
[6] Mirvakili S M and Hunter I W 2018 Artificial muscles: mechanisms, applications, and challenges *Adv. Mater.* **30** 1704407
[7] Berzowska J and Coelho M 2005 Kukkia and Vilkas: kinetic electronic garments *9th IEEE Int. Symp. on Wearable Computers (ISWC'05)* (Osaka: IEEE) pp 82–5
[8] Shan Y, Philen M, Lotfi A, Li S, Bakis C E, Rahn C D and Wang K W 2009 *J. Intell. Mater. Syst. Struct.* **20** 443
[9] Jiang A, Xynogalas G, Dasgupta P, Althoefer K and Nanayakkara T 2012 Design of a variable stiffness flexible manipulator with composite granular jamming and membrane coupling *2012 IEEE/RSJ Int. Conf. Intelligent Robots and Systems (IROS 2012)* (Vilamoura-Algarve: IEEE) pp 2922–7
[10] Song S-H, Kim M-S, Rodrigue H, Lee J-Y, Shim J-E, Kim M-C, Chu W-S and Ahn S-H 2016 *Bioinspir. Biomim.* **11** 036010
[11] Stoppa M and Chiolerio A 2014 *Sensors* **14** 11957
[12] Coyle S, Wu Y, Lau K-T, Rossi D D, Wallace G and Diamond D 2007 *MRS Bull.* **32** 434
[13] Cheng J *et al* 2017 Textile building blocks: toward simple, modularized, and standardized smart textile *Smart Textiles (Human–Computer Interaction Series)* (Cham: Springer) pp 303–31
[14] Paik J K, Kramer R K and Wood R J 2011 Stretchable circuits and sensors for robotic origami *2011 IEEE/RSJ Int. Conf. on Intelligent Robots and Systems* pp 414–20
[15] Kim R *et al* 2010 *Nat. Mater. Lond.* **9** 929
[16] Kramer R K, Majidi C and Wood R J 2011 Wearable tactile keypad with stretchable artificial skin *2011 IEEE Int. Conf. on Robotics and Automation (ICRA)* (Shanghai: IEEE)) pp 1103–7
[17] Biswas S, Reiprich J, Cohrs T, Arboleda D T, Schoeberl A, Mozafari M, Schlag L, Stauden T, Pezoldt J and Jacobs H O 2017 3D metamorphic stretchable microphone arrays *Adv. Mater. Technol.* **2** 1700131
[18] Biswas S, Schöberl A, Mozafari M, Pezoldt J, Stauden T and Jacobs H O 2016 *NPG Asia Mater.* **8** e336
[19] Castano L M and Flatau A B 2014 *Smart Mater. Struct.* **23** 053001
[20] Bao L and Li X 2012 *Adv. Mater.* **24** 3246
[21] Zhai S, Karahan H E, Wei L, Qian Q, Harris A T, Minett A I, Ramakrishna S, Ng A K and Chen Y 2016 *Energy Storage Mater.* **3** 123
[22] Bauer S, Bauer-Gogonea S, Graz I, Kaltenbrunner M, Keplinger C and Schwödiauer R 2014 *Adv. Mater.* **26** 149
[23] Haines C S *et al* 2014 *Science* **343** 868
[24] Jee K K, Han J H, Kim Y B, Lee D H and Jang W Y 2008 *Eur. Phys. J. Spec. Top.* **158** 261
[25] Kim S, Hawkes E, Choy K, Joldaz M, Foleyz J and Wood R 2009 Micro artificial muscle fiber using NiTi spring for soft robotics *2009 IEEE/RSJ Int. Conf. on Intelligent Robots and Systems* pp 2228–34
[26] Holschuh B T and Newman D J 2016 *Aerosp. Med. Hum. Perform.* **87** 84
[27] Yuen M C, Bilodeau R A and Kramer R K 2016 *IEEE Robot. Autom. Lett.* **1** 708
[28] Yuen M, Cherian A, Case J C, Seipel J and Kramer R K 2014 Conformable actuation and sensing with robotic fabric *2014 IEEE/RSJ Int. Conf. on Intelligent Robots and Systems (IROS 2014)* (Chicago, IL: IEEE) pp 580–6
[29] Iamsaard S, Aßhoff S J, Matt B, Kudernac T, Cornelissen J J L M, Fletcher S P and Katsonis N 2014 *Nat. Chem.* **6** 229
[30] Feng G-H and Zhan Z-H 2014 *Smart Mater. Struct.* **23** 045002
[31] Fang Y, Pence T J and Tan X 2011 *IEEEASME Trans. Mechatron.* **16** 656
[32] Haines C S, Li N, Spinks G M, Aliev A E, Di J and Baughman R H 2016 *Proc. Natl Acad. Sci.* **113** 11709
[33] Moretri G, Cherubini A, Vertechy R and Fontana M 2015 Experimental characterization of a new class of polymeric-wire coiled transducers *SPIE Smart Structures and Materials + Nondestructive Evaluation and Health Monitoring* vol 9432 ed N C Goulbourne (San Diego, CA: International Society for Optics and Photonics) p 94320P
[34] Mirvakili S M, Rafie Ravandi A, Hunter I W, Haines C S, Li N, Foroughi J, Naficy S, Spinks G M, Baughman R H and Madden J D W 2014 Simple and strong: twisted silver painted nylon artificial muscle actuated by Joule heating *SPIE Smart Structures and Materials + Nondestructive Evaluation and Health Monitoring* vol 9056 ed Y Bar-Cohen (San Diego, CA) p 90560I
[35] Chen P, Xu Y, He S, Sun X, Pan S, Deng J, Chen D and Peng H 2015 *Nat. Nanotechnol. Lond.* **10** 1077
[36] Gong J, Lin H, Dunlop J W C and Yuan J 2017 Hierarchically arranged helical fiber actuators derived from commercial cloth *Adv. Mater.* **29** 160510
[37] Lima M D *et al* 2012 *Science* **338** 928
[38] Chen P, He S, Xu Y, Sun X and Peng H 2015 *Adv. Mater.* **27** 4982
[39] Tonazzini A, Mintchev S, Schubert B, Mazzolai B, Shintake J and Floreano D 2016 *Adv. Mater.* **28** 10142
[40] Kim Y-J, Cheng S, Kim S and Iagnemma K 2012 Design of a tubular snake-like manipulator with stiffening capability by layer jamming *2012 IEEE/RSJ Int. Conf. on Intelligent Robots and Systems (IROS 2012)* (Vilamoura-Algarve: IEEE) pp 4251–6
[41] Maziz A, Concas A, Khaldi A, Stålhand J, Persson N-K and Jager E W H 2017 *Sci. Adv.* **3** e1600327
[42] Vatansever D, Siores E, L R and Shah T 2011 Smart woven fabrics in renewable energy generation *Advances in Modern Woven Fabrics Technology* ed S Vassiliadis (InTech) (https://doi.org/10.5772/24790) https://intechopen.com/books/advances-in-modern-woven-fabrics-technology/smart-woven-fabrics-in-renewable-energy-generation
[43] Abel J, Luntz J and Brei D 2012 *Smart Mater. Struct.* **21** 085011
[44] Abel J, Luntz J and Brei D 2013 *Smart Mater. Struct.* **22** 125001
[45] Simeonov A, Henderson T, Lan Z, Sundar G, Factor A, Zhang J and Yip M 2018 Bundled super-coiled polymer artificial muscles: design, characterization, and modeling *IEEE Robot. Autom. Lett.* **3** 1671–8
[46] Chenal T P, Case J C, Paik J and Kramer R K 2014 Variable stiffness fabrics with embedded shape memory materials for wearable applications 2014 *IEEE/RSJ Int. Conf. on Intelligent Robots and Systems (IROS 2014)* (Chicago, IL, USA: IEEE) pp 2827–31

[47] Berzowska J and Bromley M 2007 Soft computation through conductive textiles *Proc. Int. Foundation of Fashion Technology Institutes (IFFTI) Conf. Extreme Fashion (Toronto, Canada)* pp 12–5
[48] Roberts S D 2009 Bobbin work: when threads are too thick for the needle *Threads* **97** 64–8
[49] Hunter L and Cawood M P 1979 *Textiles: Some Technical Information and Data, IV: Sewability, Sewing Needles, Threads and Seams* (Port Elizabeth: South African Wool and Textile Research Institute) p 43
[50] Hunter I W and Lafontaine S 1992 A comparison of muscle with artificial actuators *Technical Digest IEEE Solid-State Sensor and Actuator Workshop* (Hilton Head Island, SC: IEEE) pp 178–85
[51] Naciri J, Srinivasan A, Jeon H, Nikolov N, Keller P and Ratna B R 2003 *Macromolecules* **36** 8499
[52] Shenoy D K, Laurence Thomsen D III, Srinivasan A, Keller P and Ratna B R 2002 *Sens. Actuators Phys.* **96** 184
[53] Leary M, Schiavone F and Subic A 2010 *Mater. Des.* **31** 2124
[54] Sun X, Chen T, Yang Z and Peng H 2013 *Acc. Chem. Res.* **46** 539
[55] Chen P, Xu Y, He S, Sun X, Guo W, Zhang Z, Qiu L, Li J, Chen D and Peng H 2015 *Adv. Mater.* **27** 1042
[56] Guo W, Liu C, Zhao F, Sun X, Yang Z, Chen T, Chen X, Qiu L, Hu X and Peng H 2012 *Adv. Mater.* **24** 5379
[57] Park J *et al* 2017 *Smart Mater. Struct.* **26** 035048
[58] Yang S Y, Cho K H, Kim Y, Song M-G, Jung H S, Yoo J W, Moon H, Koo J C, Nam J and Choi H R 2017 High performance twisted and coiled soft actuator with spandex fiber for artificial muscles *Smart Mater. Struct.* **26** 105025
[59] Foroughi J, Spinks G M, Aziz S, Mirabedini A, Jeiranikhameneh A, Wallace G G, Kozlov M E and Baughman R H 2016 Knitted carbon-nanotube-sheath/spandex-core elastomeric yarns for artificial muscles and strain sensing *ACS Nano* **10** 9129–35
[60] Meng Y, Jiang J and Anthamatten M 2016 *J. Polym. Sci. Part B Polym. Phys.* **54** 1397
[61] Kofod G, Stoyanov H and Gerhard R 2011 *Appl. Phys.* A **102** 577
[62] De Rossi D, Suzuki M, Osada Y and Morasso P 1992 *J. Intell. Mater. Syst. Struct.* **3** 75
[63] Della Santa A, De Rossi D and Mazzoldi A 1997 *Synth. Met.* **90** 93
[64] Choy C L, Chen F C and Young K 1981 *J. Polym. Sci. Polym. Phys. Ed.* **19** 335
[65] Chan Vili Y Y F 2007 *Text. Res. J.* **77** 290
[66] Zhang M, Fang S, Zakhidov A A, Lee S B, Aliev A E, Williams C D, Atkinson K R and Baughman R H 2005 *Science* **309** 1215
[67] Voyer J, Schulz P and Schreiber M 2008 *J. Therm. Spray Technol.* **17** 818
[68] Kim E, Arul N S and Yang L 2015 *J. In Han, RSC Adv.* **5** 76729
[69] Lili L, Dan Y, Le W and Wei W 2012 Electroless silver plating on the PET fabrics modified with 3-mercaptopropyltriethoxysilane *J. Appl. Polym. Sci.* **124** 1912–8
[70] Lee J-H, Choi H and Nam J-D 2009 *J. Mater. Res.* **24** 253
[71] Kularatne R S, Kim H, Boothby J M and Ware T H 2017 *J. Polym. Sci. Part B Polym. Phys.* **55** 395
[72] Li C, Liu Y, Huang X and Jiang H 2012 *Adv. Funct. Mater.* **22** 5166
[73] White T J and Broer D J 2015 *Nat. Mater.* **14** 1087
[74] Ji F, Zhu Y, Hu J, Liu Y, Yeung L-Y and Ye G 2006 *Smart Mater. Struct.* **15** 1547
[75] Hu J, Meng H, Li G and Ibekwe S I 2012 *Smart Mater. Struct.* **21** 053001
[76] Kiefer R, Temmer R, Aydemir N, Travas-Sejdic J, Aabloo A and Tamm T 2014 *Electrochim. Acta* **122** 322
[77] Gaihre B, Alici G, Spinks G M and Cairney J M 2011 *Sens. Actuators B Chem.* **155** 810
[78] Madden J D W, Schmid B, Hechinger M, Lafontaine S R, Madden P G A, Hover F S, Kimball R and Hunter I W 2004 *IEEE J. Ocean. Eng.* **29** 738
[79] Madden J D, Cush R A, Kanigan T S and Hunter I W 2000 *Synth. Met.* **113** 185
[80] Foroughi J, Spinks G M and Wallace G G 2011 *Sens. Actuators B Chem.* **155** 278
[81] Pelrine R, Kornbluh R, Pei Q and Joseph J 2000 *Science* **287** 836
[82] Chen J-A, Lee Y-T, Chang Y-M, Liu C-H and Shih W-P 2016 Stretchable spring electrodes for cylindrical dielectric elastomer actuators *2016 2nd Int. Conf. on Control, Automation and Robotics (ICCAR)* (Hong Kong: IEEE) pp 273–6
[83] Lu T, Chiang Foo C, Huang J, Zhu J and Suo Z 2014 *J. Appl. Phys.* **115** 184105
[84] Liu L, Zhang C, Luo M, Chen X, Li D and Chen H 2017 *Smart Mater. Struct.* **26** 085018
[85] Arora S, Ghosh T and Muth J 2007 *Sens. Actuators Phys.* **136** 321
[86] Liu Z F *et al* 2015 *Science* **349** 400
[87] Shan W, Diller S, Tutcuoglu A and Majidi C 2015 *Smart Mater. Struct.* **24** 065001
[88] Kawamura S, Yamamoto T, Ishida D, Ogata T, Nakayama Y, Tabata O and Sugiyama S 2002 Development of passive elements with variable mechanical impedance for wearable robots *Proc. 2002 IEEE Int. Conf. on Robotics and Automation (Cat. No.02CH37292)* vol 1 (Washington, DC: IEEE) pp 248–53
[89] Wu R, Han M-W, Lee G-Y and Ahn S-H 2013 *Smart Mater. Struct.* **22** 125007
[90] Huh T M, Park Y-J and Cho K-J 2012 *Int. J. Precis. Eng. Manuf.* **13** 1255
[91] Kearney R E and Hunter I W 1990 System identification of human joint dynamics *Crit. Rev. Biomed. Eng.* **18** 55–87
[92] Schubert B E and Floreano D 2013 *RSC Adv.* **3** 24671
[93] Zhao R, Yao Y and Luo Y 2016 *J. Med. Devices* **10** 021002
[94] Kim Y J, Cheng S, Kim S and Iagnemma K 2013 *IEEE Trans. Robot.* **29** 1031
[95] Chen Yi, Chang J H, Greenlee A S, Cheung K C, Slocum A H and Gupta R 2010 Multi-turn, tension-stiffening catheter navigation system *2010 IEEE Int. Conf. on Robotics and Automation (ICRA 2010)* (Anchorage, AK: IEEE)) pp 5570–5
[96] Zhang X X, Wang X C, Zhang H, Niu J J and Yin R B 2003 Effect of phase change material content on properties of heat-storage and thermo-regulated fibres nonwoven *IJFTR* vol 283 (*September* 2003) http://nopr.niscair.res.in/handle/123456789/22673
[97] Mondal S 2008 *Appl. Therm. Eng.* **28** 1536
[98] Pause B 2003 *J. Ind. Text.* **33** 93
[99] Zuckerman J L, Pushaw R J, Perry B T and Wyner D M 2003 Fabric coating containing energy absorbing phase change material and method of manufacturing same *Patent* #US6514362B1
[100] Kim Y J, Cheng S, Kim S and Iagnemma K 2014 *IEEE Trans. Robot.* **30** 382
[101] Granberry R, Duvall J, Dunne L E and Holschuh B 2017 An analysis of anthropometric geometric variability of the lower leg for the fit & function of advanced functional garments *Proc. 2017 ACM Int. Symp. on Wearable Computers-ISWC '17* (Maui, Hawaii: ACM) pp 10–7
[102] Stylios G K and Wan T 2007 *Trans. Inst. Meas. Control* **29** 321
[103] Winchester R C C and Stylios G K 2003 *Int. J. Cloth. Sci. Technol. Bradf.* **15** 359
[104] Gök M O, Bilir M Z and Gürcüm B H 2015 *Procedia - Soc. Behav. Sci.* **195** 2160

[105] McCann J and Bryson D 2014 *Textile-led Design for the Active Ageing Population* (Amsterdam: Elsevier) p 188
[106] Granberry R, Abel J and Holschuh B 2017 Active knit compression stockings for the treatment of orthostatic hypotension *Proc. 2017 ACM Int. Symp. on Wearable Computers-ISWC'17* (Maui, Hawaii: ACM) pp 186–91
[107] Holschuh B, Obropta E, Buechley L and Newman D 2012 Materials and textile architecture analyses for mechanical counter-pressure space suits using active materials *AIAA SPACE 2012 Conf. Exposition* (Pasadena, CA: American Institute of Aeronautics and Astronautics) (https://doi.org/10.2514/6.2012-5206)
[108] Holschuh B, Obropta E and Newman D 2015 *IEEEASME Trans. Mechatron.* **20** 1264
[109] Stirling L, Yu C-H, Miller J, Hawkes E, Wood R, Goldfield E and Nagpal R 2011 *J. Mater. Eng. Perform.* **20** 658