ADVANCED MATERIALS TECHNOLOGIES
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Actuating Textiles: Next Generation of Smart Textiles

Nils-Krister Persson, Jose G. Martinez, Yong Zhong, Ali Maziz, and Edwin W. H. Jager*

Smart textiles have been around for some decades. Even if interactivity is central to most definitions, the emphasis so far has been on the stimuli/input side, comparatively little has been reported on the responsive/output part. This study discusses the actuating, mechanical, output side in what could be called a second generation of smart textiles—this in contrast to a first generation of smart textiles devoted to sensorics. This mini review looks at recent progress within the area of soft actuators and what from there that is of relevance for smart textiles. It is found that typically still forces exerted are small, so are strains for many of the actuators types (such as electroactive polymers) that could be considered for textile integration. On the other side, it is argued that for many classes of soft actuators—and, in the extension, soft robotics—textiles could play an important role. The potential of weaving for stress and knitting for strain amplification is shown. Textile processing enables effective production, as is analyzed. Textile systems are made showing automatic actuation asked for in stand-alone solutions. It is envisioned that soft exoskeletons could be an achievable goal for this second generation of smart textiles.

1. Introduction

The fabrication of textiles was early out to be automatized. The first steps were taken by the introduction of the flying shuttle in 1733 by John Kay[1] and James Hargreaves' Spinning Jenny[2] from 1764. This resulted in larger scale industrial manufacturing in England from around 1790. Production has since then been tuned into almost perfection, with high repeatability, at minimal cost, with fast setup times, and at maximal speed. The contemporary weaving speed[3] is >1000 m min^{-1} at full width (≥2 m). This applies to all three main classes of textiles; a) garments, b) interiors (bed linen, carpets, curtains, tablecloths, etc.), and c) technical textiles (fluid filtration membranes, geotextiles, airbags, safety belts, reinforcements for composites, many types of medical implants, etc.). A paradigm has for long been that among technical artefacts[4] textiles are passive (no need for power to perform its function), which could be compared with items from other technical spheres such as computers, radios, or cars, that are regarded as active, i.e., needing power, electrical, or otherwise, to perform their function. The dichotomy passive–active is often used in electronics[5,6] and control theory to classify components. Passive components[7] (conductors, chassis, resistors, etc.) are those that are not intended to impact any signal or energy transferred through it, whereas active ones (batteries, fans, storage device, transistors, diodes, integrated circuits, etc.) are there exactly for doing this. The smart textile community is at a meeting point between textiles and electronics and the distinction of active and passive as used in electronics is mixed with a general common-language one, where active means "doing something." Any mechanical impact on the surrounding, such as moving a mass spatially, is deemed to exert work, i.e., utilize energy. In this text we stipulate as active such artefacts that are able to move any masses, either of the artefact itself or outside of it. As more and more instances accumulate showing that also textile artefacts could be given this property, also textiles are entering into the domain of being regarded as active.

In retrospect, there are some early examples of what today could be defined as active textiles. One such example is the Ventile fabric[8] from the 1940s that was used as a waterproof protecting layer. This fabric operated by the swelling ability of cotton yarn hindering water to penetrate beyond the amount used for the very swelling. However, it was not until the 1980s that textiles—especially garments—were "discovered" as a potential arena for enrichment by other kinds of technologies such as sensorics for measuring the wearer as well as monitoring the surrounding. These have interchangeably been denoted as smart textiles,[9] intelligent textiles,[10] or electronic textiles.[11] This "(re)discovery" of textiles as an interesting field for new technical developments is in parallel with the "(re)discovery" of paper, which, although started later moved at a faster pace and printed electronics,[12] paper electronics,[13] or smart papers[14] now have emerged as branches on their own. Both textiles and papers are polymeric, fiber-based, cheap, pliable, flexible, large area (semi) 2D materials that take part in everyday activities of humans and by this being ubiquitous ever present. Textiles and papers have their respective benefits; textiles for

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DOI: 10.1002/admt.201700397

example are washable, a property enabling them to be in contact with humans as hygienic demands can be fulfilled. Textiles are also used for protection, and for given stiffness and support. Textiles are also constructed in a special way enabling the rather unique property of drapability used in clothing. Nowadays we see a convergence of the textile and paper industry not least due to the chase for a new kind of fibers in a "peak cotton"[15] and "peak oil"[16] era, where cellulose based materials are interesting candidates. Cellulose is the most abundant regenerating polymer on earth.

The ubiquitous character of textiles goes hand in hand with ideas emerging at the same time in the 1980s of portability, smart environments,[17] and ubiquitous computing.[18] The blooming of the mobile phone technology history took another direction that the smart textile technology could not match. Nowadays smart textiles should be seen as part of a larger system where much of the very computation and signal control is performed outside the fabric and only dedicated functions are integrated in the textile. Often identified fundamental building blocks[9c] of a smart textile item include a) sensing element, b) actuating element, c) communication element, d) powering/generating/storing component, e) data processing unit, and f) interconnects.

Textilification[9a] is a term used when functions from a certain technology are transferred into textiles either by realizing the functionality, such as an antenna, by textile processes like weaving or by integrating the technological component, such as a light emitting diodes (LED), into the textile while simultaneously taking care of the special requirements such as pliability, comfort, and need for washing.

There are many definitions of smart textiles[19] around, such as "smart textiles are defined as textiles that interact with their surroundings"[20] putting forward the factor of being interactive, they are responding to an external stimulus,[21] putting forward the factor of being responsive; and if more elaborated, "Textiles that are able to sense stimuli from the environment, to react to them and adapt to them by integration of functionalities in the textile structure."[22] Even if such definitions in a way are unsatisfactory (all physical artefacts are interacting in some way such as by gravitation or surface forces with other objects, all technical artefacts have a function[4]), a conceptual core is found in these. "Interaction" and "interactivity" are important and interactive is according to the dictionary relating to, or allowing two-way electronic communications (as between a person and a computer).[23] What is to be noticed is that still smart textile is in a phase where one-way functions like measuring, sensing, and monitoring are emphasized (e.g., an IEEE Xplore search on "smart textile and sensors" gives 232 records and "smart textiles and actuator" 26 records for the years 1991-Dec 2017). Iconic smart textiles products are electrocardiography-T-shirts, electromyography training pants, electroencephalography caps, and photovoltaic curtains, which all are focusing on the harvesting of a different kind of input or stimulus, e.g., electrical, mechanical, acoustic, optical, and where the output leaving the textile part of the product is more or less always as an electrical signal. (Bio)feedback systems and actuation that act in a direction from the textile are far less considered.

We now see an enhanced interest for such kind of smart textiles where the textile is acting upon its surrounding. This could include medical treatment by transdermal drug release,[24] giving relief from spasticity by antagonistic muscle stimulation technique,[25] or large area water purification techniques having contaminated water as input and leaving detoxified water as output.[26] One could say that now a second generation of smart textiles is being developed, where the output is central, complementing the first generation, where the focus was on input. We will here discuss this second generation smart textiles with special emphasize on actuating devices.

Specifically, we report on mechanical output such as form change, strain amplification, and force amplification. We start by a schematic overview of different types of actuators and then discuss those that are either fiber shaped, mesh-like, or otherwise relevant for textile integration. We then review a number of cases of textile-based actuators. Issues with some of the actuator types are identified and we show by two examples how the problem of nonautomatic devices can be addressed by textile lamination processing and how the low force and low strain issues can be handled by weaving and knitting, respectively.

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2. Different Kinds of Actuators

An actuator is a device that transforms energy from one physical domain into motion, i.e., into a displacement, rotation, force, or moment. Common examples are rotary or linear electrical motors or pneumatic and hydraulic pistons that convert electrical energy or pressure change into motion. Actuators can be found in a large range of shapes and sizes, employing a wide variety of transduction principles (e.g., electric, magnetic, and chemical). However, most of the actuator technologies are hard, noncompliant, heavy, and make noise. With the raise of wearable devices there is a need for actuators that are soft, compliant, lightweight, and silent. This is driving the field of soft actuators[27] and soft-robotics[28,29]

We use the following definition:

Actuators $=_{\text{def}}$ devices capable of moving or controlling objects and systems by applying mechanical forces on them.[30]

The simplest movement (**Figure 1**) is to exploit some change mechanism (CM) of the material to achieve a displacement or increase in pressure/force. Next, forming the material in a long

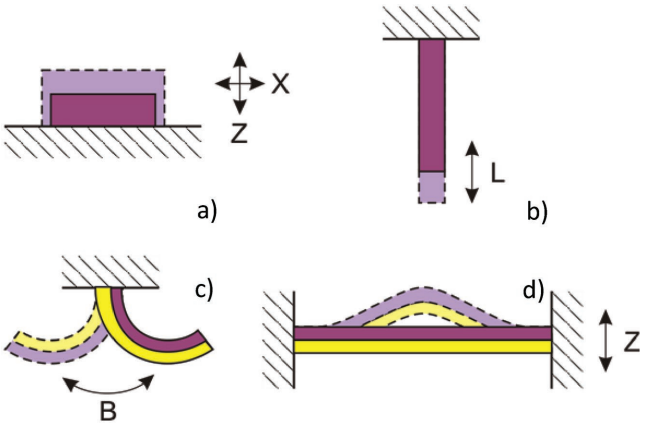

Figure 1. Various actuation movements. Some mechanism that initiates change of the material is used to create a,b) linear actuation, c) bending motion, and d) buckling motion.

fiber or film would result in a linear actuation (for isotropic expansion, the perpendicular displacement would typically be relatively small), similar to a mammalian muscle. One can also combine two materials which different expansion coefficient (i.e., the expansion coefficient of layer 2 is smaller than layer 1, zero, or in the opposite direction of layer 1) in into a bilayer (or multilayer) structure which when activated will create a bending motion. Taking the same bilayer or multilayer structure and clamping it on at least two sides will create a buckling motion (Figure 1). Finally, one can take twist or even curl a fiber and when activating, it will untwist or uncurl creating both a rotary motion and elongation.

Parameters that are important in evaluating such actuators are force generation (blocking force or isometric force, i.e., constant length), stress (force per area), elongation or strain (ratio of change of length to the initial length) at a specified stress, speed in the form of strain or stress rates, response time after stimulus, work capacity, average power (both these possibly normalized by mass or input energy), and lifetime (number of cycles, stability, shelf-life, and creep). An aspect is also to give direction of the strain or stress such as "in-plane," "z," or "y." Another aspect is the question of reversibility (if at all) or irreversibility of the movement. In addition to these more standard parameters for actuators, textile integration puts things into new perspectives and adds some further constraints: Is the actuator pliable, can it be washed, and for aesthetic reasons can it be dyed/colored or made in different colors? As always also any synthetic conditions and related cycling (if any) characteristics (scan rates, number of precycles) should be given. It could be noted that many design parameters that are common in classic hard robotics such as work envelope, accelerations and decelerations of parts, and resolution are still not that common for soft actuators.

In **Figure 2** different types of actuators are schematically categorized. Also given are typically properties of the different types, both positive and negative. Actuators are based on certain physiochemical CM that is utilized for creating mechanical actuation.

We make (Figure 2) a classification into hard and soft actuators where the former are not further discussed here. Among soft actuators gels have experienced much interest, so have dielectric elastomers. These areas are so established[30,31] that they constitute classes by their own. Gels are characterized by having a very low Young modulus and thereby a very low load bearing capacity. Dielectric elastomers are operating based on an elastomer being exposed to high electrical potential difference between to deformable electrodes and by this reshaping the soft dielectric material sandwiched between the two electrodes (Maxwell stress). Further on piezoelectrical phenomena could be taken use of for actuation. Historically, one of the earliest types of soft actuators is air-containing bladders.[32] Its operating mechanism where a mesh-surrounding bladder is filled with air and the mesh directs the expansion of the bladder ending up in contraction is distinct from the others makes it a type of its own, often addressed as McKibben actuators. Based on distinct CMs four other actuator types could be introduced. These are soft actuators based on a) change in order, b) change in volume due to thermal expansion, c) change in volume due to absorption and intercalation, and d) change in distance. This classification is compatible with that of others.[33]

Change of order means that a stimulus, it could for example be temperature, creates a reordering at the molecular level, typical conformation changes of polymers or internal morphology of alloys. In principle no mass transport occurs. Phase transitions of liquid crystal systems, shape memory effects, transitions between amorphous and stretched conformations are all examples hereof. The overall (macroscopic) volume change is moderate but the stimulus creates in effect a change in a significant property (stiffness, reshaping) that is utilized for creating (macroscopic) actuation.

As densities of materials are temperature dependent thermal expansion and contraction is a CM for actuation. Here also phase transition phenomena such as melting, vaporization, and crystallization could be taken use of. In principle no mass transport occurs.

Change of volume is induced by absorption of small molecular species into amorphous parts of a material body. By this, the receiving material is expanding. The attraction is mediated by electrical potential differences, concentration differences (osmosis), and chemical affinity. In this case mass transport is central.

Change in distance here means that due to electrostatic attraction or repulsion between conductive constituting parts of a device the overall shape of the device is impacted, in turn creating actuation. Examples include carbon nanotubes (CNTs) in a soft matrix of polymers. When the CNTs are electrically charged they move relative to each other and the effect hereof is magnified if there are many CNTs and they are aligned.

Before going further we discuss the inherent properties of textiles and, as will be seen, many of the drawbacks different actuator types show could be addressed by textiles and textile properties.

3. Textile Characteristics

Textiles have a number of properties that not many other material classes show. These include what could be called $D = M$

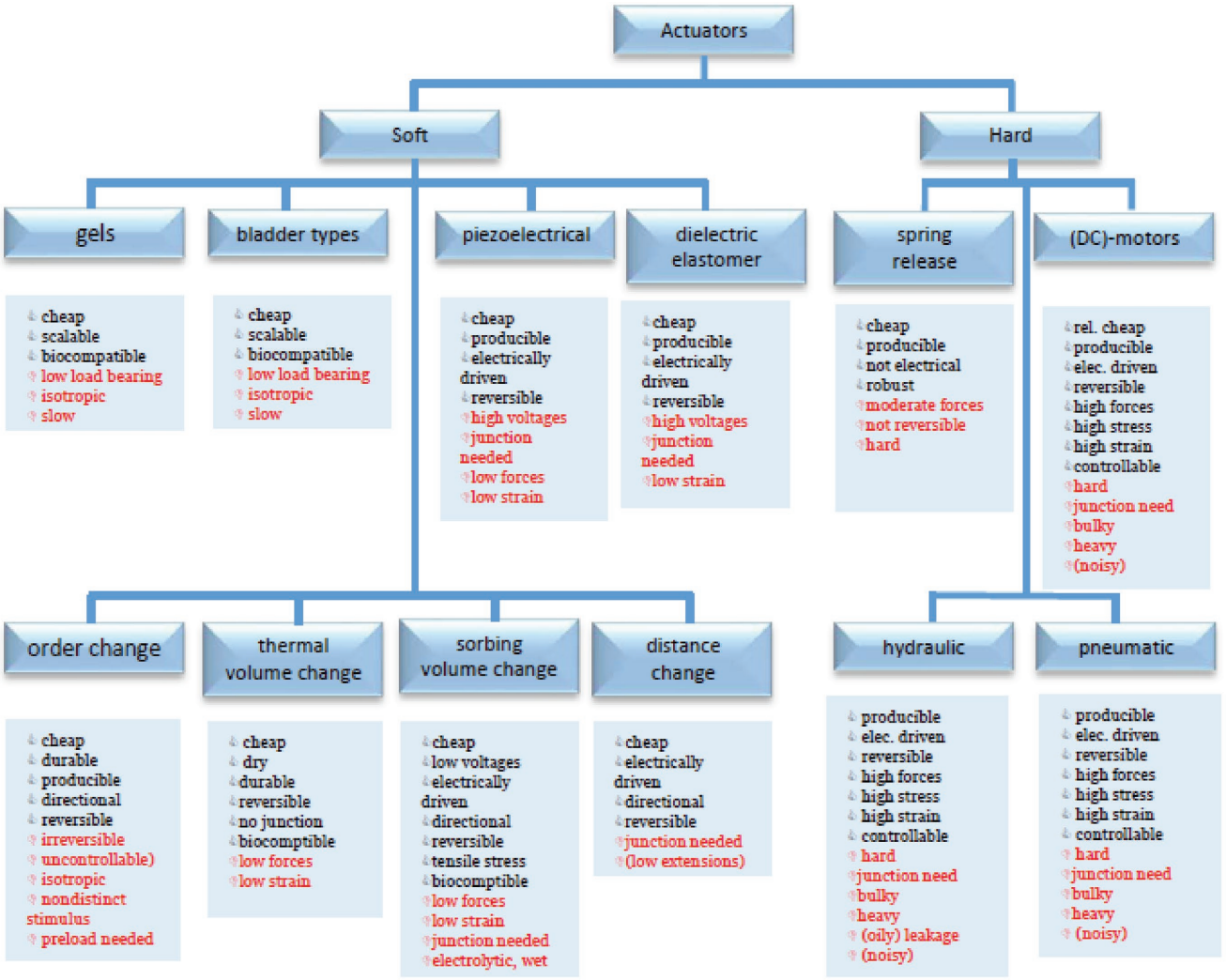

Figure 2. Classification of actuators. Actuators are here divided into soft and hard according to their physical appearance. Soft ones are divided into eight subgroups and hard ones into four. For each type the beneficial properties are given in black and 👍. The problematic characteristics are given in red and 👎. This assignment is admittedly both relative and context dependent. In general hard actuators are more developed and better controlled. Taking into account already established research fields such as gel actuators and EAP (electroactive polymer) systems, it is not possible to create disjoint classes based on every type relaying on one unique, change mechanisms (CM). There are also hybrids between the types, mixing different CMs. It is not easy to give numbers for the different types as actuation is a rapidly developing field of research. Soft actuators typically are of smaller size than hard ones even if for the latter a miniaturization process is on-going where even small piston-cylinder pneumatic systems are realized at the sub-micrometer scale. Operating pressures for soft actuators are kPa till MPa, forces cN and elongations of the order of mm. A benchmark is mammal skeleton muscles which could generate 20% strain and 100 kPa stress. This could be compared with dielectric elastomeric actuators that could have very high strains of >1000% but in general need high voltages and field strengths (10 MV m^{-1}) close to the breakdown of the materials. Electroactive polymers (type: sorbing volume change) already early showed strains of 1–2%—now higher only within the same magnitude—and worked with voltages of ±1–2 V. Change of order actuators based on liquid crystal polymers could have 20% strain at 0.5 MV m^{-1}.

property, x–y addressability, truss similarity, mechanical parallelism, and mechanical serial connectivity. These will be explained in this section.

It should be noted that for textiles the chemical composition alone does not determine the properties. The ways yarns are spun and twisted, and the way fabrics are made, are factors that are equally important for determining properties and application areas and for defining what is regarded as a material in the sense the textile community is using the term. The very same polyester batch could be used for a filtration mesh and a woman's fine dinner dress with completely different hand and drapability and thickness, i.e., different material from a textile fabric point of view.

The $D = M$ property stands for Doing devices while making the material. When weaving a set of warp threads (on the order of 1000 m or more, O (km) of length), T, these are interlaced with perpendicular weft (or filling) threads (typical 1–2 m of breadth), U, by lifting a subset, T', of T in a predefined order (the pattern) by this making a tunnel (shed) for one (or occasionally a few) weft thread(s), j, that is guided through the tunnel by a shuttle, or rapier. In the subsequent step the warp threads T' are lowered and warp threads $\in T - T'$ are lifted and

by this locking the thread *j*. The processes are then repeated. In summary, an additive manufacturing process is performed. Weft tread (diameter *O* (10 μm)) by weft tread the fabric is built. If the thread *j* is functionalized for example being an electrical conductor or an actuator, a device is made while making the fabric material. This is in contrast to for example paper where functionalization (printing, etc.) typically comes after the paper is made.

Inherent *x*–*y* addressability means that many types of textiles, but foremost weaves, are in principle forming the basis of an *x*–*y* system, where the warp threads form the columns and the weft threads the rows. Assume warp and weft are made of conducting materials, by applying a voltage on one of the warp threads and one of the weft threads, the crossing point where these threads meet, forms an (*x*,*y*)-position that could in principle be addressed.

Textiles as per definition made of intricate assemblies of (semi) 1D elements; threads and yarns. This assemblage creates a framework, a truss.[34] Compared to a solid body "unnecessary" parts of the real object are nonpresent. This makes textile lightweight materials. Textiles are for example used as reinforcement in composites where a textile framework of carbon fiber mesh is load bearing and is giving structure to the overall object. Thus, a textile could be said to have a similarity to a truss.

Textile processing embraces techniques for assembling many small, prolonged, flexible objects, namely threads, together. This could be done in parallel seen for example within weaving for both the warp, *T*, and the weft, *U*, threads. In the latter case on the order of 10^6 threads in parallel are possible. Thus, textiles show what could be called mechanical parallelism.

In the same way, seen for example in knitting or in weaving reports, there are parts that are repeated over and over again. An example is a certain loop pattern in a knit. We denote this mechanical serial connectivity. Both mechanical parallelism and mechanical serial connectivity will be important in the future discussion.

4. What Types of Actuators Could be Textilified?

We now relate these to the characteristics of textiles. As mentioned, actuators come in all shapes and sizes. In order to be relevant for textiles, actuator classes that are having or benefit from small or flat form factor or high aspect ratio, such as fibers, thin tubes, ribbons, sheets, or films are of interest. Hard types are then not considered. For wearables—where textile garments are an important subset—the transduction principle would be based on a material where changes occur due to nearby physical or chemical processes, since employing principles that rely on external stimulation, e.g., magnetic fields would not be considered portable. Gels, at least in its archetypical form with low modulus, are only moderately textile compatible. Also, classical plate-like dielectric elastomers are operating at high voltages are not obvious candidates for textilification, even if exceptions exist.[35]

As textiles are per definition made of fibers it is interesting to ask which of the actuator types of Figure 2 that can be realized in fiber form. All of the actuator types based on the CMs of a) change in order, b) thermal change in volume, c) absorbing change in volume, and d) change in distance are having aspect ratios (length:width) that often are high which is compatible with textile fiber shapes. Furthermore, these types are already realized by polymers, the basic material also of textiles. These are then all candidates for textilification. To this comes that change-in-order types embrace shape memory alloys that are available as metallic threads.

Polymeric textile fibers could be manufactured in many ways. For melt and wet spinning a number of properties of the polymer are preferred:[36]

a) Linear chains are better than those with side chains or bulky side groups.
b) Molecular mass should be intermediate to high, i.e., between say 20 000 and 250 000 g mol^{-1}.
c) Still, by a moderate polymer length avoiding a too high intermolecular bonding making stretching and drawing easier.
d) A regularity of the repeating unit to allow close packing of the chains which also support rapid formation of ordered or crystalline structures when solidified from the melt or when precipitated from solution.Recently, alternative ways of making fibers have been presented.[37] By these also particulates such as CNTs, too short to be yarn spun, can be utilized.

Most of the conjugated polymers employed for electroactive polymers (EAPs) might be of too low molecular weight or are heavily cross-linked to make weavable and knittable fibers thereof. By blending with fiber forming polymers[38] and by using coating of such EAPs on existing ordinary textile fiber in different layers it is possible to overcome these limitations. Shape memory polymers (SMP) in fiber formed have been presented.[39] Piezoelectrical fibers exist and have been proven to be able to be handled by textile processing like weaving and embroidery.[9a] Bladder type actuators are already made with a textile mesh.

Summarizing, many of the actuator types of Figure 2 already come in a fiber/yarn/thread shape. This is by itself inside the frames of the textile realm, but also an enabling factor for making fabrics.

If actuating fibers are at hand it is possible to apply fabric forming processes on them, this under the assumption that weavability and knittability properties are enough. The above-mentioned textile characteristics of mechanical parallelism would enable to address the low force problem as the assembly of many actuating units would render a larger total force. The textile property mechanical serial connectivity would enable to address the low strain problem, again assembling a multitude of units with moderate strain properties into an overall system having a useful total strain performance.

As textile processing is highly developed making large area structures at low cost, with high repeatability, and at high speed the manufacturing issue could also be addressed by textiles. Not only weaving and knitting, the foremost fabric forming technologies, but also braiding and the textile processing techniques of lamination and fabric coating are all available for this.

5. Different Types of Textile Related Actuator Types

We now turn to the different actuators types that are relevant for textiles. These are the bladder types (fiber reinforced bladders, McKibben), piezoelectrical types, order change type (including shape memory alloys (SMA), SMP), thermal volume change (including, TATA, many twisted ones), volume change due to absorption and intercalation (EAP), and distance change types (CNT). To textile actuators are counted fibrous ones. Also structures where textile processes have been employed are included.

5.1. Bladder Type

Fiber reinforced bladders actuators consist of an elastomer bladder wrapped with inextensible or low extensible reinforcements, which are usually based on fabric reinforcements. These reinforcements are arranged in a pattern to create anisotropic stiffness. When the bladder is inflated, the inextensible reinforcements guide its movement to produce movement in the desired direction(s).[40] The most studied are linear actuators, consisting of a bladder wrapped with inextensible fibers, so it can only expand in the axial direction.[41] There are also bending actuators: by attaching an inextensible material to one side, expansion in the region of that sheet is prevented avoided, and when inflated, the bladder pushes the inextensible material and the actuator bends.[42] The perhaps most used variant is the McKibben type,[32,43] where inflated air to the bladder and its accompanying expansion tendency is redirected by a knitted fabric wrapped around the bladder. The overall effect is that a contraction is performed. This mimics natural mammal muscles.

5.2. Piezoelectrical Types

Piezoelectricity is the interplay between mechanical and electrical features of a material or a device. Changing one feature will influence the other. There are several types of materials that show such properties including quartz and tourmaline minerals; human and animal bone tissue and different proteins. Piezo fibers are not that common, examples include fibers made of lead zirconate titanate and barium titanate, most often of very short length from a textile processing point of view. More textile compatible are piezo fibers and filaments made of the polymer poly (vinylidene fluoride).[44] From these, sensors and monitoring systems have been constructed. Actuators on the other side are not that explored. Most work on fibrous piezoelectrical actuating systems is on composites and then mostly systems made of ceramic piezofibres.[45]

5.3. Order Change

As said change of order means that a stimulus, typically temperature, creates a reordering at the molecular level with in principle no mass transport involved. SMP are a class of material that belongs here. They have a latent "programmed" shape not seen under normal conditions but which is activated when the material is exposed to heat making the material to deform. SMP could be one way or two way meaning that there are one or two shapes the material "remember" but reversibility without considerable heat/mechanical treatment is rarer. Thermoplastic SMP fibers have been developed and employed as smart sutures.[46] Similar fibers could be integrated in textiles.

SMAs are alloys that are able to recover their initial shape when a source of energy (typically heat) is applied.[47] Thus, they can convert thermal energy into mechanical work, promoting movement when heating is applied. They have been widely combined with textiles, since most of them are available in a yarn or fiber form. In this way, it is possible to either combine them to obtain fabrics or to incorporate them as part of a passive fabric.[48] This property has allowed to develop t-shirts that do not need ironing,[49] clothes that can help to maintain the body temperature,[50] peristaltic devices,[51] or dynamic light filters.[52]

SMAs also present behavior called superelasticity or pseudoelasticity. This property is observed when, without any temperature change, the alloy can return to its original shape after a mechanical strain has been applied and then is withdrawn.[53] This property has been tested combined with textiles in different fields for instance in ballistics to improve high impact resistance.[54]

Selecting good SMAs is a key point to incorporate new features to textiles: they should be able to be obtained in yarns and they should have a low activation temperature compatible with both, the passive textile component (if present) and the end-user.

5.4. Thermal Volume Change

Thermal expansion and contraction are useful CMs for actuation. Here in principle no mass transport takes place. Quite a number of textile actuators fall under this category.

Lamination belongs to the repertoire of the textile community. It is widely used in industry both for garments (e.g., wind shielding and breathable items) and technical textiles (e.g., airbags, car interiors, and acoustic plates). By lamination two (solid) materials are combined, typically in a face-to face manner with a large interfacial area. Therefore, it is relevant to talk about layers. These layers could be thicker or thinner textile fabrics, thinner webs, foams, or massive or perforated plastic films. The adhesion is due to merging the two layers either by melting a thermoplastic or using glue. Whatever method used, heat or pressure, as a general rule passing the layers to be merged through between two rollers in many variants[55] is almost always part of the manufacturing. Thus, the apparent two-layer structure consists in principle in three layers, where the adhesion component is applied in the form of a solvent based or aqueous emulsion, adhesive net, or powders, generally applied on one of the layers. It could also be that one or both of the layers partly melted and therefore made to create a cohesive joint. Depending on complexity, the production could be fast, with manufacturing speeds up to 100 m min^{-1}.

Using different kinds of materials of the layers with different properties, introduces an anisotropic overall behavior in the

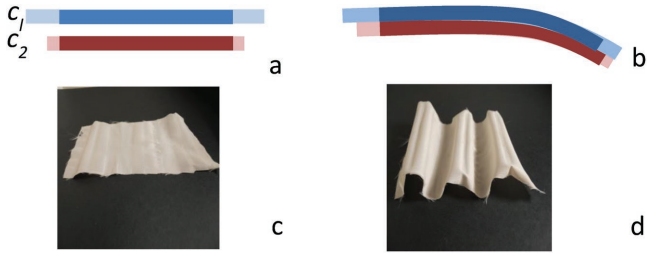

Figure 3. a) Two different materials (dark red and dark blue) having thermal expansion coefficients c_1 and c_2, respectively, ending up in expanded structures at enhanced temperature (light blue, light red). b) When laminated together using the low temperature processing of gluing the properties of the individual layers are conveyed to an overall behavior. c) The laminated system in room temperature (23 °C), d) when heated the laminated system, as a whole, is impacted by the different expansion coefficients of its constituents (layers).

laminated fabric. Here this is exploited for the case of different (linear) expansion coefficients, c, as in $\Delta l = c\Delta T$ (neglecting higher order terms) with Δl linear extension [m] and ΔT change in temperature [K]. Two materials of low area weight in order to handle the eigenweight were chosen. This—what has been called a thermally activated textile actuator, TATA[56]—is shown in **Figure 3**.

However, more complex designs and movements can be achieved by patterning the fabric using laser cutting. **Figure 4** shows one such example where individually fingers have been cut out. At low temperature, room temperature (RT), the fingers are straight and are still positioned within the fabric. At high temperature the fingers bend in a curling motion opening the fabric. The intelligent fabric could be designed also to operate reversely, i.e., close at higher temperatures and open at low temperatures. By simple lamination of two different materials, the textile construction has been engineered to become an automatic system suitable for controlling ventilation. The work exerted to bend the fingers is energetically driven by the surrounding heat. The reversibility is good. The cycling could be repeated many times without any pronounced hysteresis.

The good electrical and mechanical properties of CNT have made them an alternative to the traditional electrical actuators for macroscopic actuator applications. CNTs are very good conductors of both electricity and heat, and are very strong and elastic molecules in certain directions. These properties are difficult to find combined in the single material and well-needed for high performance actuators. It has been shown that CNT yarns can provide tensile actuation, after an extreme degree of twisting to form CNT coils.[57] The CNT coils mechanically behave like tight springs and can provide tensile contraction of ≈7.3% when pristine coiled CNT yarns are heated to incandescent temperatures in an inert environment. More practically, by infiltrating CNT yarns with a guest material having a large coefficient of thermal expansion, these hybrid CNT yarns could provide torsional and tensile actuation in lower temperature ranges. For instance, a coiled CNT yarn infiltrated with paraffin wax delivered over 5% contractile stroke when heated to 200 °C.[57] More recently a coiled, silicone rubber infiltrated CNT yarn has provided a tensile stroke of more than 34% when heated electrothermally. Adding to the fabric level repertoire of textile actuators, lately a stretchable and conductive textile was developed by combining CNT and spandex fibers in 3D knitted structures.[58] Spandex yarn was continuously wrapped with CNT aerogel sheets and fed into an interlocking circular knitting machine to fabricate stretchable, electrically conducting textiles. Stretched fabrics were actuated by Joulean heating, resulting in large tensile contractions of up to 33%. The actuators generated a mechanical work capacity during contraction of up to 0.64 kJ kg^{-1} and a maximum specific power output of 1.28 kW kg^{-1}.

Overall, much attention has been paid to fishing line based actuating systems.[59] The attractive mechanical properties of

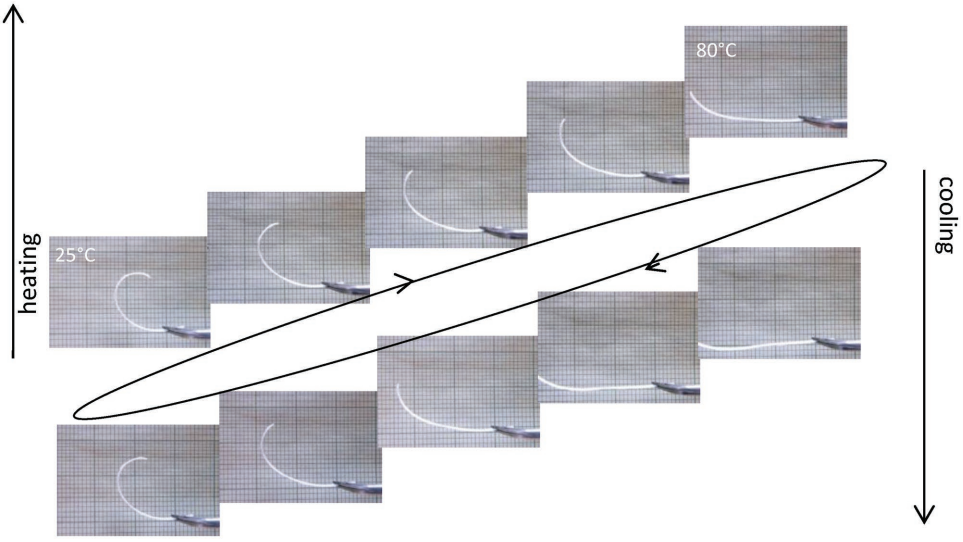

Figure 4. Reversibility in heating–cooling cycle, 25 °C → 80 °C → 25 °C. In this construction, the low temperature state is curled. One heating–cooling cycle showing a reversible unbending/bending behavior resulting in a flat shape at ≈80 °C. When the thermal heating stopped and the temperature decreased the stripe recovered back to a curled shape. The samples have a low temperature shape and a high temperature shape. The application in mind was a technical textiles for use in high temperature (>70 °C) surrounding.

fishing lines, especially high tensile strength, have made them an interesting material to be used as a mean to develop mechanical actuators. Fishing lines here, are sometimes a monofilament (a single strand of a material, usually a polymer as nylon) or, commonly, several monofilaments twisted together (occasionally also including metal constituents enabling heating). Fishing lines are readily available commercially and combine thermal contraction with large to provide enhanced muscle stroke.[59b]

Fishing line of made of polyethylene and polyamide have been combined with an electrical heating element (Ni–Cr yarn,[60] carbon nanotubes yarn,[61] for example) to induce the increment of the diameter of the nylon and the subsequent decrease of the actuator's length through resistive heating.[60,62] To increase the strain of these actuator they have been twisted and coiled.[63] It has been possible to integrate them into a woven textile containing the coiled nylon muscles, conductive silver-plated fibers for electrothermal heating, and polyester and cotton fibers as the structural material. This resulted in faster actuation as the heat could dissipate over a much larger area than for a single large-diameter muscle of similar strength.[59b] This similar principle has been also used to develop bending actuators.[64]

One option is also to combine a braided fishing line with a SMA, thus getting the best of both technologies, i.e., reduce system's weight and cost, increase power-to-weight ratio, and offer safer physical human–actuator interaction. However, this system has also disadvantages such low percentage of contraction, and being complex to drive due to the high hysteresis of the SMA.[65] Similar to SMAs, selecting the proper materials, able to produce actuation in a range of temperatures close to ambient temperature, or at least in a safe and comfortable temperature for the end-user is a key issue in the development of these actuators.

5.5. Absorption Volume Change

Another kind of materials that can be combined with textiles to produce stimulus-active actuators are intrinsically conducting/conductive polymers, synonymously called conducting polymers (CPs) of which ionic EAPs is a subclass. CPs are widely investigated for the development of lightweight, noiseless, high stress, large strain, and low driving voltage actuators.[66] In CPs, reversible electrochemical oxidation and reduction reactions can be promoted. This redox change results in a change of the material composition and its properties such as ionic content, color, shape, and volume.[67] Indeed, when the CP is oxidized or reduced electrochemically, ions and solvent molecules are incorporated or expelled from the CP in order to ensure the overall electroneutrality and result in a variation of the CP volume (**Figure 5**c, low).

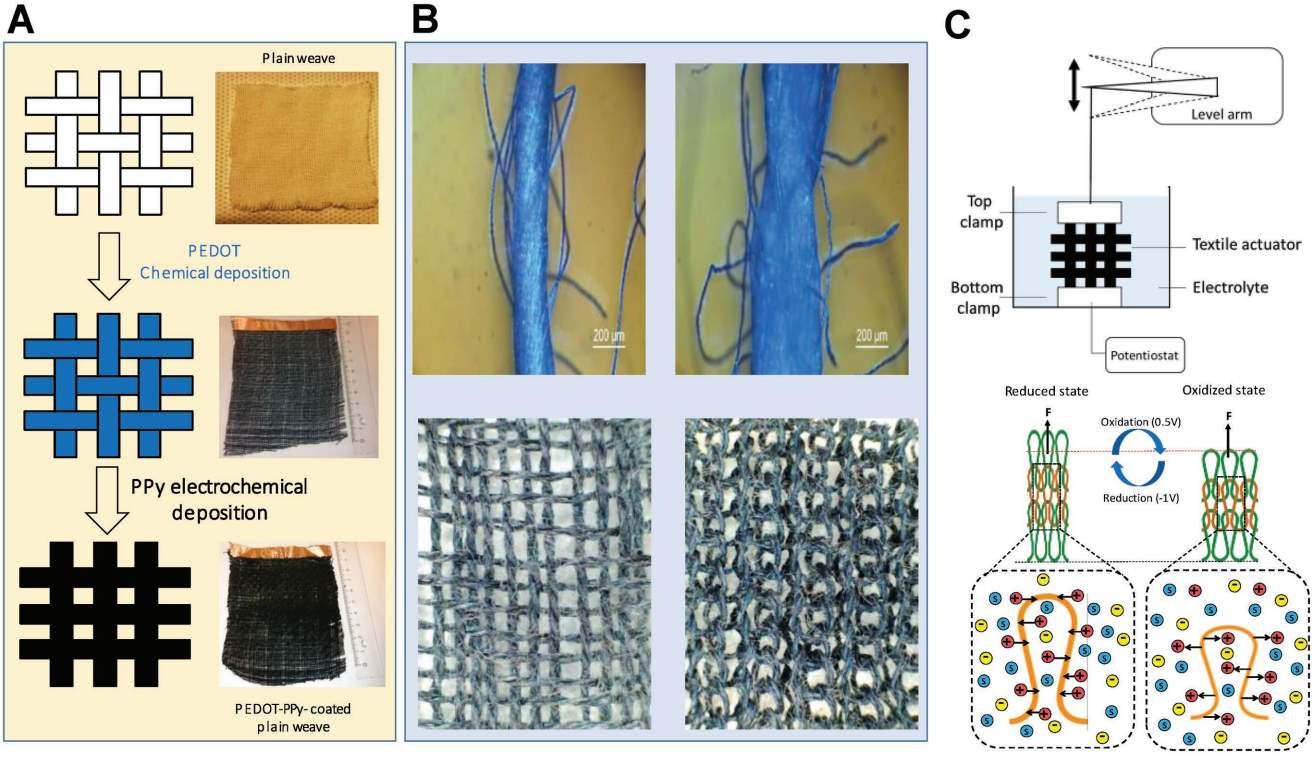

Figure 5. EAP based textile actuators for enhanced force and enhanced strain. a) Schematic description of the manufacturing process using deposition of and polymerization of PEDOT and polypyrrole. b) Single and 2-ply yarns used in the study coated with PEDOT (left and right up), photograph of VPP PEDOT-PPy-coated (2.0 wt%) Lyocell-based weave to the left down and knit, right down. c) Set up of the textile actuator (up) and (down) schematic description of the actuation process. The fabric is inserted in an electrolyte solution containing cations (+), anions (–), and solvent molecules (S). When reducing the PPy, cations are attracted into the yarn (orange), causing an elongation of the yarn. Subsequent oxidation of the PPy then causes the ions to be expelled. Then, the yarn shrinks, and the loop closes, which result in a net contraction of the fabric. Reproduced with permission.[78b] Copyright 2017, The Authors, published by American Association for the Advancement of Science.

In order to incorporate CPs into textiles, two main pathways have been followed: synthesizing solid CP yarns/fibers or coating passive yarns with CPs.[68] The second strategy is the most extended one, as it has been the easiest one. Thus, various conducting polymers, e.g., polyaniline,[69] poly (3,4-ethylenedioxythiophene) (PEDOT),[70] or polypyrrole,[71] have been used to coat passive yarns such as polyethylene terephthalate, cotton, polyester, or hydrogels.

Usually, this is done by chemical polymerization on the passive yarn. The yarns are precoated with a powerful oxidant by dipping them in an oxidant solution and thereafter the monomers being polymerized on the yarn, resulting in a yarn coated with a uniform layer of an oxidized CP. If the monomer is dissolved in the same oxidant solution in which the yarn is immersed during the polymerization, then it is a classical chemical polymerization.[72] If on the other hand, the yarn impregnated with the oxidant molecules and thereafter is inserted in the monomer vapor, it is called a vapor phase polymerization[73] Both methods have been used extensively to make the passive yarns conducting. Once the yarns are conducting, often an additional electrochemical polymerization is performed to get a better CP for mechanical actuation.[72,74]

As mentioned, yarns of pure conducting polymers can also be obtained. They are usually synthesized through wet spinning, a specialized form of extrusion that uses a spinneret to form multiple continuous filaments or monofilaments.[75] The resulting CP yarns are usually very thin and brittle that, although they present great features for applications as energy storage, makes them difficult to use them as part of textile actuators. However, polyaniline yarns could be obtained and a linear actuator working in air was constructed.[76] Electrospun silk fibroin bundles have been realized to construct artificial muscles.[77]

Following the same procedures, it is possible to functionalize a set of yarns, either in the form of thicker threads or in the form of a fabric.[78] Besides the above mentioned chemical polymerization,[79] spray or dipping coating with commercially available poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS) solution, sometimes complemented with additives to increase the electrical conductivity, has been used to make conducting fabrics.[80] These conducting fabrics have been mainly used as strain sensors to develop wearable position sensors.[80,81] A textile actuator where moisture is utilized has been shown.[82] Here a commercial cloth template was impregnated by a 3D nanoporous polymer/carbon nanotube hybrid network. Tunable folding, twisting, and rolling were achieved via design of single twin-bundle actuator, double twin-bundle actuator, triple twin-bundle actuator, and flat cloth actuator. By hierarchical and helical assembly of aligned carbon nanotubes[83] into fibers actuation was created that respond to solvent and vapor stimuli due to the existence of nanometer-sized and micrometer-sized gaps in the fibers. These fibers were flexible and strong and can be woven into a smart textile actuator.

5.6. Distance Change

A mechanism for many CNT containing fibrous actuating system is electrostatic repulsion among the CNT fiber inclusions. By this repulsion the material is made expanding. Lee et al. developed an all-solid-state actuator based on two parallel braided CNT yarns, able to work in air, providing tensile contractions up to 11.6%.[84]

6. Issues of Soft Actuators

As seen in Figure 2 and in the previous discussion there are a number of issues for many of the actuator types.

The issues these types of actuators show include that force and stress are low,[59c] at least for every day, anthropocentric applications. Strategies to overcome this include morphology control and enhanced synthesis quality in the case of order changing shape memory polymers, increasing the conductivity for electroactive polymer based absorption volume changing types and ordering and dispersion of the conductive inclusions for CNT containing distance-changing actuators.

A second issue is the reversibility. For example many shape memory alloys and shape memory polymers need considerable heat/mechanical treatment for "reprogramming" them, thus making them impractical in applications where actuation is needed continuously or where the product is of low cost and associated with low readiness for maintenance.

A third question is whether the actuator is automatically activated or controlled. Automatic here means that some change of state of the ambient environment such as temperature occurs that trigger the actuator into action. This is wanted for stand-alone devices. Controlled means that activation could be done when demanded. Most common is to utilize devices where the operation mechanism is already based on electrical phenomena and control these devices by current and voltage.

Another problem is that of effective production of the actuators. The different soft actuator types of Figure 2 show different degrees of maturity but most of them are still at a lab scale. Common is that small items need to be assembled together, at low cost, and with maintained repeatability and quality. Added to this is that large area devices—in accordance with the general contemporary trend of electronics—are wanted. This is at the moment far from what is possible to achieve in research laboratories labs.

6.1. Addressing the Low Force Problem

As a mean to overcome the low force problem we recently developed a new class of textile actuators using polypyrrole (PPy) as the active material.[78b] The approach to creating the actuating fabric is similar to the dyeing process routinely used in textile industry; the method involved to first fabricate the textile fabrics and thereafter coat them with the electroactive polymer PPy (Figure 5a). Cellulose-based materials (Lyocell) produced by a renewable green chemistry were used here, including single and two-ply twisted staple yarns. The yarns were assembled into two different textile constructions, a twill weave and a rib knitwear, using standard industrial textile production machines (Figure 5b). The textile is coated using a two-step chemical–electrochemical synthesis. First, a chemically "seed layer" is synthesized on the fabric to form a highly electrically conductive surface, allowing the consecutive electrochemical

deposition of the functional, actuating PPy layer. To achieve a uniform coating of the conductive seed layer, vapor-phase deposition of PEDOT was used (Figure 5a). Electrochemical actuation of the devices is performed by immersing the electroactive textile in a three-electrode electrochemical cell containing ions and solvent molecules. The individual fibers or yarns mechanically behave like linear actuator and can provide an isotonic contraction/expansion of ≈0.14% and an isometric force of 8.0 mN upon the oxidation and reduction of the PEDOT-PPy. Textile processing allows here rational parallel assembly of fibers/yarns by weaving the yarns (the mechanical parallelism property discussed earlier) and this increased the total force of the actuators while conserving the strain and keeping the advantages of single, thin yarns, that is, a high surface-to-volume ratio. The absolute output force increased and was proportional to the number of parallel-assembled CP yarns in the weave fabric. For instance, a textile weave with 6 parallel yarns exhibited a force of 64, and with 12 parallel yarns exhibited a force of 100 mN, compared to the individual T-yarn (8 mN). The weave also added a mechanical stability to the textile actuators which resulted in an increased operational lifetime of the PEDOT-PPy textile actuator as compared to single CP films or fibers.

6.2. Addressing the Low Strain Problem

Another advantage of textile processing is that one can knit the yarns into highly stretchable fabrics. We employed this effect too in the textile actuators.[78b] A textile actuator constructed from a knit rib wear showed 53-fold more strain as compared to a single yarn. Here the textile property mechanical serial connectivity is explored.

6.3. Addressing the Production Problem

The textile community offers robust high-speed production with a considerable degree of repeatability, at low cost and at large volumes. Textile processing embraces techniques for assembling many small, elongated, flexible objects, i.e., threads or fibers. By also taking the $D = M$ property of textiles into account where single threads are acting as devices and these are assembled by weaving and knitting simultaneously as the material—the fabric—is produced, textiles offer interesting opportunities for how soft actuators could be produced. A prerequisite is that the actuators are fiber formed and as has been discussed many of the soft actuators types indeed are or are compatible with such form factor.

6.4. Addressing the Automatic Issue

As discussed with the TATA system above it is possible to introduce a functionality of textiles actuators where actuation is taking place due to change in the surrounding. Thus for textile actuators a broad spectrum of automatization is at hand with the thermal volume change and order change belong to the most automatic and distance change, piezo and absorbing types as the most controlled (following the definition of actuation on demand).

7. Summary

In conclusion, textile characteristics like the $D = M$ property, x–y addressability, truss similarity, mechanical parallelism, and mechanical serial connectivity enable textiles to address some of the issues of present soft actuator technologies. This includes the low force and low strain issues of many soft actuator technologies. But textiles could also add the question of how to produce soft actuators. Textile technology allows industrial scale technology thus enabling low cost as well as large area devices.

To take wearables to the next level, the soft actuators should be integrated with textiles, preferably already during the production process. That is, actuators should be formed in the shape of yarns or fibers that can be woven or knitted into or onto the fabrics. We can take exoskeletons as an example. While the progress in exoskeleton is impressive and commercial exoskeletons for (re-)habilitation[85] are available, they still look and feel like wearing a "robot-suit." It would be more user-friendly if such assistive devices could be shaped as a piece of clothing, like a pair of tights with integrated textile actuators to assist the wearer in walking. Mechanical, as compared with mere electrical, output is highly anticipated as this will enable textiles to mimic shapes and gentile movements of organisms as well as those of machines, opening up a wealth of interesting opportunities.

Acknowledgements

This study was supported by the Carl Trygger Foundation (grant CTS 12:206), the Swedish Research Council (VR-2014-3079), and the Smart Textiles Initiative, University of Borås.

Conflict of Interest

The authors declare no conflict of interest.

Keywords

knitted muscle, smart textiles, TATA, textile actuators, textuators

Received: December 29, 2017
Revised: May 16, 2018
Published online: July 25, 2018

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