Textiles have emerged as a promising class of materials for developing wearable robots that move and feel like everyday clothing. Textiles represent a favorable material platform for wearable robots due to their flexibility, low weight, breathability, and soft hand-feel. Textiles also offer a unique level of programmability because of their inherent hierarchical nature, enabling researchers to modify and tune properties at several interdependent material scales. With these advantages and capabilities in mind, roboticists have begun to use textiles, not simply as substrates, but as functional components that program actuation and sensing. In parallel, materials scientists are developing new materials that respond to thermal, electrical, and hygroscopic stimuli by leveraging textile structures for function. Although textiles are one of humankind's oldest technologies, materials scientists and roboticists are just beginning to tap into their potential. This review provides a textile-centric survey of the current state of the art in wearable robotic garments and highlights metrics that will guide materials development. Recent advances in textile materials for robotic components (i.e., as sensors, actuators, and integration components) are described with a focus on how these materials and technologies set the stage for wearable robots programmed at the material level.

1. Introduction

We spend most of our lives in direct contact with textiles, whether in the form of clothing, bed sheets, pillows, bandages, reusable bags, or even face masks used to prevent the spread of disease. Recently, the field of robotics has begun to adopt textiles as materials of choice for wearable robots and devices because of many of the advantages textiles exhibit in these everyday applications. For example, compared to the rigid metals, composites, and plastics used in wearable robotic exoskeletons, textiles—and in turn, robotic garments constructed from them—are lightweight, soft, and flexible, and can improve safety for the wearer and others in the vicinity of the wearable robot. In addition, textiles promote garment comfort: they are inherently breathable because their porous structures permit the transmission of vapor, allowing evaporative heat flow away from the body.[1] Textiles are also robust, and they resist abrasion and tear propagation due to the ability of individual yarns to move.[2] Unique structural and mechanical properties are possible due to the textile structure (**Figure 1**); for example, knit loops enable stiff and relatively inextensible fibers and yarns to become stretchable metamaterials. Therefore, when traditionally hard components, such as electronic circuits, are integrated into wearable robotic systems, a textile architecture can enable the necessary materials to be a part of a flexible and soft system through its geometry. Last, researchers and designers can create 3D shell structures through knitting, weaving, and sewing that cannot be made easily with many traditional manufacturing methods. And because textiles are commercially available materials, they support the rapid transition of devices from the research lab to medical or consumer products.

The field is undergoing a transition from viewing textiles as substrates—that is, base materials upon which we attach sensors, actuators, and power supplies—to utilizing textiles as programmed active textile systems, in which robots can be formed from the ground up in an integrated manner (**Figure 2**). Originally, textiles were used as passive substrates, materials that primarily acted as scaffolds to comfortably and conformally fit the body and anchor rigid components (e.g., LEDs, motors, printed circuit boards). In such a configuration, the textile lends little functionality to the wearable robot beyond that provided by everyday clothing. In the early 2010s, researchers began to leverage the unique mechanical properties of textiles in order to design and improve the function of wearable robot components. Engineered actuators with varied textile structures direct forces[3–5] and define motions,[6–9] while sensors employ carefully selected and developed textile architectures to increase sensitivity.[10–13] A majority of this work is done in a discrete manner; generally, sensors and actuators are developed separately and full systems are subsequently built through cut-and-sew techniques, piecing these components together into a robotic garment.[14–20]

The field is moving towards an approach based on programmed active textiles, which we define as systems wherein a majority of the textile robots' passive (fit, shape, comfort) and active (actuation, sensing, signal lines and integration) functionality can be pre-programmed through textile-structural fabrication processes in an additive, hierarchical manner. Through modification of the scale and placement of components, the textile microstructures, and the materials, a systematic and iterative device development loop will form that will ultimately

Figure 1. A selection of materials produced through textile structuring and post processing. a) Jacquard weaving enables a variety of materials to be integrated on the front and back of a textile in a programmed manner. Textile designed by Brandon Wen, worn by Ben Adam, and photographed by Oxiea Villamonte. Reproduced with permission. Copyright 2020, the designer and photographer. b) Multi-color, or jacquard, weft knitting patterns multiple yarns into a monolithic structure while providing intrinsic stretchability. c) Sewing enables attachment of many discrete rigid components (here, glass beads), while maintaining material flexibility. Textile designed and photograph provided by Johnathan Hayden. Reproduced with permission. Copyright 2020, the designer and photographer. d) Textile structures program larger scale shaping; here, a combination of knit and purl stitches self-folds into a wrinkled structure. e) Low-cost nonwoven formation processes shape fibers directly into textiles. f) Some textile structuring processes create 3D globally shaped shells: for example, braiding produces tubes that act as springs, while 3D weft knitting can make g) complex shapes like branching tubes. h) Post processing techniques like pleating can modify the mechanical properties of a textile—a relatively stiff woven material can become stretchable. i) Spacer knit textiles have been used to provide padding or as 3D structuring for sensors. A research sample highlights the unique knit construction used to achieve this type of structure. Textile designed by Suzanne Oude Hengel and Milou Voorwinden and photographed by Lieke Biel. Reproduced with permission. Copyright 2020, the designers and photographer. j) Textile finishing processes like lamination create composite materials with textiles and films; here a knit textile is bonded with thermoplastic polyurethane (TPU) films. All scale bars represent 10 mm.

enable full textile robots. The advantages and capabilities of this textile-based approach parallel those offered by 3D printing.

In a programmed active textile formation technique, such as 3D multi-material weft knitting, multiple materials can easily be mechanically coupled together without adhesives, and without the challenges that would be encountered in subtractive processes like computer numerical control (CNC) milling. Analogous to multi-material 3D printing, in which material placement and shaping can be controlled, programmed textile formation is an additive process which enables technical textile structures that are completely unique to the device needs by defining global shaping and placement of varied micro-structured areas, as seen in the recently-developed Nike Flyknit sneakers. However, unlike 3D printing, textile formation allows for structures with more internal open spaces, without the use of support material and with little consideration for the component materials' chemical compatibility. Yarns are predominantly in a solid phase during textile formation, and no inter-material adhesion is typically required to hold structures together. These processes are being used currently at production scale; however, the speeds are slower and the costs are higher than producing yardage of material and using cut-and-sew processes to form simple shapes. As such, this approach is not yet optimized for making basic structures, like a simple T-shirt.

Similar to CNC machining and 3D printing, there is less operator involvement in programmed active textile fabrication processes as compared to cut-and-sew techniques. This automation can reduce variation between samples due to

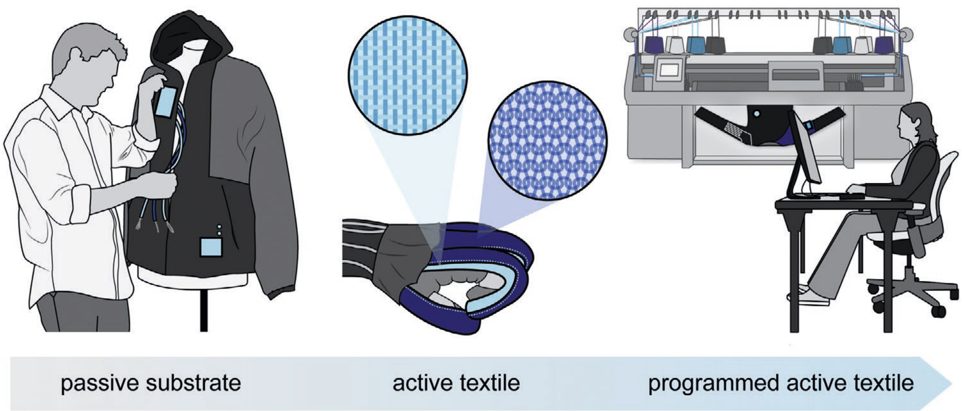

Figure 2. The future of textile-based wearable robotics. Incorporation of textiles in wearable robots has evolved from using textiles as passive substrates to considering them as active materials. Recent developments are paving the way for a future where active textile systems can be pre-programmed and where global garment shaping and distributed sensing and actuation patterns can be created at the time of design.

human variability in fabrication. Additionally, the programming approach enables higher resolution patterning than cut-and-sew; for example, knit stitches on a fine gauge 3D knitting machine can support 7.2 stitches per centimeter (i.e., each stitch is approximately 1.4 mm in width, not considering pre-strained material effects which will further decrease stitch size when relaxed). Typical minimum tolerances for machine sewn garments made by human operators are in the 3–5 mm range.[21,22]

A programmed active textile system approach is highly supportive of customizable mass manufacturing. Mass customization is on an uptick for consumer purchases[23] and supports a more sustainable apparel manufacturing route because excess fabric scraps are not generated, as opposed to cut-and-sew processes. Wearable robotic systems can be produced as needed, limiting excess inventory of raw materials. Additionally, in the field of functional apparel, experts on size and fit have argued that there is no universal sizing standard to accommodate the broad range of human body types; statistical averages used to define size sets result in garments that truly fit "no-one" perfectly, or that consistently leave out less common body types.[24,25] In addition to cultural traditions and societal norms, our current everyday clothing is worn for modesty, warmth, and aesthetics. Although ill-fitting everyday clothing has limited negative consequences for the wearer, for robotic clothing which incorporates function that is highly dependent on precise placement of components (such as force-paths) on the body, poor fit can reduce performance,[3] motivating the need for customization.

With this change underway, in this review we have compiled and generalized current findings in the active textile material area and preliminary work in the programmed active textile area of textile robotics research in order to provide a framework on how textile structures are employed in these systems, highlight the lessons learned in the literature, and identify promising areas of future research (**Figure 3**). We note that, while wearable robots may take many forms, in this review we exclusively focus on wearable robots that function by changing shape or applying force to the wearer, thereby incorporating a clear mechanical actuation component in their operation. Because textile-based robots are so closely linked to their wearable applications, this review first describes several common use cases of textile-based robotic garments and their generalized system-level needs in Section 2. We then provide a brief overview of textile structures, machinery, and general textile terms for a materials science, engineering, and robotics audience in Section 3. Next, we highlight how the properties of textiles are being leveraged in the constituent components of robotic garments, including: actuators described in Section 4, sensors in Section 5, and integration including signal, power, and fluidic lines in Section 6. We link the performance of these components back to implications for wearable devices, while highlighting gaps and areas for future directions. Last, we conclude this review and discuss the current state of the field and our outlook for the future in Section 7.

2. Applications for Textile-Based Wearable Robots

Research into textile materials as sensors, actuators, and integration lines is largely driven by the needs of applications—wearable robots are the primary application area for this work. Wearable robots require actuators to change garment shape or apply forces to the body, sensors to detect the wearer's state, determine interaction between the robot and the wearer or their environment, and monitor the robot's independent state, and integration components to link these constituent parts distributed throughout the garment to processing, power, and control elements.

Textile-based wearable robots have been developed through research efforts in fields including robotics, biomedical engineering, and human-computer interaction. By compiling this research, it is apparent that several classes of wearable robots are emerging, including locomotion assistance, grasping and reaching, shape-change for dressing, thermoregulation, haptics and communication, and therapeutic compression (**Figure 4**). Even within these classes, the mechanisms of operation and form factors of wearable robots can vary considerably, yet there are clear and distinguishable trends defining these separate application areas. The goal of this section is to describe these textile-based wearable robot application areas, dissect area-dependent performance goals, and compare the performance metrics across areas in order to provide materials scientists defined targets in their development of textile components for wearable robots.

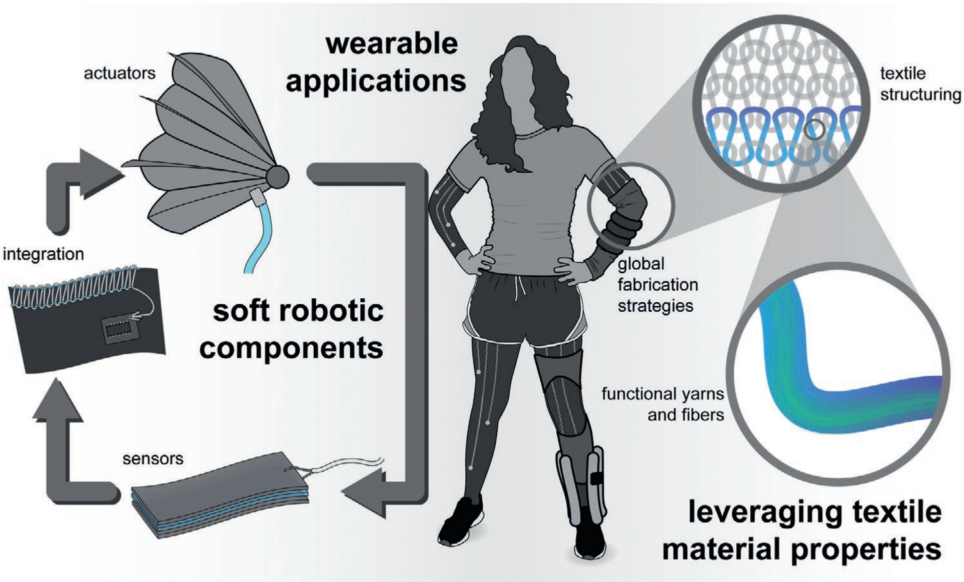

Figure 3. An overview of the contents of this review paper. We identify major application areas for garments with embedded robotic elements and their system-level metrics, driving performance requirements for new materials. We then provide a brief overview of the hierarchical textile structure and summarize how properties unique to textiles are leveraged when developing sensors, actuators, and integration components necessary for soft robotic and autonomous garments.

2.1. Locomotion Assistance

Wearable robots for locomotion augment able-bodied people and assist people with mobility disabilities in activities including walking,[26–30] running,[31] and sit-to-stand motions,[18,32] which enable the user to begin locomotion. These devices can be used as assistive garments or as training and rehabilitative devices. A majority of these devices do not provide the full forces

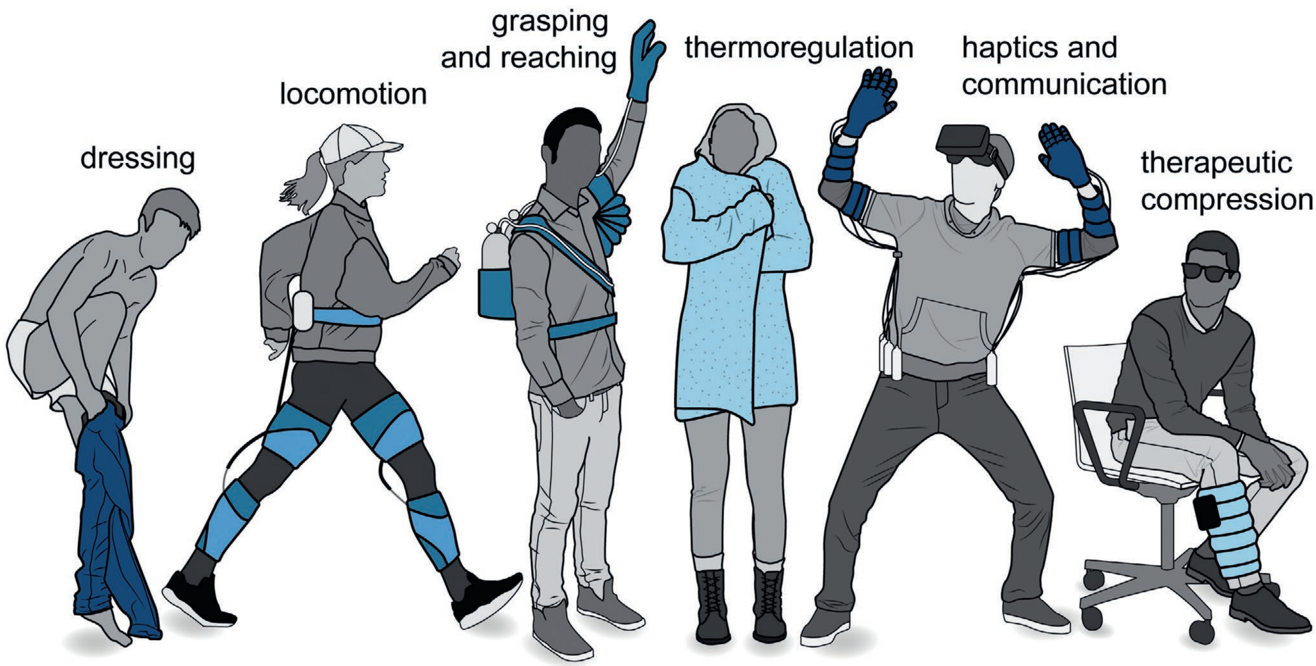

Figure 4. Common use cases for textile-based wearable robots. Autonomously extending and retracting garments assist with dressing. Garments that apply forces to biological muscle aid locomotion while using sensors to detect gait cycle timing and provide support to assist with grasping and reaching while determining arm and hand motion through sensing. Dynamic thermoregulation assistance through shape-change alters garment coverage area or modifies textile porosity. Garments provide physical cues for haptic feedback and communication while obtaining information about the wearer's posture and motion. Compression wearables assist with rehabilitation and therapy while gaining sensor information to provide correct pressure doses.

necessary for locomotion and instead work in parallel with the wearer's biological muscle. For example, when used to assist walking, these robots actuate along with the user's step, as opposed to the robot providing all of the force to walk and support the wearer. This approach is possible because research has shown that relatively low levels of assistive force can enable significant reductions in metabolic cost, although these reductions scale with the magnitude of assistance.[33] The use of textiles improves comfort, enables devices to fit more users, and allows these devices to reduce mass around distal components and concentrate it in a central location to increase efficiency.[33,34]

Commonly, textile-based robotic garments for locomotion employ actuators that contract or use displacement mechanisms (e.g., pulleys) to pull across a joint (typically the ankle, knee, or hip) to assist with extension or flexion, similar to the contraction of biological muscles. These actuation profiles are achieved in textiles through cable driven systems that use separate electric motors and mechanical linkages,[18,27,35] or textile-based pneumatic artificial muscles,[7,28,29,36] which require a compressor or compressed fluid tank in addition to a power supply. In addition to fibrous cables and textile pneumatic artificial muscles, textile materials find function in passive areas of these wearable robots. Fabrics with high tensile stiffness are designed into the garment structure as anchoring points for actuators so that the forces may be efficiently transferred through the system, reducing losses due to stretching the material.[33,37] In addition, textile-based foam composites and meshes dampen the applied forces for wearer comfort.[31] The fluidic actuation approach implements global patterning of woven textile pouches with high tensile stiffness (described in more detail in Section 4.2) to create tailored fluidic actuators that can assist with flexion at a joint,[17] extend at a joint,[30,32] provide support through a change in material stiffness,[7,29] or implement a combination of these strategies. Few instances of "shape-changing-material-based" wearable robots for locomotion have been demonstrated to date, and those developed employ few textile-based components.[38,39]

These wearable robots require sensors in order to estimate the position of the wearer, determine the force the actuators are applying to the body, establish the position of actuators, and obtain information used to estimate timing in the gait cycle. Commercially available load cells have been integrated into cable driven implementations of these robots because they can accurately determine the force of the cable; however, they remain rigid and bulky.[27,31,35,37] MEMS-based inertial measurement units (IMUs) are commonly employed to determine wearer joint angles[31,36,40] and to estimate gait timing measurements because they provide multi-axis data and are commercially available at a low cost. However, these sensors are rigid, often bulky, and typically not fully integrated into the textile garments to allow for maintenance including washing. Alternatively, softer film-based force sensors,[29] pressure sensors,[40] and switches[28,37,41] implemented in insoles or shoes can help estimate gait cycle timing by mapping the amount of contact between the wearer's foot and the ground,[38] signaling the heel-strike and toe-off times,[41] or potentially by determining the center of mass. In addition to film-based composites,[29] textile-based implementations have demonstrated utility as soft sensors. Soft textile-based sensors have been employed to characterize the pressure profiles delivered by textile robots; however, these sensors are not integrated into the garments.[3] Although less commonly used in full wearable robotic systems, soft strain sensors for joint angle determination[36] and gait measurement have been proposed[42] and highlight a potential approach for creating fully textile-based wearable locomotion assistance robots. While not typically used in textile based garments for locomotion outside of evaluation, electromyography (EMG) is another potential strategy in determining wearer intent.[43] Sensor drift has been identified as an issue in these systems,[40] and can affect all types of sensors, signifying the importance of developing and characterizing sensors that are robust to continuous and cyclic use in variable environments.

The requirements for wearable robots that assist with locomotion vary based on the targeted user population (e.g., people who have experienced a stroke compared to able-bodied users), the joint being assisted, and the type of locomotive activity (e.g., walking, running, sit-to-stand). Speed requirements for wearable robots change with the desired speed of locomotion—when people run or walk at faster speeds, their stride time typically decreases, meaning that the gait cycle bandwidth increases. In one experiment on running, an average gait cycle bandwidth per leg for a speed of 4.1 m s^{-1} was 1.44 Hz, while at 3.1 m s^{-1} bandwidth dropped to 1.38 Hz.[44] In another study focused on walking, gait cycles per leg ranged from 0.56 Hz at a walking speed of 0.53 m s^{-1} to 1.25 Hz at 2.1 m s^{-1} walking speed.[45] These speeds guide requirements for textile-based robots, but because assistance can be most effective when applied at specific timings during the gait cycle, often with actuation cycles taking 50% or less of the stride period, locomotion assistance robots must be faster.[17,28,31,46,47] Generally, textile robots for populations with mobility disabilities operate at slower speeds and apply lower forces than those made for able-bodied populations.[7,27,31,47] Assistive forces provided by the wearable robot can be scaled in proportion to those provided by the body, and scaling must also take speed into account. Peak torques generated by muscle motion can vary based on speed, as seen with the torque of the knee flexor, where one study reported a maximum torque of approximately 45 Nm at a walking speed of 5 mph and a minimum of approximately 11 Nm at 0.5 mph.[48] When assistance magnitude was scaled to body mass for a locomotion assistance textile-based robot for able-bodied wearers, higher forces provided a higher metabolic reduction.[33] Sit-to-stand motions can require higher torques than those in a typical gait; in one study, the average joint torque was determined to be approximately 180 Nm per leg for extension of the knee, 120 Nm per leg for dorsiflexion at the ankle, and 80 Nm for flexion at the hip for a "fast sit to stand motion."[49] Many of these values are affected by the weight and anthropometric measurements of the person, and additionally often only enlist male participants, meaning women may have different requirements.

2.2. Grasping and Reaching Assistance

In a typical day, people reach for, grasp, lift, and manipulate a variety of objects in order to interact with their environment for tasks like opening doors, eating meals, or taking showers.

Textile-based wearable robots that assist and rehabilitate users with grasping, reaching, and lifting actions enable users with upper extremity mobility disabilities to be empowered and independently interact with their environment,[5,16,50–52] and to reduce fatigue or increase power of able-bodied wearers.[22,53] Here, textiles offer similar capabilities in terms of comfort, safety, and lighter weight to those seen in robotic locomotion assistance. The "transparent" nature of textiles has additionally enabled these robots to be magnetic resonance imaging-compatible for simultaneous rehabilitation and imaging exercises.[54,55] Because of the lighter weight of the upper extremities compared to the legs, more robots used for grasping and reaching assistance have been developed to fully support motion, but those used in parallel with biological muscle are still common.

Grasping and reaching assistance robots use actuators that either flex or extend the joints of the fingers,[14,56] the wrist,[57,58] the elbow,[22,59] or the shoulder.[16,59,60] Strategies to support abduction of the shoulder, provide a scaffold to support the limb, or a combination of these methods are also common.[61–63] Cable driven systems are commonly employed and use textiles to define and route anchoring points across the body.[19,51,61,64] Fluidic textile actuators are frequently used to "push" and create temporary supporting structures to cradle the body.[22,62] In addition to global shaping of textile fluidic actuators,[16,22,60,65] seen in locomotion assistance robots, multi material textile actuators consisting of combinations of knits and wovens have been employed to create motions such as bending to match those of the body.[6,20,66–68] The lesser forces required in some applications may enable the use of these stretchable knit materials.

Many of these robots have been developed with control systems that consider the state of actuators (e.g., position, pressure, force) but do not include the state of the wearer and their environment in their controller. This is potentially a consequence of the added uncertainty and complexity involved with grasping, reaching, and lifting tasks compared to the relatively consistent motions seen in walking and running. In addition to the force or pressure sensors used to determine the force of a cable or pressure of a fluid within a textile pouch, researchers have begun to employ additional sensors to estimate the position of the limb,[14,20,69,70] acquire environmental cues,[5] obtain wearer inputs,[53,71] and detect intent.[20,72,73] For these applications, textiles have been used as a substrate to hold IMUs to obtain the position of the arm.[61,69] EMG sensors help detect user intent and may include traditional adhesive electrodes that are not part of the wearable robot,[20,74] or can employ garment-integrated textile electrodes.[75,76] Textile-based strain and pressure sensors can determine assistive glove position and grasping force.[14,67] Recently, textile-based strain sensors have been used to estimate the position of the shoulder, which is particularly complex due to its multi degree-of-freedom (DOF) motions.[15]

Depending on the device use case, joints assisted, and ratio of user to robot effort, the metrics of these robots vary accordingly (e.g., a robot built to help warehouse workers lift boxes would require higher forces than a robot built to assist a person who has a spinal cord injury lift their food on a fork). Considering interactions with the objects encountered during activities of daily living (ADL), baseline metrics can be determined. For grasping, the bulk of the objects encountered in everyday life weigh 1.5 kg or less.[77] Experimental data on pinch force requirements for a variety of daily living tasks were determined to range from 1.4 to 31.4 N, with a majority of tasks requiring 10.4 N or less.[78] Maximum grip strength of healthy young adults may be more than an order of magnitude higher than these forces.[79] Forces and moments for the elbow can be higher than those of the hand during ADLs, with maximums reported as high as 25 N along the humeral longitudinal axis and 5.8 Nm for elbow flexion when raising an object to head height and lowering it to a shelf.[80] For reaching with the shoulder, Rosen and colleagues found the highest torque required for ADLs to be 10 Nm.[81] The bandwidth for both sensors and actuators can be dictated by the motions of the human body. Hand speeds and movements can be quite fast, with a maximum range of 6–12 Hz and movements >2 Hz often utilized during ADLs,[82] while most motions of the body are <10 Hz.[83] However, when considering a rehabilitation approach, these speed requirements may be slower. For example, in assistive gloves, typical rehabilitation exercises for fingers are performed at <0.5 Hz.[84,85]

2.3. Shape-Change for Dressing

Dressing is an ADL which approximately 4% of non-institutionalized Americans over 65 and approximately 79% of institutionalized Americans over 65 have required help from another person to perform.[86] And, paradoxically, while dressing is the most burdensome ADL on assistive staff, dressing has seen the most limited use of assistive technologies.[87] While several groups have proposed at-home robotic systems (typically containing rigid robotic arms) to aid with dressing, self-fitting and assistive dressing garments may potentially enable the wearer to dress and undress throughout the day regardless of location. Self-fitting garments may also alter their fit (i.e., varying their shape and compression on the body) for functional support or aesthetics, which holds promise for light compression garments in particular, as they can be difficult to don and doff.

For self-fitting and assistive-dressing garments, multiple approaches can be taken; the garment may dynamically expand and contract (either by simply modifying its amount of "ease,"[88,89] or by expanding into a structure into which the user may enter[90]) so the user may put on the garment, or vary its compression force over time to alter "fit."[91] Oftentimes shape-changing materials, such as SMAs[92] or coiled polymer actuators,[91] integrated into textile garments have been employed because high forces and speeds are not as critical. Fluidic actuation systems have also been used.[89,90] In these systems, the shape-change is reversible over many cycles, as opposed to one-time shape-changing garments that are permanently "tailored" for the body.[93]

Most of these garments have not yet incorporated sensors or closed-loop control schemes; however, one could envision the potential of sensors in these systems. Force and pressure sensors can ensure that safe, prescribed levels of compression could be implemented in garments that apply light levels of compression for fit, while strain sensors could be used to optimize the amount of expansion and prevent unnecessary over-stretching to save the user time.

Garment "fit," the end goal of a dressing action, is a challenging metric to quantify and measure because the body itself changes shape during motion, and thus fit can vary immensely.[25] A general takeaway is that these garments require large amounts of expansion. For example, 50% strain is noted as a textile requirement for use in activewear, which is assumed to include the needs for donning and doffing.[25] When considering compressive fit of standard garments, one may note that estimates of the maximum comfortable normal pressure of orthoses are typically around 5 kPa,[94] while other sources indicate that blood flow drops but remains stable at 30 mmHg (≈3.9 kPa);[95] additionally, others have selected values below those reported for medical compression (<2.4 kPa).[88,96] As for speeds, providing someone the ability to dress themselves may not have as strict time constraints, and actuation cycles that last several minutes may be acceptable.

2.4. Thermoregulation

Standard thermal comfort is defined quantitatively as a balance between the metabolic heat generated by a person and the heat loss to the environment.[97,98] Garments play a role in this relationship because they dictate the body's interactions with moisture, heat, and light. By dynamically altering the properties of their constituent materials, robotic garments may actively assist in wearer thermoregulation.

Robotic and autonomous textile systems for thermoregulation actuate and change their shape to alter the coverage area of the garment[99] or change the textile on a microstructural level to modify porosity or radiation blocking properties.[100] In these systems, reversible, cyclical shape-change is achieved without any user actuation, unlike semi-passive systems including phase change garments in which the user must manually put the garment into a cold environment to solidify a liquid[101,102] or replenish fluid that has evaporated[103] to maintain the effect. Although there are other approaches to develop responsive garments for thermoregulation, including integrated fluidic cooling systems[104,105] and textile-based Joule heating wearables,[106–108] because there is no mechanical actuation directly associated with the textiles used in these systems, these areas will not be considered in the scope of this review. For a detailed review on smart textile-based systems for thermoregulation, beyond robotics, we recommend the article by Tabor and colleagues.[109]

Typically, shape-changing materials are integrated into textiles to actuate and change structure on a garment level to alter garment breathability,[99,110] and thus its heat transfer and moisture management properties, allowing for more sophisticated temperature regulation than simple passive protection from the elements. Going deeper, some garments incorporate structural changes on the yarn scale (described further in Section 3) to modify IR properties of the textile.[100] These systems most often respond to a stimulus through self-sensing, or have not yet had an electronic closed-loop controller accounting for the state of the environment and the wearer. Additional sensing elements could be incorporated into devices that use non-environmentally actuated shape-change for dynamic temperature and humidity-regulated electronic feedback control.

General formalized metrics have not yet been reported for robotic garments developed in this field. As changing the garment shape is the goal of these devices, forces are not typically measured, and indicators of success include lower temperatures between the garment and skin or less IR transfer through the garment when compared to a control garment.[99,100] As many of these robotic textiles require distributed active material networks to open large numbers of pores or to work together to change a structure, it may be quite hard to accurately measure and understand the discrete force contributions in the textile structure, opening up some interesting research questions. When considering speeds, relatively slow systems are currently acceptable, with actuation speeds of approximately 0.01 Hz reported.[100]

Aside from metrics, some design rules should be considered. For thermally driven actuation systems, the actuator material should either be i) minimized to prevent injecting additional heat into the system, unless it can be coupled with a change to increase insulation of the wearer, or ii) optimized to change with ambient temperature. For example, an SMA-driven system, which often requires >100 °C to actuate, may be best actuated when contraction of the fiber results in more insulation, leading to a synergistic heating and insulating effect. Meanwhile a material that contracts upon a temperature differential encountered in the ambient environment may be used without artificially injecting heat into the system, allowing environmental change to drive textile shape-change.[111]

2.5. Haptics and Communication

Wearable robots for haptics and communication provide a diverse range of functions for the wearer, including user interfaces, navigation cues, movement cueing and guidance, and notifications. While some garments in this area change their shape to communicate visually to others,[112,113] a large subset of the area of communication and haptics includes tactile feedback wherein several main mechanisms are employed including vibration, point-based pressure, compression, skin stretch, curvature change, temperature change, and impedance (or resistance to wearer motion).[114–116] Wearables for tactile haptics and communication can take many forms including sleeves,[114] gloves,[117] bracelets,[118] and entire garments.[119–122] Based on the location of the haptic device, the feedback mechanism used, and the device goal, the component design and performance metrics change.

Haptic systems for tactile feedback apply vibrations and forces to the body[118,123] or restrict its motion.[124] Rigid vibration motors, often attached to textile substrates, have been one of the most ubiquitous methods used because they are inexpensive and can reach the higher range of frequencies that skin mechanoreceptors can sense.[120,125,126] Recently, in order to provide more comfortable, conformable, and soft haptic wearables, textile integrated approaches have been explored using cable driven systems, fluidic systems, and shape-changing materials. Textile-integrated cable driven actuation systems have moved the torso for drone steering,[127] textile-integrated elastomer DEAs have provided vibration cues,[128] and SMA-integrated textile robots have applied compression to the body.[129–131] One of the most predominant new approaches is the utilization of fluidic textile-integrated actuators,[116,122,132,133] and often global patterning of woven fabrics has been used to program inflation.[114,118,121,134]

Many initial haptic devices used closed-loop control to monitor only the actuator state independently. More recently, sensing is increasingly incorporated into many of these devices to detect the state and intent of the user and interactions between the actuators and user. Similar to previous application areas, IMUs placed onto textiles have been used to determine user position[127] and film-based force sensors have been used in insoles for gait detection.[132] Flexible-film[121] and textile-based[114,134] resistive and and capacitive pressure and force sensors have been employed for force control of actuators to ensure desired forces are applied to the wearers' bodies.

Several key metrics determine the materials and development of wearable robots for haptics, including actuation mechanism, feedback stimulus type, DOF, actuator resolution, actuation displacement, and bandwidth. The tactile receptors in the skin are sensitive to varied frequency ranges, spanning approximately from 1 to 1000 Hz,[116,126,135] driving relevant bandwidths for both actuators and sensors. The spatial resolution of these receptors also varies from 0.5 to >20 mm.[116,126] And when differentiating between two stimuli, differentiation thresholds vary based on the location on the body. The fingers and lips require lower spacial detection thresholds (<10 mm) compared to the forearm and calf (>40 mm).[136] When this receptor density and differentiation ability are considered along with the amount of information the robot needs to convey, the materials and viable fabrication strategies with compatible resolutions can be determined. Mechanoreceptors in the skin are not equally sensitive to different feedback mechanisms (e.g., point pressure, skin stretch, compression), which in turn can define which textile actuation mechanisms and materials are practical. For example, fluidic actuation has been used for skin stretch and pressure feedback,[114] while SMA approaches have been primarily used for compression feedback.[129–131] Force parameters can define which sensors and actuators are well suited to these systems, and for tactile information, studies have indicated relatively low forces (3–4 N) enable the user to perceive large amounts of information.[137,138] For more information, we suggest the following resources.[116,136,138]

2.6. Therapeutic Compression

The clinical use cases for therapeutic compression range from treatment of burns and burn scarring,[139–142] to sensory-based interventions for children with mental health and developmental disorders such as attention deficit hyperactivity disorder and autism,[143–145] to treatment and prevention of lymphedema, deep-vein thrombosis, and venous ulcers.[146–151] Recent evidence has suggested that cyclic mechanical stimulation can also improve regeneration of injured skeletal muscle when compared to no intervention.[152]

Passive pressure garments have been used clinically; however, a large amount of customization is required to create garments that impart the required pressures,[142] intermittent compression cannot be achieved, and in some applications, such as developmental disorder intervention, users become acclimated to sustained pressure over time.[143] To overcome these challenges, wearable robots for therapeutic compression have been developed to apply cyclic and reprogrammable sustained pressures, with the caveat of requiring power sources. Unlike the compression seen in dressing applications, these garments typically operate at higher pressures and for longer functional activation time frames (e.g., >20 h of continuous pressure per day has been suggested to treat lymphedema and burns[139,146] vs a few minutes of actuation needed to don and doff the garment in dressing activities). By incorporating variable compression systems into robotic garments, the cost of treatments can be lowered,[153] and the dosage of treatment can be increased. These outcomes are made possible by requiring less garment customization to achieve specific pressures (i.e., by using force- and pressure-based feedback control schemes, garments of a set size could potentially apply prescribed pressures to wearers of different body types), which can potentially expand device availability and enable users to remain mobile during treatment.

Robotic garments that deliver therapeutic pressure have incorporated fabric-based actuation systems in cable driven, fluidic, and active shape-changing material configurations. Cable driven fabric sleeves with a hybrid fabric-ABS design have been used to generate pressure for the arm.[154] Fluidic-based robots incorporating textile-based actuators have been used to apply forces to the limbs while remaining lightweight and compliant.[155–157] SMA-based wearable robots have been used to apply compression to the torso and limbs,[158,159] where the fabric acts as a scaffold to support compression and maintains a thermal barrier between the SMA and the skin. An additional consideration includes developing actuation systems for distributed pressure in order to avoid pressure peaks, which are a potential safety hazard.

Sensors can potentially play a key role in wearable robots for therapeutic compression. Although many pressure garments currently used in clinical settings do not offer facile and quick continuous monitoring of pressure applied by the garment, in some cases the dose (e.g., frequency and amount of applied pressure) has been noted as a determining factor in treatment effectiveness.[140,160] As illustrated in passive pressure garments, the shape of the area of the body the garment is worn on can affect the interfacial pressure applied to the body[161] and, in fluidic active pressure garments, tissue fluid pressures generated can be lower than the set pressure in the inflated chambers.[162] Recent therapeutic compression robots with integrated textile pressure sensors measure pressure at the skin-robot interface for force-based feedback control schemes. Using this strategy, the prescribed forces applied to the body were more accurately delivered than when simply monitoring the air pressure delivered to actuators.[155] Building on this work, fabric-based sensors have been used in control schemes for cable driven compression systems,[154] while arrayed soft film-based sensors have enabled monitoring and control of multiple chambers in fluidic systems.[163,164] The variability of the body shape and additional

Table 1. Representative required metrics based on a literature survey.

	Locomotion	Grasping and reaching	Dressing	Thermoregulation	Haptics and communication	Therapeutic compression
Device goal	Apply force to wearer	Apply force to wearer	Change garment shape OR apply force to wearer	Change garment shape	Apply force to wearer OR change garment shape	Apply force to wearer
Duration of use	A few to many hours per day	A few to many hours per day	A few minutes per day	Many hours per day	A few minutes to many hours per day	Many hours per day to several days at a time
Typical required force	High (<500 N)	Moderate (<100 N)	Estimated low (<10 N)	Estimated low (<10 N)	Low to moderate (<50 N)	Low to moderate (<75 N)
Required strain	Low to moderate (<40%)	Moderate (<75%)	Estimated moderate to high (<100%)	Estimated low to moderate (<50%)	Estimated low to moderate (<40%)	Estimated low to moderate (<50%)
Typical required speed relative to human motion	Moderate to slow (<5 Hz)	Moderate to slow (<10 Hz)	Estimated slow (<1 Hz)	Estimated slow (<1 Hz)	Varies (<1000 Hz)	Slow (<1 Hz)

precision offered by monitoring interfacial pressure signifies the need for distributed soft and conformable fabric pressure sensors to map and regulate pressures in these wearable robots.

Recommended amounts of pressure vary based on the application. Recommended pressures to treat hypertrophic scars, which can occur after burns, are between 24 and 44 mmHg (approximately 3.2 to 6.9 kPa),[139] while prescribed pressures for lymphedema treatment can range between 30–60 mmHg (4–8 kPa),[146] with some devices offering up to 300 mmHg (40 kPa) of pressure.[148] Pressures of 45–160 mmHg (6–21.3 kPa) have been reported for the treatment of deep vein thrombosis.[165,166] Such prescribed pressures are often for the actuator inflation; as discussed, interfacial pressures can vary. Robotic compression garments for autism have been built based on the above specifications.[158] In some applications such as sensory interventions for autism, sustained pressures are used, and in others, like treatment for lymphedema and deep vein thrombosis, intermittent compression is more common.[146,148] For example, in the case of lymphedema treatment, reported cyclic actuation speeds range from 0.5 to 0.008 Hz,[148] while for deep vein thrombosis cycle times up to 0.45 Hz have been reported using rapid inflation (as quick as 0.5 s) and moderate to slow deflation to complete the cycle.[165,166] While some of the above metrics are currently being applied in clinical settings, experts suggest that more work must be done to determine the optimal effective parameters.[146–148,167] An upside for materials scientists and roboticists in regards to this challenge is that by using robotic garments in future studies, better control of pressure profiles and doses can be achieved and monitored, and thus these parameters can be more accurately and systematically studied.

2.7. Comparing Metrics Based on Applications

To provide a quantitative set of metrics for materials scientists to refer to as they develop constituent textile materials and components for wearable robots, a survey of 163 textile-based wearable robot device papers was conducted. Maximum forces, speeds, and displacements were tracked based on application area, with findings described in **Table 1**. Graphical representations of several key metrics are shown in **Figure 5** and Figure S1, Supporting Information. More detailed information on these metrics and devices is provided in the Supporting Information. As expected, some of the highest forces are required for locomotion assistance because of the requirement to move the lower extremities. Grasping, lifting, and reaching also had relatively high force requirements, although there is large amount of force variation owing to specific variations in use cases and joints assisted—for example, ranging from assisting a post-stroke patient moving their fingers to assisting the elbow of a warehouse worker lifting heavy boxes. In addition to these quantitative metrics, the actuation strategy for devices in each application was recorded as well as the presence of sensors, as displayed in **Figure 6** along with medians across all metrics for each application area.

Compiling these results provides insights into the metrics that fields choose to characterize and report, and how they vary based on the application. For example, wearable robots for haptics are commonly characterized in terms of pressures and not torques because devices usually apply normal pressure to the body, as opposed to rotating a joint. Additionally, gaps in the field can be identified. For example, based on this survey, few thermoregulation garments have been demonstrated to date, and little characterization of the actuation forces, speeds, and strains for garments used for thermoregulation exists, opening up some interesting research questions: for example, what distributed forces are required? With the synthesis of this information, we hope to provide some specific ranges to target when developing robotic materials.

3. Textile Science and Technology for the Future of Wearable Robots

Textiles are one of humankind's oldest technologies, with human-made cords dating back tens of thousands of years.[168,169] Although this long history provides a number of techniques to draw from when developing wearable robots, advances in equipment and scientific understanding of textile structures are still made every day.

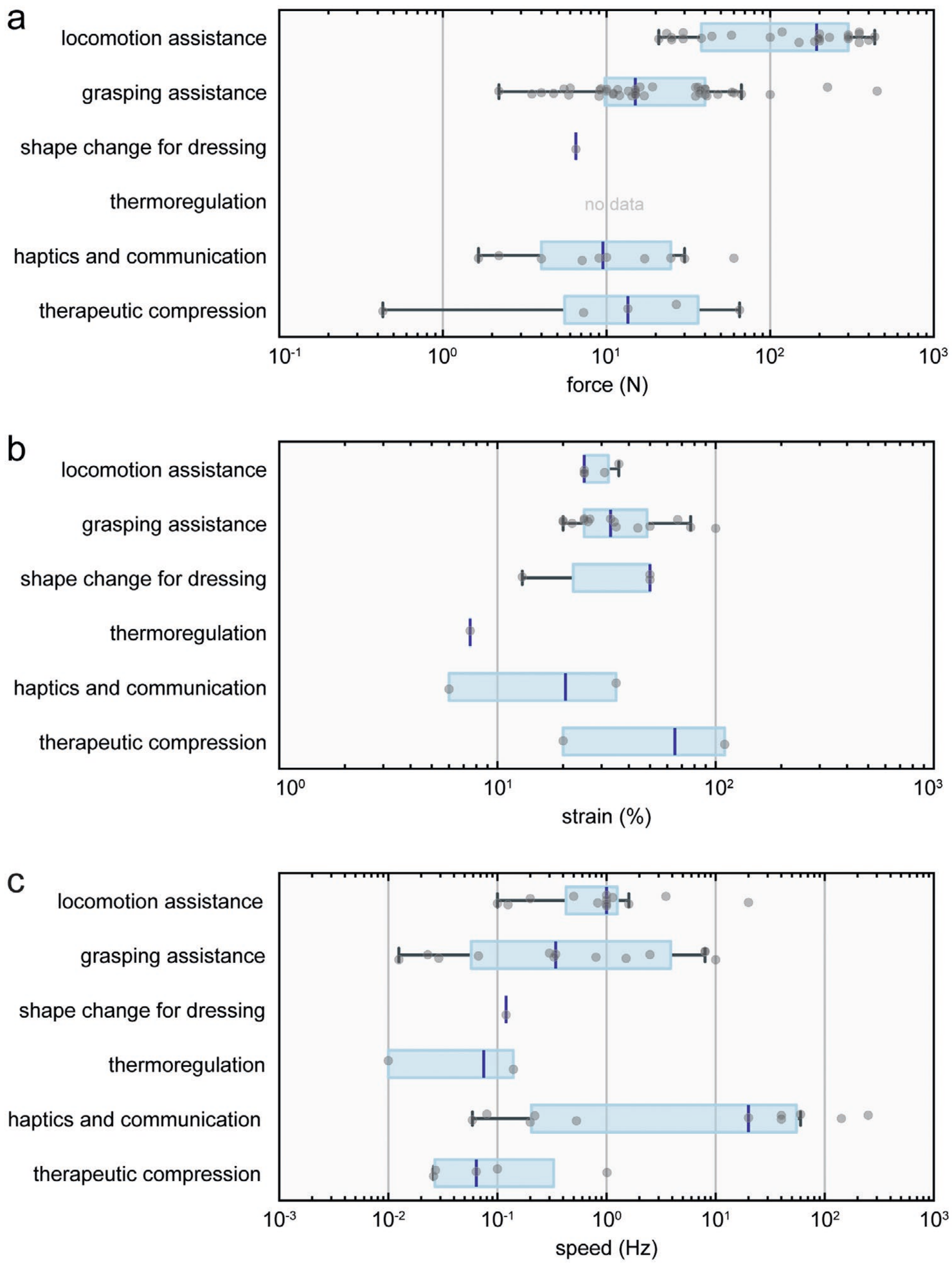

Figure 5. The maximum metrics of a) forces, b) strains, and c) speeds across device applications.

In the simplest sense, textiles are networks of interlacing and inter-looping flexible rods, or yarns, whose length is much greater than their diameter. When incorporated into textile architectures, these seemingly simple yarns can generate complex materials and behaviors, resulting from the inherent hierarchy in their structuring (**Figure 7**). As such, textile science is a field that follows a geometric and fabrication-focused nomenclature system. The smallest material unit (above the molecular level) when considering textiles is the fiber. Fibers are spun into yarn, commonly encountered as sewing thread or knitting yarn. Yarns are structured into textiles, wherein the structuring parameters can impart unique mechanical properties, including anisotropy and stretchability. Several of these textile structuring processes support simultaneous global shaping into 3D shell structures. Alternatively, sewing and bonding techniques are used to adhere multiple pieces of textiles into shell shapes in what is known as cut-and-sew processing.

3.1. Fibers, Yarns, and Cords

Fibers are the smallest unit of textiles. Fibers have two classifications: filament fibers, which are functionally infinite continuous strands; and staple fibers, which are short pieces less than several inches in length (Figure 7). Most synthetic fibers are available in filament form, while natural fibers are typically limited

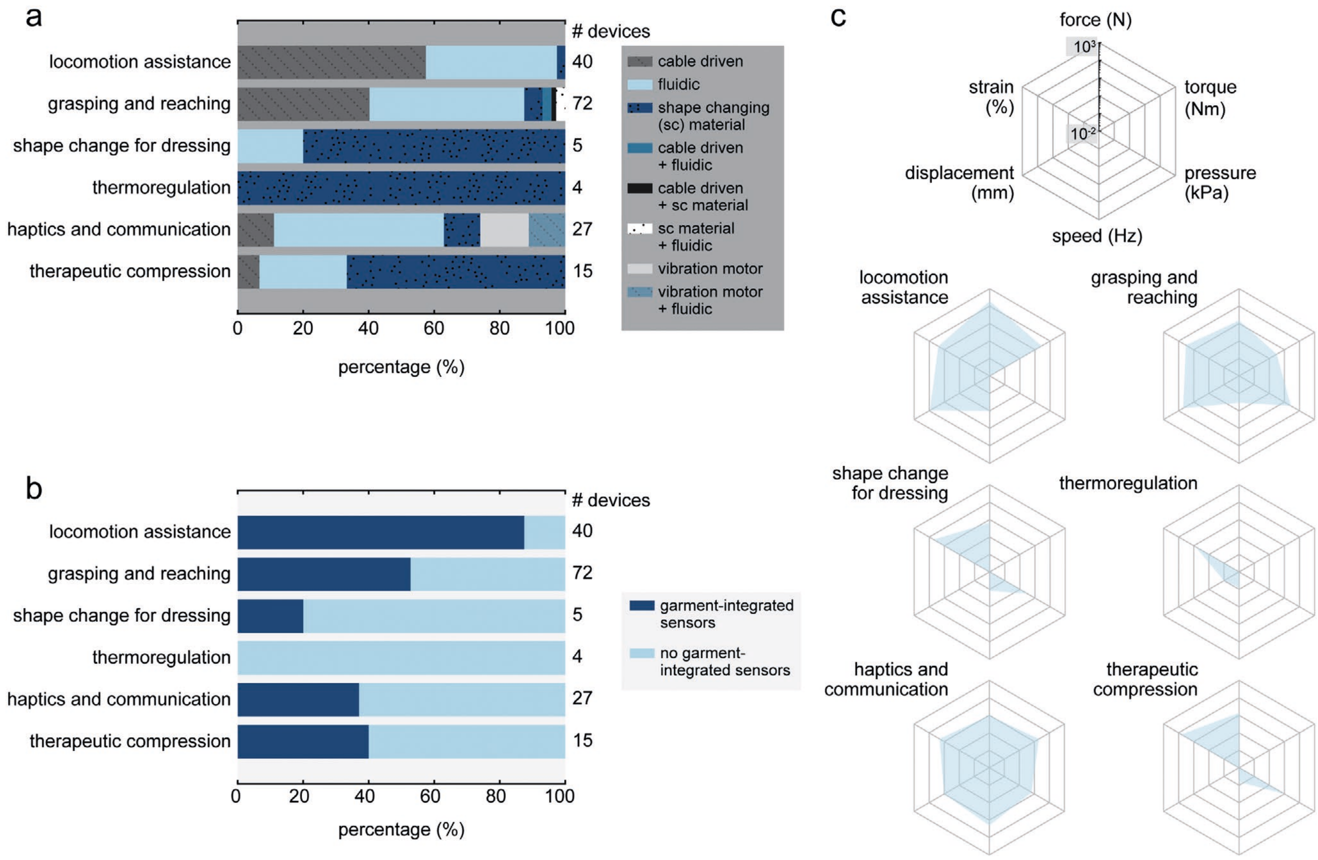

Figure 6. Metrics across textile-based wearable robots based on application. The a) actuation method and b) use of sensors vary based on end application. These variations may be related to the required metrics for the devices. c) Plotting the median maximum values on a logarithmic scale helps visualize these differences in device requirements.

to staple. Synthetic fibers are formed through several processes including melt spinning, thermal drawing, and wet spinning, and resulting fibers can be made of multiple materials and may have complex (non-circular) cross-sections. Multi-material fibers have been employed by materials scientists as actuators,[111] sensors,[170] and conductors used as power and signal lines.[171]

Fibers are then structured, or spun, into yarn, with several yarn constructions illustrated in Figure 7. For staple fibers, this process requires the fibers to be aligned and twisted into shape. While filament fibers can be twisted, they do not require twist insertion or multiple fibers to constitute a final "yarn," instead inherently functioning as a monofilament yarn without further modification. In addition to these basic yarns, more complex yarn structures are possible; multiple yarns can be twisted together (typically in the opposite direction that the constituent yarns were twisted, e.g., counterclockwise if originally twisted clockwise) into a "plied yarn." A yarn can be corespun, wherein "cover" fibers or yarns are wrapped around a core yarn; typically this core is an elastomeric monofilament and is covered with non-stretch staple, resulting in a stretch yarn with non-stretch material at its surface. This construction is commonly employed by materials scientists developing strain sensors.[172–174] "Fancy yarns" are a class of yarns that intentionally introduce defects into the structure, and, although not yet embraced by materials scientists, they offer another promising avenue of imparting anisotropy.[175,176]

Cords include ropes, filled braids (as opposed to the hollow braided tubes covered later in this section), and fibrous materials with other post-processing techniques including knotting. These materials are less commonly structured into textiles; however, some of the capabilities of these materials find function as materials for textile robots. Unlike common twisted yarns, braids do not twist under load due to their self-balanced enlaced structure, potentially motivating their current use as tendons in cable driven actuation systems. Conductive wires are braided to impart more flexibility as opposed to a solid core wire of the same gauge, and materials researchers have recently structured these wires into knit and woven textiles to be used as signal lines.

3.2. Textile Structural Formation

3.2.1. Wovens

Woven textiles are made by perpendicularly interlacing yarns in a machine called a loom (Figure 7). The yarns held in the longitudinal direction during production are known as the warp, while yarns that are inserted into these warp yarns in overlapping configurations are known as the weft. These directions may define the fabric's mechanical properties; warp

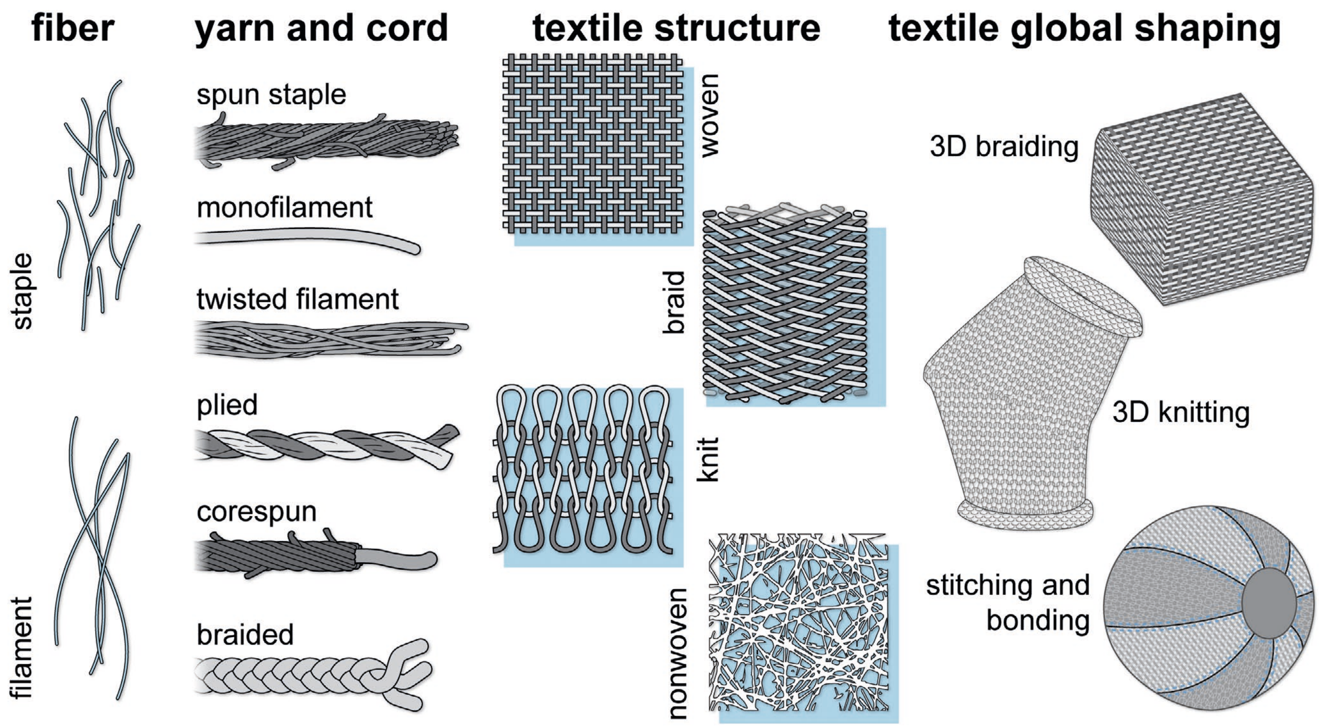

Figure 7. The hierarchy of textiles. Fibers are spun or twisted into simple yarns which in turn may be structured into complex yarns and cords (plied, corespun, braided). These yarns and cords can then be made into textile micro-structures. Some textile formation techniques, such as knitting and braiding, support 3D shaping during structural formation, while others, such as wovens, are typically formed into 3D structures through stitching and bonding.

yarns must be pulled taught for long periods of time in the weaving process, and therefore stiffer yarns are typically used, while thicker yarns are often used as the weft to improve production speed. By varying how the weft yarns pass over or under warp yarns in formation, the weave structure and textile properties change.[177] Plain weave (a checkerboard pattern) is the most common, while twills impart a diagonal, and satins and sateens have long floats (lengths of yarn without interlacings). Jacquard looms allow for the greatest amount of design complexity in this patterning due to individual warp control (Figure 1a).

Wovens are typically non-stretchable textiles (e.g., a button-down dress shirt or a pair of jeans) unless elastomeric yarns are included in their structure. Wovens are used specifically for their high tensile stiffness in wearable robotics, exemplified by the use of narrow woven seatbelt webbing to distribute force in locomotion assistance robots.[3,41] However, there is some inherent stretch in wovens. Because woven fabrics are formed with perpendicular 90° interlacings, when a force is applied at a 45° angle, also known as the bias direction, the textile can stretch because there are no yarns in a linear configuration in this direction. Regardless, when elastomeric yarns are incorporated into woven structures, unique mechanical properties can be achieved quite simply; for example, woven waistband elastic typically has a Poisson's ratio of approximately zero.

Machinery variations have enabled the production of more complex woven structures including gauzes that achieve the crossing of multiple adjacent yarns.[177,178] By using looms with multiple warps, and subsequently cutting the two textile layers apart, pile weave textiles, wherein additional yarns protrude perpendicularly from the structure, can be produced with increased material surface area (e.g. velvet).[177] Although weaving perhaps lends itself least easily to the formation of 3D geometries based on standard equipment, multiple warp looms have been further developed and repurposed to produce 3D woven geometries. 3D wovens produced in this manner include solids where multiple layers are interlaced, as well as shell-like 3D spacer fabrics with large air gaps between connected structures, similar to cardboard.[179,180]

Researchers have recently leveraged simple woven structures to create textiles with even more unique mechanical properties. Auxetic wovens have been formed on basic looms by inserting a combination of elastomeric and non-stretch yarns as the weft and varying the type of woven structure to produce blocks of looser and tighter weaves. Zulifquar and colleagues first demonstrated this principle with uniaxial elastomeric yarn insertion,[181] while Cai and others translated this concept to woven textiles that could stretch biaxially.[182,183]

3.2.2. Braids

Braids are familiar textile structures formed with three or more yarns, and typically are structured through machinery with sets of two or more of interlacing yarns, similar to wovens (Figure 7). However, unlike wovens, braids are produced when two or more sets of yarn carriers rotate in circular patterns (one set clockwise, and the other counterclockwise) to intertwine yarns into a structure.[184] A third set of yarns fed parallel to the formed length of the braid may be inserted in triaxial braiding.[185] Braids are commonly produced with yarns at various angles (compared to the 90° angle standard in wovens), described by the "braid angle" between each yarn and an imaginary line parallel to the axial direction of the overall braid structure. This angle has consequences for the mechanical properties of the braid, as seen in McKibben actuators.

Braids easily lend themselves to simple 3D shell shaping. A predominant method of forming braids is maypole braiding, which may be performed by braiding around a circular mandrel[184] and creating a braided textile that is pre-formed in a tube shape, depicted in Figure 1f; this technique is commonly used for McKibben fluidic actuators. Methods of creating more complex 3D braided shell structures by forming braids over mandrels with additional shaping have been suggested and demonstrated.[179,186,187] In the fields of braiding and composites, these 3D shell shapes are known as 2D braids (because of the shell nature of the textile). Meanwhile, "true" 3D braids exist, but require additional systems of yarn carriers.[179] For more information on the braiding process, we suggest these references.[179,185]

3.2.3. Knits

Knits are systems of interlaced loops of yarns that afford the greatest diversity in terms of mechanical properties among textile structures.[188] By varying the manner in which yarns interlock, very stiff and very stretchable regions of material can be made in a monolithic manner on one piece of equipment. For example, most people are familiar with the stretchable jersey knit of a T-shirt, but by adding inlay (or weave-in) yarns during the knitting process, taut linear yarns can be incorporated into one direction of the looped structure, forming a material with highly anisotropic stiffness.[179]

The two automated knit fabrication methods are warp knitting and weft knitting. 3D flatbed weft knitting (or V-flatbed or X-flatbed knitting) can seamlessly produce a wide variety of microstructures and 3D shapes.[188–190] Industrial 3D weft knitting machines by manufacturers such as Stoll and Shima Seiki are widely available for production manufacturing, and recently, a simplified benchtop version with core capabilities for prototyping has been developed by the company Kniterate (Figure S2, Supporting Information). In a weft knitting machine, rows of knit loops are formed by pulling new loops through previously formed loops in a horizontal, or "weft-wise", manner, while in warp knitting individual yarns at each needle form loops in a "warp-wise" manner. For both knitting strategies, the rows of loops are called the courses, while columns are known as wales, and these directions typically have anisotropic mechanical stiffness, affecting the behavior of textile components like knit sensors.[10,13]

The weft knitting process enables users to vary parameters like the loop length and yarn tension while also providing the ability to employ a wide variety of stitch operations.[190] These stitch operations include knit (a loop), purl (a reverse loop), tuck (a loop made while holding the loop from the previous row(s)), miss (do not form a loop), and transfer (move the loop to a different needle), which, when used together, alter the geometry and mechanics of the resulting knit material. Machines also enable the direct placement of multiple materials illustrated in Figure 1b through techniques like stripes (where the yarn type is changed at a row), plating (where a machine varies which one of two or more yarns is on the "face" of the knit), or intarsia (which enables discrete material placement within a row). Knitting machines also enable the simultaneous ability to impart global shaping of a material "shell" through operations called short row knitting, transfer-based increases and decreases, or formation of a tube using two separate needle beds. For more detailed explanations of the knitting machine operations and global shaping process, we recommend the following resources.[113,189–191]

In soft robotics, several programmed material concepts, such as origami[192,193] and kirigami,[194] have been leveraged for actuator and sensor development to introduce directed and controlled anisotropy for desired kinematics or structural properties. Researchers working in the area of knit structure development have been able to use knit operations to incorporate similar structuring into knit textiles. Self-folding knits, reminiscent of origami, have been formed through alternating knit and purl loops[195,196] (Figure 1d), or through varying the number of stitches in adjacent rows, forcing "bubbling" through short row and transfer-based increase and decrease shaping techniques.[196] Unlike origami, these knit structures have the advantage that they can potentially be made in tubes without added adhesives or connection strategies, enabling complex shell structures like multi-branched tubes (Figure 1g).

Some of the same strategies for self-folding knits can be utilized to form auxetic knit structures. Zigzag blocks of knit and purl stitches[197,198] as well as alternating horizontal and vertical knit and purl stripes[199] have been used to form auxetic fabrics on flatbed weft knitting machines. Inspired by the kirigami process, knit structures with integrated holes and "hinges" function as auxetic textiles based on rotations of geometric planes.[199] Although this section focuses on flatbed weft knitting due to the range of machine functions, other knitting methods such as warp knitting enable the production of unique materials as well; for example, auxetic warp knits have been structured with a hinging technique.[200] Although not yet used in robotic garments, these programmed materials highlight some of the newest capabilities in knitting structuring and, based on their success in other soft robot implementations, may have potential in programming actuator motion or improving sensor performance.

3D flatbed knitting provides levels of automation not available with manual knitting and enables placement of variable knit microstructures, and thus mechanical properties, in specified areas on 3D shell shapes. However, programming the 3D flatbed knitting machinery is an infamously complex process where each individual needle operation must be controlled, with only a few experts able to produce full knit patterns.[191,201] The description by McCann and colleagues may explain the process best; programming these machines is akin to "requiring all CNC machine users to write toolpath G-code by hand, or all computer programmers to work in assembly."[191] To improve the usability of 3D knitting machines, computer science researchers are developing new computer-aided manufacturing